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"Cities on Volcanoes 10"

Millenia of Stratification between Human Life and Volcanoes: strategies for coexistence

2 | 7 September 2018, Napoli, Italy

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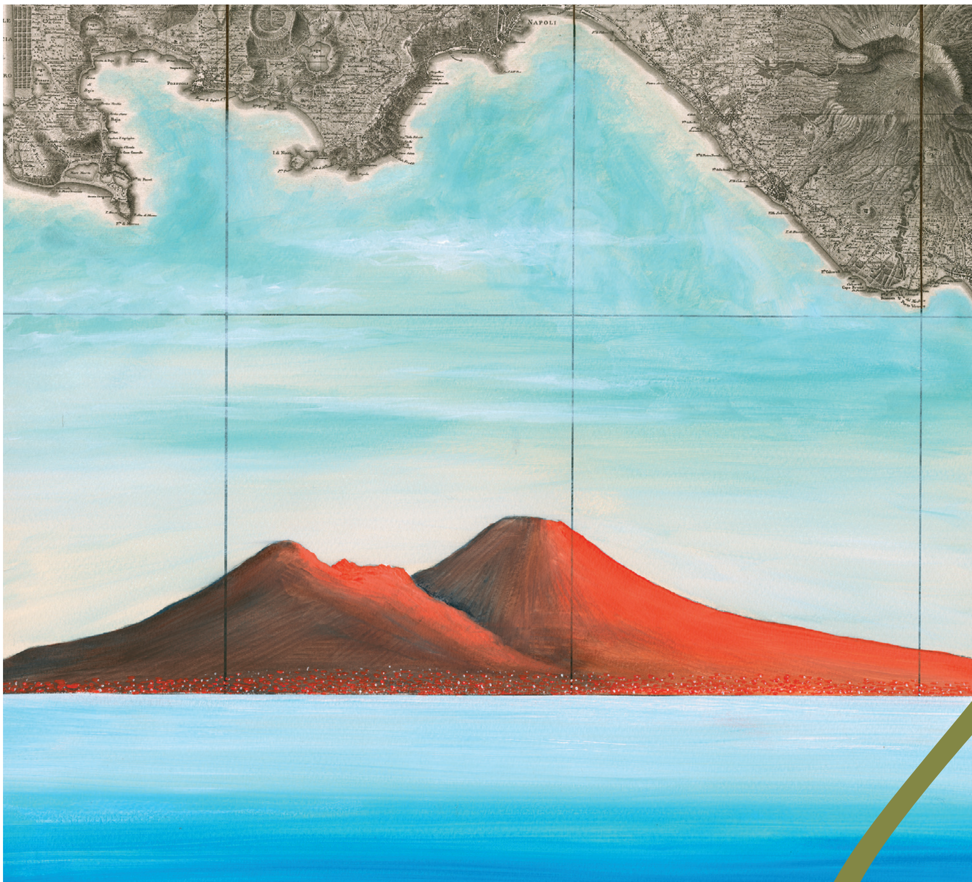
MILLENIA OF STRATIFICATION BETWEEN HUMAN LIFE AND VOLCANOES: STRATEGIES FOR COEXISTENCE

2 | 7 SEPTEMBER 2018, NAPOLI, ITALY

Editors Rosa Anna Corsaro, Maria Giulia Di Giuseppe, Roberto Isaia, Angela Mormone, Rosella Nave



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NAPOLI - ITALIA 2018

CITIES ON VOLCANOES 10

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Symposium 1

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S01.01 - Analogous studies of volcanoes, their eruptive activity and their preceding unrest

New Insight on the 2014 Initial Eruption Deposits of Mt. Kelud, Indonesia

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Four years have passed since the Plinian eruption of Mt. Kelud, Indonesia occurred in 2014. During observations in September – October 2017, we found at least 3 pyroclastic units surrounding Mt. Kelud. A new outcrop near the crater has exposed complex layers of pyroclastic deposits produced in 2014 and previous eruptions. We will focus on the discussion about the latest product sequences prior to the Plinian eruption.

The approximately 4 m of pyroclastic deposits exposed on the western flank of Mt. Kelud represent the sequence of the eruptions from 2014 and older products. The recent eruption products are piled up to about 1.7 m with 7 layers of pyroclastic deposits, preserving the initial eruption prior to the Plinian eruption. The initial eruption produced deposits with organic materials whereas the Plinian eruption produced deposits with abundant pumice. We found out that the initial eruption deposits are distributed along the southern, northern, and western flanks as well as inside the crater. The southern flank deposits show a single layer of deposits containing carbonized wood whilst the northern flank deposits show gradational layers with uncharred organic content. However, the western flank and the crater record multiple layers of deposits with carbonized wood. These variations in thickness can be accounted for by the crater shape. The western crater rim, which has no barrier wall, might accommodate the PDCs thus allowed the formation of multiple layers deposit.

Petrography and SEM-EDS analyses have been and will be conducted to characterize the volcanic ash in each layer of the newly exposed outcrop, correlated with the crater deposits. The abundance of oscillatory zoning and sieved-texture in the plagioclase showing the disequilibrium of magma may indicate rapid decompression and magma mixing, correspond to the lava dome devastation. SEM-EDS analysis will be performed to obtain detailed data for further interpretation.

S01.01 Poster

Fuzzy Inference System for Merapi Alert Level Decision Making

Agus Budi-Santoso[1], Indra Rudianto[1], Rahmad Widyolaksono[1], Sulistiyani[1,2], Erickson Fajiculay[3], Nang Thin Zar Win[3], Christina Widiwijayanti[3], Fidel Costa[3,4]

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The most challenging task faced by volcanologists during volcanic crisis is to interpret the monitoring data, using background knowledge on past eruptions, to better anticipate the evolution of unrest and implement timely mitigation actions. At present, around 5 million people live on the flanks of Merapi volcano and some major infrastructures (airports, national roads, schools, etc.) can be at immediate risk from volcanic hazards. During volcanic crisis, early warning issuances by volcano observatory in the form of alert level is critical. Incorrect decision-making and improper response in terms of timing and recommendations could lead to fatalities and socio-economic losses. To anticipate future crisis and to improve decision-making, we have examined the progressive alert level changes of the 5 past eruptions of Merapi between 1996 and 2010; from normal-to-advisory (1-2), advisory-to-watch (2-3), and watch-to-warning (3-4). We created an inference system based on past unrest data that include daily earthquake counts, deformation, and gas. These time series data were analyzed using WOVOdat analytics tools (e.g. Bayesian inference, rate, etc.) to detect changes of behavior of each data type ("evaluative indicators") within 10 days prior to the onset of alert. The evaluative indicators obtained were then used as the basis of creating input variables and membership functions of a Fuzzy Inference System (Mamdani model), which yields two output variables: the alert level change and eruptive style (effusive or explosive). For validation we tested the robustness of this approach with Merapi 2010 crisis (VEI4 eruption). Using the multi-parameter monitoring data of 2010 unrest, we obtained a consistent result that reflected the corresponding escalating unrest and timing of progressive alert change. Fuzzy inference system obtained from this study will be inferred as one of the reference for future alert issuance at Merapi.

Explosive or effusive? What controls the eruptive style of volcanoes

Mike Cassidy[1], Michael Manga[2], Katherine Cashman[3], Olivier Bachmann[4]

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[4]*ETH Zurich, Switzerland*

One of the biggest challenges in volcanic hazard assessment is to understand how and why eruptive style changes from one eruption to the next, or even within the same eruptive period. Here, we review the different ways of producing both explosive and effusive eruptions from silicic magmas. Eruptive style depends on a set of interrelated magmatic properties, such as viscosity, processes such as gas loss and external properties such as conduit geometry, which altogether initiate various feedbacks. Ultimately, these control the speed at which magmas ascend, decompress and the extent of outgassing en route to the surface, and thus determines eruptive style and evolution. Understanding the dominant parameters and processes that affect eruptive style and striving to measure these during volcano monitoring, may be the most promising way to improve forecasts of eruption style and explosivity.

S01.01 Talk

Automated growing of miniature volcanoes in lab: new opportunities for observing long-term trends on basaltic oceanic islands volcanoes

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Eruptive vents (e.g. cones and craters) at oceanic island volcanoes tend to cluster in preferential injection zones, while eruptions in exceptional, often inhabited areas occur less frequently. Especially the latter may threaten human lives and property. Such distal eruptions often involve horizontal magma transport over long distances. Understanding the processes behind vent repartition and producing vent opening probability maps constitute a step further towards a better volcanic rick mitigation. We conducted gelatin lab experiments that replicate an oceanic island volcano. Both magma and host rock were made of gelatine at 4.5 weight percent. Identical volumes of “magma” were injected 360 times from below an initial crust at intervals of 30 minutes. Each injection was characterised by the emplacement of a new dyke/sill/laccolith/external flow. The magmatic pathways naturally developed in a geometrical manner as opposed to a random pattern. Three sub-vertical “rift zones” at approximate 120˚ angles were accompanied by the formation of deep (near-source) and shallow (near-base) sill complexes. Consistently with previous studies, stress permutations inside the edifice were key factors dictating magmatic pathways and vent locations. Over time, near-surface extensional stresses became mostly radial in the summit zone and tangential on the central cone flanks, explaining the orientation of eruptive fissures. At depth, extensional stresses permuted between vertical and tangential, explaining the cycles of sill/dyke intrusions. Analogue experiments abstaining from regional stress field can replicate the behaviour of intraplate basaltic shield volcanoes remarkably well and therefore open new opportunities for observing long-term trends of edifice growth and internal stress field variations. The effect of parameters such as repose time between injections or injection rate have yet to be explored, promising interesting developments for such models.

S01.01 Talk

Anticipating Volcanic Eruptions using DNA-like Precursors through machine learning

Erickson Fajiculay[1], Agus Budi-Santoso[2], Sulistiyani[2,3], Nang Thin Zar Win[1], Christina Widiwijayanti[1], Fidel Costa[1,4]

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The anticipation of eruptions remains one of the most challenging problems in volcanology. Here we take a new look at the problem using machine learning with a representation of the time series data into symbols similar to a DNA sequence derived from Symbolic Aggregate Approximation and position penalized Sørensen-Dice similarity coefficient. We focus our analysis on the seismicity patterns of Merapi Volcano hybrid earthquake counts from 1983 to 2017, which includes 28 unrest episodes and 21 eruptions, ranging from phreatic to VEI4. The seismic data are transformed to log(y+1), normalized to a range of 0 to 1, and smoothed using Piecewise Aggregate Approximation with a bin of 6 days. The transformed y-axis is then divided into bins and integrated into 7 equiprobable regions, which are given symbols from A to G. The approach was also tested on synthetic data with the same distribution as the Merapi hybrid earthquake counts generated using Markov Chain Monte Carlo (MCMC). Different levels of noise were introduced to the synthetic data to investigate the extent DNA-like precursor can match regions before eruptions. Initial results show that the pattern "ACGFGGGGGG", the precursory sequence 60 days before the 1996 VEI3 eruption, matches 7 eruptions with sequence match > 40 %. There are two false positives with sequence match > 40 %, and 13 unmatched eruptions with sequence match < 40%, but 10 of which are phreatic eruptions. These are encouraging results that able to identify characteristic unrest patterns before eruption and distinguish between different eruptive styles. Automation of pattern extraction, threshold detection, optimization of sequence length, and number of symbols to use are currently under development. The potential of the used of DNA-like eruption precursor to other data type will be further investigated. This machine learning algorithm is available as part of WOVOdat' analytics tools (www.wovodat.org).

S01.01 Poster

Comparative study of lava dome eruptions at Sinabung and Unzen

Setsuya Nakada[1,4], Akhmad Zaennudin[2], Mitsuhiro Yoshimoto[3], Fukashi Maeno[4], Natsumi Hokanishi[4], Masato Iguchi[5]

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Though the analogy of different lava dome eruptions is useful to prepare for future hazards, a minor difference in the background may introduce hazards beyond the expectation. Continuous magma discharge for >4 years and with the largest discharge rate (6 - 8 m^3/s) at the beginning characterizes lava dome eruptions at both Sinabung and Unzen. Lava dome grew near the volcano summits, PDC event repeated due to the partial collapse. So far, Sinabung continues its activity with the rate as low as <<0.5 m^3/s, its eruption style becoming much different from at Unzen. The lava dome grew endogenously in the discharge rate <1 m^3/s at Unzen, and a lava spine formed above the vent in the rate <<0.5 m^3/s. On the contrary, daily explosive events repeated at Sinabung for more than 2 years. The largest explosion occurred on 19 February 2018 at Sinabung, the dome at the summit was completely brown off, and the activity had declined since then.

The discharge rate is inversely proportional to the dome thickness above the vent, implying that the discharge rate is controlled by the lava load on the vent. When the lava spine formed in other lava dome eruptions including Unzen, the thickness reached *c.*250m. At Sinabung, however, it was as small as *c.*150m, due to successive collapses of lava dome grown at the narrow summit area. As a result, the lava load was not balanced with the overpressure of magma in the upper conduit at Sinabung. Magma flowing became sluggish for some reasons, such that explosion events repeated for a long time (bubble pockets rose with equally spaces). A large dome collapse accidentally triggered by a small explosion, generated a large magma's depressurization in the upper conduit, resulting in the largest explosion on 19 February.

Volcanic hazard assessment at Jailolo Volcano, Indonesia: Challenging the total epistemic uncertainty

Luigi Passarelli[1], Laura Sandri[2], Pablo Tierz Lopez[3,4], Sophie Mossoux[5], Claus Milkereit[1]

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[3]*British Geological Survey, The Lyell Centre, Edinburgh, UK*
[4]*University of Edinburgh, School of Geosciences, Edinburgh, UK*
[5]*Vrije Universiteit, Brussel, Belgium*

Long-dormant volcanoes challenge volcanologists to produce unbiased hazard assessment. They are less attractive in triggering the same scientific interest than the more-active, data- rich volcanoes, by resulting in a lack of geological and petrological that can reduce epistemic uncertainties on the eruption. In addition, little studied volcanoes make difficult the quest for analogous systems that could be used to reduce epistemic uncertainty. However, when these volcanoes become restless, there is a societal need for immediate hazard assessment of magnitude and style of a future eruption. This is the case of Jailolo volcano, located in the West Halmahera, North Moluccas, Indonesia. Jailolo volcano is not included in the Indoensian list of active volcanoes whereas the Global Volcanism Program database classifies it as potentially active. In the last three years, Jailolo showed signs of unrest. An energetic seismic swarm occurred in winter 2015-2016, presumably of magmatic origin and again in fall 2017, an intense swarm struck underneath Jailolo. The long volcanic unrest and the large number of people (>40.000) and dwellings surrounding Jailolo volcano motivated this study. We use the Bayesian Event Tree (BET_VH) to infer volcanic hazard conditional to the occurrence of an eruption. We set up a spatial probability of vent opening, and account for different possible eruption sizes. We run specific simulations of pyroclastic density current invasion, tephra fall-out and lava flow inundation. Simulation results are combined in a probabilistic framework by BET_VH. To overcome the lack of knowledge about Jailolo's past activity, we combine together theoretical considerations and clear assumptions; we also tentatively select analogous volcanoes and use available studies on the latter ones to constrain the simulations' input parameters. The outcoming probability and/or hazard maps will be communicated to the local authorities and civil defence of West Halmahera Regency for long-term disaster management and risk reduction.

S01.01 Talk

Enlarging or reducing data sets: the support of information from analog volcanoes

Laura Sandri

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Italy

In assessing probabilistic volcanic hazard in the long term, common starting and open issues concern the likelihood of an eruption in a given time window, the range of possible eruptive magnitudes, styles or types (or "scenarios"), and their relative likelihood. However, we often face volcanological records with few, if not zero, past events on which our assessment can be soundly based. In this view, the recognition of analog volcanoes is a necessary task, as the inclusion of data from such analog volcanoes can enlarge the set of available data helping us to answer more quantitatively to the issues above.

On the other hand, when searching for possible recurrent patterns in a data set, common schemes among data may be blurred by the inclusion of data from very different volcanoes, characterized by very different features, tectonic settings and mechanisms governing their processes. In such cases, the extraction from the entire data set of a subset of records coming from analog volcanoes may let emerge some peculiar patterns common only to the subset of analogs.

In this presentation I will show a few examples in which, in my experience, I have benefited from (i) enlarging a dataset through data from analog volcanoes to better constrain the statistics of my target volcano in terms of eruption size, or (ii) narrowing a large dataset of volcanic unrest episodes down to a subset of unrest from volcanoes which are deemed similar for composition of magmas or for the state of opening of their conduits, to identify patterns that are recurrent only among the episodes of unrest at these analog volcanoes.

What controls sill formation? Insights from analogue models

Giulia Sili, Stefano Urbani, Valerio Acocella

Università di Roma Tre, Dipartimento di Scienze, Italy

The mechanisms of magma storage and transport within the crust have important implications for the development of volcanic plumbing systems and for the construction of the continental crust. In particular, sill emplacement represents the easier mechanism to create space into the crust, giving rise to magma chamber formation. Many factors (such as crustal layering and tectonic stress) control sill emplacement by favoring the rotation of an ascending dike. In order to define a hierarchy between a selection of these factors (rigidity contrasts in the host rock, strength of the interface between the layers, tectonic stress, density ratio between host rock and magma, magma flow rate, layer thickness), we performed analogue models by injecting water (magma analogue) within gelatine (crust analogue).

In the analogue models, each of the studied parameters has been varied systematically, fixing all the other variables, comparing semi-quantitatively the variations of area and dip of the intrusions and quantifying the surface deformation due to the different dip of dikes and sills.

Three different experimental classes are discerned based on the imposed rigidity contrasts (defined as the ratio between the young modulus of the upper and lower layer, Eu/El): set H (high rigidity contrast, Eu/El=1.8), set L (low rigidity contrast, Eu/El=1.3) and Set N (no rigidity contrast, Eu/El=1).

The results indicate that a high value of rigidity contrast (i.e. a stiffer layer overlying a weaker one) is a necessary and sufficient condition for sill emplacement while, for medium or low values, rigidity contrasts must be combined with other factors such as a weak interface between the layers or a compressive stress. On the contrary, density ratio between host rock and magma, magma flow rate and layer thickness show a minor effect on sill emplacement despite the value of the rigidity contrast.

Strombolian eruption styles: insights from Yasur Volcano, Vanuatu

Benjamin Simons, Shane Cronin, Jennifer Eccles

School of Environment, The University of Auckland, Auckland, New Zealand

Strombolian eruptions are characterised by explosions of large gas bubbles in near-surface conduits of mafic magma, ejecting spectacular showers of lava bombs, ash and gas. There is a large variation in dynamics and consequent hazard of these eruptions, captured in several classification schemes. Event classifications rest mainly on comprehensive observations of the type-locality of Stromboli (Italy). Yasur in Vanuatu is a Southern Hemisphere site of similar continuous Strombolian eruptions and is often cited as the closest analogue to Stromboli. It is the most significant tourist destination in Vanuatu with many hundreds of visitors each week drawn by easy access to the vent and frequent explosions. Despite this, typically only brief periods of geophysical observation have been made so far. We report on an 11-week campaign of continuous observations including thermal-IR, seismic, SO_2 and daily systematic visual records. Based on >5000 explosions, we note similar styles of events at Stromboli, although with differences in mean magnitudes. We also identify an explosion type not seen at Stromboli, resulting when several gas pockets erupt multiple tephra jets, followed by minute-long vigorous ash emission through a hidden vent, deeply buried by loose pyroclasts. The findings in this work extends the global applicability of the Strombolian eruption classification scheme and provides insights into understanding processes that control variations in this range of activity. This study also has important implications for understanding and managing of hazard to visitors at Yasur. The newly described explosions, for example, pose a particular hazard because they have long return times and erupt suddenly from an apparently featureless tephra-filled crater. This may lead to a false sense of safety for visitors. Identifying periods when these types of eruptions occur is thus an important ongoing goal.

S01.01 Talk

The Cretaceous volcanic rocks in the Yeosu area of the South Korea

Kyo-Young Song, Hyeoncheol Kim

Korea Institute of Geoscience & Mineral Resources, Korea

The Cretaceous volcanic and granitic rocks occur along the NNE trend in the southern coastal region of South Korea. The study area, the Yeosu, is located in the south-western part of the Yeongnam massif, and mainly consists of the Cretaceous sediments, andesitic to rhyolitic tuffs and tuffaceous sediments intruded by the Cretaceous granitic rocks. This study is focusing on mainly geochemical characteristics and relationship of the Cretaceous volcanic and granitic rocks in the Yeosu area.

Most of the Cretaceous volcanic rocks belong to sub-alkaline series, and show compositional variations ranging basaltic andesite-andesite-dacite-rhyolite. The other volcanic rocks belong to alkaline series trachy-andesite to trachyte ranges. Most of sub-alkaline series volcanic rocks samples belong to High- to Medium-K calc-alkaline series whereas the others belong to shoshonite-series or Low-K tholeiite series in SiO_2 vs. K_2O plot. The whole-rock K- Ar ages dating for volcanic tuffs are 84.7±1.7 Ma, 84.4±1.7 Ma, 79.5±1.6 Ma, 66.7±1.3 Ma and 60.4±1.2 Ma. Rhyolite and andesite show wide age variation ranging 82.0-57.2 Ma and 81.1-63.2 Ma.

The Cretaceous granites show wide compositional variation ranging from diorite through granodiorite to granite in TAS diagram. Granodiorite porphyry belongs to granodiorite range whereas granite belongs to diorite-granodiorite-granite ranges. As SiO_2 content increases, Al_2O_3, Fe_2O_3, MgO, and CaO contents of the granites decrease whereas K_2O content increases in Hacker diagrams. The 206Pb/238U age for zircon rims of granodiorite porphyry is 85.3±1.2 Ma and weighted mean of SHRIMP zircon 206Pb/238U age of granite is 67.38±0.80.

Based on geochemical analysis, the Cretaceous volcanic and granitic rocks in the Yeosu area was formed under the subduction-related primitive arc magmatic environment in an active continental margin. And based on the geological distribution and geologic age, it is believed that granitic rocks filled volcanic vent.

S01.01 Poster

Application of Long-term Event Tree Analysis for Volcanic Hazard Assessment at Merapi Volcano, Indonesia

Sulistiyani[1,2], Agus Budi-Santoso[1], Dewi Sri Sayudi[1], I Gusti Made Agung Nandaka[1], Subandriyo[1], Nurnaning Aisyah[1], Christina Widiwijayanti[3], Fidel Costa[3,4]

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Merapi is an open vent basaltic-andesite volcano that produces small to moderate-size eruptions every few years. The pyroclastic density currents (PDCs) from these events threaten ~350,000 habitants in the hazard-zone area, and ~5 million within a 30km radius. Among the predominant lava-dome-forming type of events, the 2010 multi-stage (VEI 4) eruption produced PDCs that travelled ~16.5km and caused 400 casualties. Assessing the future volcano hazards of Merapi is important for land use planning and emergency management during crisis. For this purpose, we have constructed long-term event tree structures of possible eruptive scenarios of Merapi, based on historical eruptive records that span from 1768 to present. Based on 81 known historical unrests of Merapi, the eruptive scenarios are classified into five. When new unrest at Merapi starts, the probability of eruptive scenarios are: 9% no eruption, 23% phreatic, 16% pure dome forming Merapi type, 41% dome forming Merapi type and explosion, 5% Vulcanian, and 6% Sub-Plinian. The logical branches in the event tree provides way to assess the predominant phenomena, sector areas, and extent of the hazards for each eruptive style. For example, explosive-type eruptions can produce PDCs >5km distance. The flow of the event tree, covers from the onset of unrest to the hazard extent, and permits updating the probability values of any level when a new eruption occurs or as additional information becomes available. Assuming unrest episode is a precursory phase towards eruption, using monitoring data we aim to identify: how the new unrest evolve? What is the likely eruptive style? And what is the hazard extent? The long-term event tree can be used as the basis to construct a short-term forecast, by inferring to precursory pattern of each eruptive style obtained from the historical unrest database (WOVOdat).

S01.01 Poster

How similar are unique volcanoes? Insights from global databases

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A volcano is "*a geologic environment that, at any scale, is characterized by three elements: magma, eruption, and edifice. It is sufficient that only one of these elements is proven, as long as the others can be inferred to exist, to have existed, or to have the potential to exist in the future*" (Borgia et al., 2010). Common processes such as partial melting, melt migration, fractional crystallisation, volatile exsolution, fragmentation, multi-phase flow dynamics, etc. are considered to control the fate of magmatic systems, volcanic eruptions and volcanic landscapes. Yet, depending on the scale under consideration, these common processes yield what appears to be a collection of truly unique natural entities: volcanoes.

We make use of global volcanological databases to try unravelling some similarities and differences among the world's Holocene volcanoes. The Volcanoes Of The World database (GVP, 2013; version 4.6.7) provides us with general information about the tectonic setting, rock geochemistry and eruptive behaviour (e.g. eruption sizes and hazardous phenomena) of these volcanoes. The database also stores qualitative data on volcano types (e.g. stratovolcano), which we test against a unified database of volcano morphology, derived from the merging of two previous databases (Pike and Clow, 1981; and Grosse et al., 2014).

Our data analysis serves to address general questions (e.g. is the variability in eruption size higher among volcanoes in similar tectonic settings or among volcanoes with similar rock geochemistry?) as well as to calculate "degrees of analogy" among volcanoes, given the different criteria available. The latter is crucial for hazard assessment, especially in data- poor volcanoes, since it permits "borrowing" information/data in a structured way, by weighing the data coming from data-rich volcanoes according to their degree of analogy with the specific data-poor volcano(es) under study.

What drives the lateral versus vertical propagation of dikes? Insights from analogue models

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Volcanic eruptions are usually fed by dikes. Understanding how crustal inhomogeneities and topographic loads control the direction (upward, lateral) and extent (propagation/arrest) of dikes is crucial to forecast the opening of a vent. Many factors, including buoyancy, crustal layering and topography may control the vertical or lateral propagation of a dike. To define a hierarchy between these factors, we have conducted analogue models, injecting water (magma analogue) within gelatin (crust analogue). We investigate the effect of crustal layering (both rigidity and density layering), topography, magma inflow rate and the density ratio between host rock and magma. Based on the experimental observations and scaling considerations, we suggest that rigidity layering (a stiffer layer overlying a weaker one) and topographic gradient favor predominantly lateral dike propagation; inflow rate, density layering and density ratio play a subordinate role. Conversely, a softer layer overlying a stiffer one favors vertical propagation. Our results highlight the higher efficiency of a stiff layer in driving lateral dike propagation and/or inhibiting vertical propagation with respect to the Level of Neutral Buoyancy (LNB) proposed by previous studies.

S01.01 Talk

The Use of WOVOdat Platform to Identify Analog Unrests Between Eruptions and Volcanoes

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The behavior of a volcano is reflected by its eruptive history, although it may be biased due to the incompleteness of the record. The interpretation of unrest data is used to anticipate whether an eruption is likely to occur, estimate the possible outcome and its hazard, and implement timely mitigation actions. However, past data are rarely sufficient to construct statistical event prediction at a single volcano. Therefore, volcanologists must rely on monitoring data of unrest and eruptions at similar volcanoes (analog volcano) or look for systematics in other unrest cases (analog unrest). The WOVOdat platform – an integrated database, visualization, and data analytics tools – is a resource that allows comparing unrests within the same volcano or between analog volcanoes. Reference to WOVOdat is critically important at volcanoes that have not erupted in historical or 'instrumental' time and for which no previous data exist. Even for volcanoes that may erupt often and for which there is an existing monitoring database, it is critical to have access to a global unrest data, since volcanoes can change their behavior from one eruption to the next, e.g. Merapi 2010, Kelut 2007, etc. We propose the use of clustering, a machine learning technique, to classify analog volcanoes using volcano macro characteristics (e.g. petrology, morphology), and its eruptive activity (e.g. eruptive interval, eruptive style). To perform clustering we selected~350 worldwide Holocene volcanoes from literatures and open catalogues (e.g. GVP, National catalogue of the active volcanoes in Japan, GeoDIVA-AVO). To identify analog unrests between eruptions and volcanoes we used WOVOdat analytics tools, and examined seismic swarm data of 12 dome forming eruptions from 10 different volcanoes, and 14 dyke- fed eruptions of Kilauea. We also analyzed the record for non-eruptive unrest with swarm data of 10 intrusion events at Kilauea between 1970 and 1985.

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S01.03 - Multidisciplinary geophysical imaging of volcanoes

Morpho-structural study of the post- eruption crater before the August 14^{th} 2015 Cotopaxi volcano eruption

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As a result of the August 14^{th} 2015 activity of Cotopaxi volcano, important changes were detected in its crater morphology. The pre eruption crater was destroyed, leaving an open vent. Several overflights since 2015 until those days allowed to acquire a large number of thermal images and photographs. They helped to have a structural measurement of the opening and the maximum depth of the crater morphology.

Using ImageJ software and based on the ortho-photograph of January 28^{th} 2016 (Instituto Geográfico Militar), we could estimate that the vent has a pseudo-elliptic shape (surface: 11.7 x 103 m^2) with a major axis orientated to the N-S with 129 m and the minor axis to the E-W with 118 m.
During an overflights on January 30^{th} and March 13^{th} 2018, we finally saw that the walls and bottom of the post-eruption vent looks like a “vase” or pseudo-conical shape. It was estimated a maximum depth of 122 ± 6 m. We assumed that the base is formed by the cooled magma inside the conduit and also by debris collapses from the conduit walls. An apparent maximum temperature (TMA) of 315 °C was measured in the base, which is the maximum temperature that we have measured for Cotopaxi since 2002. This temperature could correspond to the rocks heated by volcanic gases that are coming out through the rocks fissures.

Moreover, the volcano edifice experienced a warming that resulted in the melting of the glaciers, including the circular glacier within the crater. Recent observations from this glacier show for the first time that the deposits, possibly originated during the eruption of 1904 on which this glacier sits, have been exposed due to the effect of thawing. This situation may confirm that the volcano experienced an important activity during 1904.

S01.03 Poster

A multi-disciplinary approach to understanding the Yellowstone Volcanic System

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The Yellowstone (YS) volcanic system has produced three large caldera forming eruptions 2.1, 1.3, and 0.64 Ma. Smaller post-caldera eruptions with rhyolite and basaltic compositions followed until 70 ka. Previous seismic and magnetotelluric (MT) studies of the crust and upper mantle beneath YS have provided insight into the origin and migration of magmatic fluids into the crustal volcanic system. However, important questions remain concerning: the origin and location of magmatic fluids at upper mantle/lower crustal depths; the preferred path of migration for these magmatic fluids into the mid- to upper-crust; the resulting distribution and composition of the magma reservoir; and implications for future volcanism at YS. To evaluate these questions, we are carrying out a multi-disciplinary (MT and seismic) study of the YS region. In summer 2017, we installed 45 densely spaced, wideband MT sites across YS. We are currently inverting these data as well as long period EarthScope MT stations located throughout YS in order to obtain a high resolution image of the 3D resistivity structure at upper crustal through upper mantle scales. Due to MT data's extreme sensitivity to the presence of melt, it is an ideal tool for constraining magma storage. In tandem with this work, we are carrying out a joint surface/body-wave velocity inversion. Since body and surface waves are sensitive to different regions of the model space, joint inversion should allow us to obtain a more complete image of YS's velocity structure and inferred magma storage. Our spatially coincident velocity and resistivity models will be interpreted jointly in order to better constrain the structure, temperature, and composition of the YS volcanic system.

S01.03 Talk

The Etna volcano borehole dilatometer network: eruptive activity and source mechanisms inferred through borehole high-sensitivity measurements

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A network of 4 borehole dilatometers has been installed on Etna in two successive phases (2010-2011 and 2014). We describe the characteristics of the network and the results of the in situ calibrations obtained after the installations by different methods which use theoretical signals as reference (tide and teleseismic waves analysis). We also applied a new proposed calibration method by direct comparison of strain recorded from strain-meters and broad-band seismic stations.
We illustrate short-term strain changes recorded during several lava fountain eruptions emitted by the summit New South East crater (NSEC) during 2011-2013, and we also show signal changes recorded at all four stations during the lava fountain on 28 December 2014. Analytical and numerical computations constrained the eruptions source depth and also its volume change that is related to the magma volume emitted. Taking into account the volcano topography and the medium heterogeneity, a Finite Element Model (FEM) was set up to accurately infer the source feeding the lava fountains from tilt and volumetric strain signals. The numerical computations indicated a depressurizing source located at 0 km b.s.l. which underwent a volume change of ~2 ×106 m^3 accompanied by a compression of ~0.5 ×106 m^3 of the resident magma. Despite the long-term drift affecting the borehole strainmeter signals, we also show the potential of the signal in the medium-term to reveal strain changes related to different phases of the volcanic activity.
More recently four powerful lava fountains occurred at the main and oldest Mt. Etna summit crater Voragine (VOR) between 3 and 5 December 2015. The recorded strain data infer a deeper depleting storage zone. During the four events the recorded strain changes were decreasing over time indicating that the sequence was going to finish, therefore providing also helpful information for civil protection purposes.

S01.03 Poster

3D Seismic Reflection Imaging of Magma Plumbing using Microearthquake Sources Recorded by Large N Arrays

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Unusually strong reflections mapped by now numerous multichannel seismic reflection surveys both on land and at sea using controlled sources have been interpreted as magma bodies at various depths in the crust. However, the cost of such surveys is substantial. Moreover, controlled source reflection surveys of volcanic terrains stereotypically result in poor data quality, presumably due to scattering in shallow volcanic materials. At the other end of the cost spectrum, pioneering work in the 1970's demonstrated how magma bodies can be detected and mapped using reflected phases recognized on microearthquake seismograms. New nodal recording technologies now make it feasible to generate oil industry quality 3D seismic reflection imagery using ambient sources. Corollary benefits of recording microearthquakes related to magmatism include:

a) lowered thresholds of event detection;
b) greater precision of hypocentral estimates and source mechanisms;
c) higher resolution mapping of P and S wave velocity at depth;
d) high resolution P and S tomography from both microearthquake and ambient noise sources.

However, the reflection methods most represent the transformative potential of recording with dense array arrays. We illustrate this potential with pilot studies of aftershocks from recent earthquakes in the eastern U.S. and geothermal microearthquakes recorded at Krafla, Iceland. Interferometric and Vertical Seismic Reflection (VSP) techniques were used to produce 3D reflection imagery comparable to that expected from multichannel surface source surveys. In the case of the Krafla study, prominent reflections were found to correspond to magma previous encountered in geothermal drilling. These 3D results point to a new approach to high resolution 4D monitoring.

Multivariate interpretation of co-located geophysical experiments at Solfatara Volcano (Campi Flegrei, Italy) using Exploratory Data Analysis techniques

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To reduce interpretation uncertainties and achieve a better understanding of the complex dynamics occurring in volcanoes it is a good practice to use different methods for geophysical imaging, due to their sensitivity to different physical parameters of rocks and fluids. Multivariate, co-located geophysical measurements contain raw, redundant descriptions of the subsurface conditions and therefore hold a high potential in decreasing model uncertainty and achieving a more detailed and truthful characterization of complex geological settings. The integration of multivariate datasets can occur at an early stage, for example during the processing, by using cooperative inversion techniques, or during the interpretation phase, when Earth scientists need to synthesize the many, and sometimes contradictory results, obtained by each single technique in a possibly univocal and meaningful model of the subsurface.

We used Exploratory Data Analysis (EDA) techniques to improve the interpretation of data from co-located seismic and electric measurements carried out along two orthogonal profiles within the Solfatara crater. EDA techniques aim at exploring the data without any pre-conceived notions or hypotheses and use the results of the exploration to guide and to develop the subsequent models and interpretations.

Here we compare the result of two EDA data clustering methods, namely: k-means and self- organizing maps, applied to two multivariate datasets: 1) trace attributes (energy, similarity, dip angle and GLCM entropy) computed from reflection seismology and 2) P-wave velocity and electrical resistivity. Our aim was to better characterize the near surface of Solfatara looking for patterns and structures that are not evident form a simple visual analysis on the single datasets and to improve the detection of faults and fractures which are fundamental features in understanding the mechanisms of massive degassing and hydrothermal circulation presently ongoing under the subsurface of Solfatara volcano.

S01.03 Poster

Anatomy of the Campi Flegrei caldera using Enhanced Seismic Tomography Models

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Campi Flegrei is a densely inhabited active caldera of Southern Italy, which suffered several unrest periods in the last centuries, causing concern among the population. As a consequence, several studies have been performed to understand the objective risk associated with these phenomena. Here we show the most detailed reconstruction of the Campi Flegrei structure obtained using Enhanced Seismic Tomography models that allowed describing seismic velocities, attenuation, and scattering patterns. The Enhanced Seismic Tomography method combines the application of well-established techniques for seismic data inversion with a post processing called Weighted Average Method (WAM), which allows refining the features of the model and reduces the biases that commonly affect an inversion method alone. For the first time a possible pluming system with diameter of 1 km feeding the shallow reservoir is clearly imaged. The models also image a strong caprock 0.5 km thick located at 2 km depth that we interpret as the main structure regulating the fluid interchange between deep and shallow sectors of the caldera. Thanks to these models, we also estimated the shape and the volume of the shallow reservoir beneath the city of Pozzuoli, which is considered the main responsible of the ground movements recorded in the last decades, as well as the presence of several small reservoirs beneath the main craters of the Caldera. These new findings are of crucial importance to better understand the dynamics of the caldera and to fairly assess the hazard during unrest episodes.

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Multidisciplinary geophysical imaging of Etna volcano resulting from TOMO-ETNA experiment data

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Etna volcano (eastern Sicily, Italy) provides one of the most intricate and studied example of magmatism at the front of a collisional belt, but its origin and spatial-temporal evolution are still object of debate.

New seismic reflection/refraction, magnetic and gravity data were acquired in the Mt. Etna area by INGV in 2014-2015, within the TOMO-ETNA experiment, to shed light on the relation between volcanism and tectonics.

The seismic tomography was achieved through airgun shots performed during the experiment and integrated by a selection of earthquakes recorded between 1999 and 2017. It is based on a dense grid of measure nodes and allows us to image the crustal structure of the area through seismic velocity variations, which highlights the occurrence of magmatic bodies and the main tectonic features of the region. The presence of both shallow and deep magmatic bodies in the offshore is also confirmed by positive magnetic anomalies. Gravity data are in agreement with the distribution of the high velocity bodies. The multichannel seismic profiles allow to characterize with higher resolution the seismo-stratigraphic and structural asset offshore Mt. Etna and identify the tectonic structures favoring the magma ascent.

The interpretation of the whole geophysical dataset confirms the scattered nature of the earlier magmatism of Etna volcano and constrains the relation between volcanism and strike-slip tectonics controlling its spatial-temporal evolution.

Ambient seismic noise tomography of the Ceboruco volcano (Mexico)

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Ceboruco volcano (Jalisco, Mexico) is one of the only historically active volcanoes at the western end of the Mexican volcanic belt. The internal structure of the volcano remains poorly constrained. This issue motivated this first seismic tomography of the shallow crust to help characterize the magma chamber and the hydrothermal system of the volcano. Seismic interferometry applied to ambient seismic noise is increasingly used to retrieve the Green's function between pairs of stations. This technique allows producing high-resolution images of the upper crust with the advantage of using continuously available, non- destructive data. We use the cross-correlations of the ambient seismic wavefield recorded by a dense network of 21 temporary short-period stations deployed to image shallow crustal structure of Ceboruco volcano.

S01.03 Poster

Seismic Tomography of Southern Tyrrhenian by means of teleseismic data

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The Southern Tyrrhenian represents one of the most interesting zones to investigate from the geological and geophysical point of view because of its volcanism. This area is a result of a roll-back subduction of Ionian slab under Apenninic chain. A roll-back subduction that "survives" yet along Calabrian arc. A result verified by several studies by means of several local seismic tomographies, with maximum reached depth of 300-350 km. Therefore, for reaching greater depths, I have investigated Southern Tyrrhenian through a teleseismic tomography.

I have gathered 2979 teleseisms recorded by 285 italian ISC seismic stations since 1980 to 2012 according to specific parameters relative to station residuals, epicentral distance, magnitude and number of phases of a single teleseism recorded by a single station.

I have realised 10 horizontal sections of final model from 50 km of depth to 500 km of depth, 8 vertical sections and 3 transversal sections, too. Results of teleseismic tomography evidence the presence of two HVA (High Velocity Anomaly) in Southern Tyrrhenian, one in Campania Region and other in Northern Sicily-South Calabria Region. These HVAs symbolize the Tyrrhenian slab. Their spatial orientation (about 70° NW) is coherent with that verified by previous works. They have a lateral extension of 150-200 km and they are surrounded by LVAs (Low Velocity Anomaly). The two HVAs previously mentioned are "interrupted" by a "slab window" that is present in [250; 400] km interval depth with a lateral extension of 150 km. This "slab window" could be interpreted as the consequence of an opened tear in Tyrrhenian subduction system.

S01.03 Poster

Joining kernel-dependent seismic coda- attenuation imaging with geology and geomorphology of Deception Island, Antarctica: a unique interpretational framework using Geographic Information Systems

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Deception Island is the most active and documented volcano in the South Shetland Islands (Antarctica). Since its last eruption (1970) several experiments have targeted an improved reconstruction of its magmatic systems. Geophysical imaging has provided new insight into Deception's interior, particularly when using space-weighted seismic attenuation tomography for coda waves. Here, we apply sensitivity kernels and a novel inversion strategy to obtain a frequency-dependent model of the magmatic systems at Deception Island using active data, where particular care has been put on data selection and model optimisation. The results have been framed in the extensive knowledge of the geology and the geomorphology of the volcano with a Geographic Information System. This inter- and multi-disciplinary analysis will become a tool to improve the interpretation of the dynamics of Deception Island and its related hazards.

S01.03 Talk

Seismicity of Tatun Volcano Group, Northern Taiwan

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The Tatun Volcano Group (TVG) locates in the north part of Taiwan, where is only 15 km away from the downtown Taipei. To monitor the seismic activity in the TVG, a broadband seismic network was initiated since 2003 and then upgraded. The network was mainly deployed around the Mt. Cising because of its clustered seismicity. Up to 2017, more than 22,000 micro-earthquakes have been detected by the dense seismic array in the Tatun volcano area. In general, around a thousand events happened in the TVG area per year. The seismicity of the Tatun volcanic area shows several features. First of all, most of events occurred in the southeast side to the Shanchiao fault, which is a normal fault dipping to southeastward. Events occurred in TVG are clustered around the Mt. Cising and Dayoukeng, in where hydrothermal activity are high from geochemical observations. Secondly, focal depths of micro-earthquake majorly range from subsurface to 5 km, occupying 90% of the TVG catalog. Rare few events occurred at depths deeper than 10 km. Third, magnitude for most of the micro-earthquake is less than 2.0. In particular, the catalog was dominated by the event with magnitude less than 1.0 during late 2009 to 2010, both for Mt. Cising and Dayoukeng area. The seismicity also shows the temporal variations, the cluster of events moved to Bayan and Mt. Huangtsun, the eastern part of TVG. It's notable that some of the variations are linked to the geochemical anomalies.

S01.03 Poster

Imaging magma chambers using seismic noise

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The shape and location of magma chambers are important to constrain in order to understand the behavior of eruptive processes on volcanoes and/or locate volcanic seismic signals. Unfortunately they are often poorly constrained. The use of earthquakes to perform velocity tomography is often difficult because they are rare and not always well spatially distributed. The use of seismic noise is a good alternative to solve this problem. We show a few examples at the volcanoes Lastarria (Chile), Colima (Mexico) and Misti (Peru).

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S01.03 Poster

Magma plumbing system of Aso volcano as revealed by broadband magnetotelluric data

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Aso volcano is one of the most active volcanoes in Japan. The caldera forming eruptions occurred from 210 ka to 90 ka, emitting the volcanic product of 600 m3 in total. The caldera has a dimension of 25 × 18 km2. After the caldera forming eruptions, post-caldera cones more than 17 were formed at the center of the caldera. Resent eruptions occurred repeatedly at Naka-dake cone. The count of the eruption events from Naka-dake crater was 73 times from 1901 to 2015. These volcanic activities suggest the stable magma supply from deep seated magma source to the surface. To investigate the magma plumbing system, the resistivity structure under Aso volcano was analyzed using the broadband magnetotelluric (MT) data. The four components of MT impedance and two components of tipper vector were used to obtain the resistivity structure by three-dimension inversion (Siripunvaraporn and Egbert, 2009). Overall structure was obtained using 55 measurement sites in and around of Aso caldera (Hata et al., 2016). We observed additional 9 sites near Naka-dake crater and revised the previous model to examine mainly the shallow structure near the active crater. The resistivity structure represents the low resistivity (< a few Ω•m) body which extends from Naka-dake crater to a depth of 15 km (bsl) with a columnar shape. The low resistivity body dips northward and roughly directs to the epicenter of deep low- frequency earthquakes. The minimum resistivity (< 1 Ω•m) centered at 6km depth overlaps the seismic velocity anomaly which is thought to indicate the magma pocket from the P and S wave velocity ratio (Sudo and Kong, 2001). From these results, we conclude that the low resistivity body indicates the upper part of the magma plumbing system of Aso volcano from deep seated magma source to the present active crater.

S01.03 Talk

NASA Disasters Program Response to the 2018 Kilauea Eruptions

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During the 2018 eruptions of the Kilauea volcano in Hawaii, the NASA Disasters Program coordinated NASA's participation and provided satellite and airborne remote sensing data and products to agencies involved in the monitoring and emergency response for the event and to the science community. This included plume heights and particle type derived from space-bore aerosol and cloud LIDAR onboard the joint NASA/CNES CALIPSO satellite; multi-angle, multi-spectral imagery, plume height maps and particle type from the Multi- angle Imaging SpectroRadiometer (MISR) onboard the TERRA spacecraft, multi-spectral imagery and spatial extent from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the TERRA and AQUA spacecraft, the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard NASA-NOAA Suomi-NPP and the NOAA Joint Polar-orbiting Satellite System (JPSS), and ASTER onboard TERRA; hyperspectal Ultraviolet (UV) spectrometer SO_2 data from the Ozone Monitoring Instrument (OMI) onboard NASA Aura and the Ozone Mapping Profiling Suite (OMPS) on board Suomi-NPP and JPSS, and airborne Ka-band radar from the NASA Glacier and Ice Surface Topography Interferometer (GLISTIN-A) instrument onboard the NASA G-III aircraft. This presentation will highlight this information and the collaboration between the many agencies that utilized it. Examples of these data and products may be found at: https://disasters.nasa.gov/kilauea-hawaii-eruption-2018.

The dynamics of La Soufrière of Guadeloupe's hydrothermal system from continuous muon tomography

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Volcanic hydrothermal systems are at the core of the most unpredictable volcanic hazards, including hydrothermal explosions, partial edifice collapse, mudflows and sudden emission of toxic gases. Characterizing the dynamics of volcanic hydrothermal systems is critical for developing efficient monitoring strategies and improving hazard and risk assessment. Here we report on the use of continuous muon measurements at La Soufrière de Guadeloupe as a novel methodology to characterize the dynamics of volcanic hydrothermal systems. Muon measurements yield a radiography of the average density of a volcano along the muon path, allowing to image large volumes of rock from a single observation point. Long-term measurements of the muon flux can be used to study density changes in the system. At La Soufrière, these changes may be related to variations in liquid/vapor content due to steam formation, condensation, and water infiltration and storage. We analyze 2 years of continuous data acquired by 2 simultaneous muon detectors. Shallow regions evidence smaller density changes than deeper parts of the hydrothermal system (200-300 m below the summit), suggesting that changes are due to internal forcing. Among the most active regions, periods of relative calm can follow periods of quasi-periodical changes. The simultaneous muon detectors scan the hydrothermal system from different angles, allowing to constraint the 3-D location of the density changes and an improved quantification of the associated mass changes. This work characterizes for the first time the dynamic behavior of an active hydrothermal system at a large spatial and temporal scale.

S01.03 Talk

The present-day structure of La Soufrière of Guadeloupe hydrothermal system explained by numerical simulations

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Modeling the physical processes in hydrothermal systems is crucial to understand their dynamics and evaluate hazards associated to future scenarios. However, realistic numerical simulations of volcanic hydrothermal systems are still rare. This results from the scarce information available on critical parameters for the simulations, such as rock properties, three-dimensional geometry and fluid-saturation distribution. At La Soufrière de Guadeloupe, multi-disciplinary geophysical, geochemical and geological studies have contributed to an in-depth characterization of the geometry and dynamics of the shallow (i.e., first 500 m) hydrothermal system. These studies include a 3-D model of the electrical conductivity and density of the lava dome, long-term structural behavior of main faults, and temporal evolution of fumarole composition and flux from multi-gas measurements, among others. We present the first results on the numerical modeling of the current structure of the La Soufrière hydrothermal system. We use TOUGH2 to solve the coupled heat and multi- phase fluid flow, and explore the main parameters controlling the behavior of the system at the lava-dome scale. Accounting for topography, we study the influence of the magmatic source (mass and temperature), rainfall and rock properties on fluid and heat flow patterns and vapor/liquid content distributions. A relatively simple model allows us to reproduce the main characteristics of the system observed by geophysical and geochemical studies as well as the presence of the main springs and fumaroles. We find that topography plays a major role in determining the structure of the main hydrothermal reservoir where fluid circulation, and thus alteration, are higher. Furthermore, several key system properties, such as permeability and magmatic input, can be constrained by restricting the resulting steady- state models to those explaining the structure of the hydrothermal system as obtained from geophysical data.

S01.03 Poster

An experiment of muon radiography for investigating the internal structure of Vesuvius

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Muon radiography represents an innovative technique for investigating the interior of active volcanoes. The method integrates the conventional geophysical techniques and provides an independent way for estimating the density of the volcano structure and for revealing the presence of magma conduits. The image of the density structure of the volcano is obtained by measuring the attenuation of high-energy muons, produced by cosmic rays in the upper atmosphere. In principle, internal discontinuities with a spatial resolution of about 10 m can be resolved, allowing the detection of small magma bodies. Moreover, an absolute average density measurement can be provided. Since the pioneer experiments on Japanese volcanoes in 2003, muon radiography was applied on different volcanoes in Japan and Europe. First experiment on Vesuvius was carried out in 2009-2010. In the current years, a new experiment of muon radiography at Vesuvius is performed by using a state of the art detector based on plastic scintillators and silicon photo-multipliers. The measurements are performed in the ambit of the MURAVES project, funded by the Italian Ministry of University, Research and Education (MIUR) and led by INGV and INFN. Here we describe the MURAVES experiment, focusing on the mechanical structure of the adopted detector, Monte Carlo Simulations and background suppression techniques.

S01.03 Poster

Total evacuation plan from island volcanoes in Tokyo: 2000 eruption of Miyake-jima volcano and EM monitoring

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Tokyo Metropolitan City has 23 volcanic islands along Izu-Bonin Arc, the northernmost eight of which have several hundreds to nine thousand population. In the past large eruptions people were obliged to totally evacuate from their islands. Tokyo City has made total evacuation plans in corporation with local villages on these islands for the past three years. A typical example is Miyake-jima volcano. The present population is 1800 in contract to that of 3800 just before 2000 eruption. After the total evacuation owing to harmful SO_2 gas, people could not return home for five years, during which young people determined to live in the mainland city area. Before and during the 2000 eruption, we observed significant precursory phenomena in EM and geodetic data. Moreover, a long-term upheaval of the island for 15 years, magnetic changes for 5 years and two days immediately before the onset of the magma intrusion as well as EM signals a few days prior to the summit collapse (July 8,2000) and August 18 the largest eruption should be particularly nominated. The total evacuation was inevitably chosen by Miyake village and Tokyo Metropolitan City, but its decision-making was rather too late, although the human damage was almost none.

S01.03 Poster

Imaging the internal structure of Stromboli by using muography

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The activity of Stromboli is characterized by some hundreds of moderate explosions per day. The volcanological context of Stromboli is characterized by a structural fragility of the summit crater area and of the so-called Sciara del Fuoco that slopes down to the sea, with a resulting potential hazard induced by the dynamics of the upper part of the edifice. In this experiment, we have performed a muography of the internal structure of the summit crater area, using a detector of about one square meter area and taking data for about five months, between October 2011 and March 2012. The muon detector was based on emulsion films designed for the OPERA experiment, and was installed at 640 m a.s.l., oriented towards the crater region. At the end of the exposure, the emulsions were extracted and developed in the OPERA facility at Gran Sasso underground laboratory, within one week from their extraction. The muon track reconstruction provided an image of the crater area of Stromboli volcano, with a resolution of about 10 meters in the center of the target area. The muography, highlights a low-density zone in proximity of the NE crater. The anomaly of the flux along the muon path through the crater zone indicates a density decrease down to 1.7 g/cm3, to be compared with a standard rock density of 2.65 g/cm3. The density anomaly can be explained by the presence of porous incoherent material that fills the collapse structure in the summit of the volcano.

S01.03 Talk

Structure and dynamics of Solfatara and Pisciarelli fumaroles (Campi Flegrei) inferred from a multiphysics approach

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The Solfatara volcano and the Pisciarelli area represent the main degassing zones of Campi Flegrei. In the current context of volcanic unrest at CF, it is crucial to precisely monitor the flow and geochemical composition of the gases of these fumaroles. Nevertheless, the presence of a surface hydrothermal system can significantly modify the chemical and thermal signatures of the fumarole vents. It is therefore important to investigate the shallow structure of these degassing systems, their thermodynamic processes, and the effect of temperature and pressure boundary conditions at the surface.

Here, our objective is first to characterise the shallow structure of these vents by a multi- physical imaging approach, then in a second step to model the dynamics of fluid flows and their interactions. At Solfatara, the multiphysics approach was based on two techniques. First we use high-resolution 3-D electrical resistivity tomography (ERT) to distinguish the liquid-dominated from the vapor-dominated structures. We then locate the sources of acoustic noise produced by interactions between the gas and liquid condensate to reveal the fumarole ‘plumbing’ system. The fumarole geometry was then incorporated in a 3D multiphase flow TOUGH2 model, constrained by surface observables (i.e., temperature, pressure, and CO_2 and H_2O fluxes). We show that near-surface mixing between gas and condensed steam can strongly affect both the geochemical composition and the temperature of the fumaroles.

We will also present a 3-D resistivity model of Pisciarelli fumarole obtained by high- resolution ERT.

S01.03 Poster

Velocity structure evolution based on Local Earthquake Tomography of the Nevado del Huila Volcano Complex (Colombia). Evaluating of the magmatic and tectonic interactions in a volcanic - glacier complex system

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The first seismic 3D velocity model of the Nevado del Huila Volcanic Complex (CVNH) was determined in two different epochs, using passive local earthquake tomography. We used 8.566 volcano-tectonic events, representing 46.811 P and S wave-arrivals, and recorded by the Volcanological and Seismological Observatory of Popayán (Colombia). We considered observations from 2007 to 2016, a period that covers stages of activation and relaxation of the volcano. The models were parameterized using a network of distributed nodes in the study area according to the best ray coverage, as well as results of synthetic tests. The velocity structure obtained for both epochs allowed distinguishing a persistent magmatic chamber located at 6 km deep with a probable lateral connection with other probably magmatic sources. We detected that during the relaxation period following the eruption, the VP/VS decreased, and no strong anomalous zones were observed. The velocity anomalies identified presented interrelation with local tectonic features and their elastic properties. We found that the Calambayú Fault shows the highest seismic activity, probably as a response to the magma mobility, suggesting a prominent interaction between this tectonic feature and the volcanic system due to changes in the stress field. This multi-temporal tomography estimation represents a suitable approach to evaluate the evolution of the volcanic systems.

S01.03 Poster

Possible large eruptive event at Taal volcano in Philippines inferred by electromagnetic and other geophysical observations

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Taal volcano with 33 major eruptions since 1572 is a dangerous volcano. It is located 55 km south of the capital, Manila, where some 13 M inhabitants live. 1 M people live within 25 km from Taal. Eruptions have devastated Volcanic Island and the inner part of the prehistoric caldera with eruptive activity types that include mild phreatic, phreatomagmatic, plinian eruptions, base surges and large ash falls. During the 1911 eruption, ash deposits fell in Manila city. The most recent major eruption occurred from 1965 to 1977 and had its eruptive center located south-west the currently active crater on Taal. No eruptions have been forecast with enough warning to effectively evacuate people. Since 1977, the volcano has exhibited episodic crises in seismicity and deformation without any actual eruption. This period is one of the longest without an eruption in historical time. Since 2005, EMSEV (http://www.emsev-iugg.org/emsev/), a working group of the International Union of Geodesy and Geophysics (IUGG) and the Philippines Institute of Volcanology and Seismology (PHIVOLCS http://www.phivolcs.dost.gov.ph/) jointly monitor volcanic activity with electromagnetic, seismic, geochemical, geodetic and others geophysical methods in order to understand volcano physics and the hydrothermal fluid system involved. A huge hydrothermal system (HS) lies at about 2.5 km depth below the Island. This HS relays and possibly buffers upwelling magmatic fluids, thermal transfer and induces ground deformation by pore pressure changes. Latest studies indicate that a new activity could involve the northern flank of the volcano with a volcanic explosivity index (VEI) of 3 or more. New thermal long lineaments areas are now active inside an a old large crater opened to the North. Therefore, new scenarios should be considered to deal with increased monitoring and the consequences of such eruptive activity on evacuation planning and the economy of the region.

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S01.04 - Advanced and non-conventional seismic methods for monitoring active volcanoes

Major explosions and eruptive style in 2017-2018 at Stromboli volcano

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Typical Strombolian volcanic activity presents some hundreds of moderate explosions per day. Sometimes it is characterized by major explosions that can generate scoria ejection up to hundreds of meters from the craters. Sporadically, effusive eruptions occur, with lava that flows on the "Sciara del Fuoco" flank (North-West side of the island). In the last decades, during the major effusive eruptions (2002-2003 and 2007), also paroxysmal explosions occurred with large ballistic blocks. After the effusive eruption of 2002-2003, the island's monitoring system was improved by the INGV, adding also two Sacks-Evertson borehole volumetric dilatometers. This allowed us to collect a large amount and variety of data that can help understanding the volcanic processes.
In the last year Stromboli has shown an increase in the explosive activity that since 2014 was moderate. Furthermore, during the same period the occurrence rate of the major explosions increased. In particular, the INGV geophysical monitoring network recorded eight major explosions occurred on July 26, October 23, November 1, December 1, 2017, March 7, March 18, April 24 and April 26, 2018. As a consequence of this period of increased volcanic activity, in December 2017 the alert level was raised from "base" (green) to "attention" (yellow) for a period of about three months. The geophysical data collected during this period can help us to improve our understanding of the physical processes of Stromboli volcano and in particular of major explosions.

Single-station seismo-acoustic monitoring of Nyiragongo's lava lake activity (D.R. Congo)

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Since its last effusive eruption in 2002, Nyiragongo has been an open-vent volcano characterized by the world's largest persistent lava lake. This lava lake provides a unique opportunity to detect pressure change in the magmatic system by analyzing its level fluctuations. We demonstrate that this information is contained in the seismic and infrasound signals generated by the lava lake's activity. The continuous seismo-acoustic monitoring permits quantification of lava lake dynamics, which is analyzed retrospectively to identify periods of volcanic unrest. Synchronous, high-resolution satellite SAR (Synthetic Aperture Radar) images are used to constrain lava lake level by measuring the length of the SAR shadow cast by the rim of the pit crater where the lava lake is located. Seventy-two estimations of the lava lake level were obtained with this technique between August 2016 and November 2017. These sporadic measurements allow for a better interpretation of the continuous infrasound and seismic data recorded at the closest station (~6 km from the crater). Jointly analyzed seismo-acoustic and SAR data reveal that slight changes in the spectral properties of the continuous cross-correlated low-frequency seismo-acoustic records (and not solely the single LP events) can be used to track fluctuations of the lava lake level on a daily and hourly basis. We observe that drops of the lava lake and the appearance of significant LP "lava lake" events are a consequence of deep magma intrusion, which induces changes in the shallow magmatic system. This study highlights the potential to continuously monitor Nyiragongo's lava lake activity (and subsequent information about pressure changes within the magmatic system) using a single seismo-acoustic station located several kilometers from the vent.

Quantifying accelerating time-series of volcanic earthquakes: Bayesian point process models for clustered and anti- clustered seismicity

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Accelerating rates of seismicity are commonly observed to precede volcanic eruptions, with the failure forecast method providing a framework for the analysis of these data and the issuing of eruption forecasts. However, the characteristics of precursory seismic sequences that have been reported are hugely varied, with examples involving a broad spectrum of earthquake types (including VTs, LPs, hybrids, explosions, and tremor), timescales and amplitudes, and eruptions styles. It is likely that a range of different physical processes are underlying apparently similar emergent behaviour. Although the signatures of these different processes may be present in the seismicity data, identifying and characterizing them may require more sophisticated analytical methods than currently employed. Here we present the results of the application of a new Bayesian point process methodology to the analysis of sequences of accelerating seismicity before andesitic and basaltic eruptions, and from potentially analogous physical systems including landslides and laboratory rock failure experiments. The methodology uses Markov chain Monte Carlo to apply rate models to earthquake occurrence time data, and incorporates different inter-event time models, such as the Gamma distribution, to account for clustered or anti-clustered (quasi-periodic or 'drumbeat') earthquake occurrence times. This approach provides new metrics for characterizing and comparing sequences, identifies the evolving statistical properties of different types of precursory sequences, and offers probabilistic forecasts of eruption timing.

"LAKIY": An automatic-supervised system for Near-Real Time processing of volcanic seismicity

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In order to extract relevant seismic information for initial analysis and interpretation during seismic crises at active volcanoes monitored by the Colombian Geological Service, "Lakiy" has been designed as an automatic-supervised system, coded in Java programming language with its own database in PostgreSQL, for primary processing for volcanic seismicity whose operation is Near-Real Time. Lakiy uses linear prediction coefficients, spectral energy, and amplitude in the time domain to represent the input signal and artificial neural networks for the stages of detection of earthquakes and their classification. The system calculates basic parameters such as approximate arrival times, duration, energy, some parameters based on spectrogram information, a preliminary automatic location based on early arrival times and a preliminary local magnitude in the case of VT events. Additionally, Lakiy implements an algorithm based on image digital processing to individualize earthquakes when these appear as swarms. The system updates the graphic information for the users as soon as the last earthquake has been processed. Another important characteristic of Lakiy is that the operator can interact with the system through its deployment results interfaces, supervising its operation and correcting errors quickly and easily, keeping the system database updated with reliable information. Lakiy was successfully tested in the management of the seismic crisis that occurred between March and April, 2018 in the Chiles and Cerro Negro Volcanic Complex located at the Colombia-Ecuador border, showing updated seismic information in Near-Real Time with high precision compared to the information processed manually by human operators after the crisis.

Towards forecasting gas-driven eruptions using continuous seismic recordings

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Gas-driven eruptions (including phreatic and hydrothermal in this study) are small-scale volcanic events that have the potential of causing substantial casualties. For example, the 2014 phreatic eruption at Mt Ontake, Japan, killed several dozens of hikers. The destructive potential of phreatic eruptions lies in the difficulty of identifying clear warning signals. Only some phreatic eruptions are preceded by physico-chemical changes, but these are extremely short-term (a few hours), and no longer term pattern has been clearly evidenced so far. This work investigates non-traditional seismic processing methodologies based on continuous seismic recordings to forecast gas-driven eruptions.

Seismic interferometry using single station and pairs of stations is first tested at different volcanoes. Precursory signals are identified at some volcanoes (Kawah Ijen, Indonesia; Ontake, Japan; Ruapehu, New Zealand) but not all of them (Tongariro, New Zealand). Results sometimes show opposite signs, i.e., a relative seismic velocity drop or increase, and strongly depends on meteorological conditions. Although seismic interferometry shows promising results to forecast gas-driven events in near-real time, an assessment of typical dv/v variations is required to support real-time forecasting of these eruptions.

We then apply a new technique based on the ratios between low and high-frequencies of continuous seismic data. We find that the most recent gas-driven eruptions at Kawah Ijen, Ruapehu and Tongariro volcanoes were all preceded by a systematic month-to-year relative increase in low-frequency seismic amplitude compared to high-frequency. We show through a mechanical model that this precursory activity reflects significant increases of seismic attenuation; this probably results from the accumulation of volatiles in the shallow crust,

which increases pore pressure and eventually leads to gas-driven eruptions. Our results highlight the feasibility to better constrain the onset and the end of an unrest episode, which is of paramount importance for agencies in charge of volcano monitoring.

S01.04 Talk

Volcano-Seismic Recognition (VSR) under noisy conditions via waveform reconstruction

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Volcano-Seismic Recognition (VSR) systems are becoming an essential tool in modern Volcano Monitoring centers: machine learning technologies are able to detect and classify volcano-seismic events in real-time. This allows an on-line tracking of the seismic activity, which plays a key role in volcano forecasting and early warning systems. This work addresses the performance of a VSR system and the evaluation of the robustness of a Hidden Markov Model based recognition system in the presence of noise.

Noisy signals recorded at Deception Island volcano by short period seismometers in the 1995 austral summer have been used to build models in order to detect and classify LP and VT events overlapped on tremor/noise acquired by a broadband station in 2009. Furthermore, the stations were placed in different locations which show a variety of site effects and noises.

To deal with the inherent data waveform variability in this setup, we propose to reconstruct the signals aiming to achieve both modeling standardization and noise reduction objectives. Several reconstruction approaches, each defined by an Empirical Mode Decomposition (EMD) technique and a reconstruction criterion, have been analyzed in order to evaluate their impact on the VSR robustness. The results score an improvement of 16% in recognition accuracy and show the potential of parallel VSR architectures to select the best reconstruction approach independently for each event type, instead of choosing just one EMD solution for the whole system.

High resolution imaging of the b-value at Long Valley caldera

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The estimation of the spatial variations of the Gutenberg-Richter b-value is of great importance in different seismological applications. One of the problems affecting its estimation is the heterogeneous distribution of the seismicity which makes its estimate strongly dependent upon the selected spatial scale. This is especially important in volcanoes and geothermal areas where dense clusters of earthquakes often overlap the background seismicity. Proposed solutions to image spatial variations of the b-value include considering, for each points, all the earthquakes within a fixed radius. This approach, however, does not allow computing the b-value in areas of low earthquake density, while at the same time does not provide an adequate spatial resolution in areas of dense seismicity.

We propose a novel multiscale approach, based on the method of Ogata and Katsura (1993), allowing a consistent estimation of the b-value regardless of the considered spatial and/or temporal scales. Our method, named MUST-B (MUltiscale Spatial and Temporal characterization of the B-value), basically consists in computing estimates of the b-value at multiple spatial scales, extracting for a given point a statistical estimator of this value, as well as an indication of the characteristic spatial scale. This approach includes also a consistent estimation of the completeness magnitude (Mc) and of the uncertainties over both b and Mc, as well as, estimates of the seismic energy release rates.

We applied this method to the seismic datasets of Long Valley Caldera, mapping with high resolution the spatial variation of the aforementioned parameters. Results show the presence of deep volumes, characterized by high b-values, possibly related to a magmatic sources, and a surface distribution of the seismic energy release which is possibly correlated to the geothermal fluid flow path.

Towards using tides to detect when volcanoes are ready to erupt

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Tidal stresses, a repeatable external excitation induced by the Moon-Sun gravitational force, cannot trigger volcanic eruptions because of their small magnitude. However, small, repeated, and predictable stress excitations may still have an effect on some of the geophysical signals measured around active craters. Here we analyze the statistical correlation between lunar cycles and persistent tremor of Ruapehu volcano, New Zealand, over a dataset that covers the last decade [Girona et al., 2018]. More specifically, we explore: (1) how volcanic tremor responds to fortnightly tides, a ~14-day amplitude modulation of the daily tidal stresses related to lunar cycles; and (2) whether the response of tremor to fortnightly tides depends on the internal conditions of the volcano. Ruapehu is a good candidate for this study because: (a) it has displayed a broad spectrum of behavior over the last fifteen years, including several episodes of unrest, periods of quiescence, and a large unforeseen phreatic eruption in September 2007; and (b) nearly-continuous data are openly available (we use data from the Geonet-GNS archive, DRZ station). Our statistical analysis reveals that the long-term (~1-year long window) correlation between lunar cycles and seismic amplitude increases significantly (up to 5-sigma confidence level) during the ~3 months preceding the 2007 phreatic eruption. This means that tremor became sensitive to lunar cycles during the 9 to 15 months that preceded the phreatic eruption, whereas it was unaffected by fortnightly tides during the rest of the 12-year period analyzed. The tidal stress excitation therefore seems to provide a way to probe the state of criticality of the volcano over the period analyzed. This suggests that repeated and low amplitude external stress perturbations can serve to monitor the state of active volcanic system, which opens new directions for volcano monitoring.

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Integrating passive seismicity with Web- Based GIS for a new perspective on volcano imaging and monitoring: the case study of Mt. Etna

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The timely estimation of short- and long-term volcanic hazard relies on the availability of detailed 3D geophysical images of volcanic structures. High-resolution seismic models of the absorbing uppermost conduit systems and highly-heterogeneous shallowest volcanic layers, while particularly challenging to obtain, provide important data to locate feasible eruptive centres and forecast flank collapses and lava ascending paths. Here, we model the volcanic structures of Mt. Etna (Sicily, Italy) and its outskirts using the Horizontal to Vertical Spectral Ratio method, generally applied to industrial and engineering settings. The integration of this technique with Web-based Geographic Information System improves precision during the acquisition phase. It also integrates geological and geophysical visualization of 3D surface and subsurface structures in a queryable environment representing their exact three-dimensional geographic position, enhancing interpretation. The results show high-resolution 3D images of the shallowest volcanic and feeding systems, which complement (1) deeper seismic tomography imaging and (2) the results of recent remote sensing imaging. The study recovers a vertical structure that divides the preexisting volcanic complexes of Ellittico and Cuvigghiuni. This could be interpreted as a transitional phase between the two systems. A comparison with recent remote sensing and geological results, however, shows that anomalies are generally related to volcano-tectonic structures active during the last 17 years. We infer that seismic noise measurements from miniaturized instruments, when combined with remote sensing techniques, represent an important resource to monitor volcanoes in unrest, reducing the risk of loss of human lives and instrumentation.

The vibrant future of seismology by using fibre optic cables

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Natural hazard prediction and efficient crust exploration require dense seismic observations in time and space. Seismological techniques provide ground-motion data, whose accuracy depends on sensor capacity and distribution. More and denser networks are being deployed on volcanic and sedimentary areas in order to improve our capability to image and monitor the crust behaviour. It has been suggested for some months that fibre optic cable technology is able to record strain as shown in industry related exploration and may be useful for seismology. In this study, we demonstrate that direct strain determination is now possible with conventional fibre-optic cables deployed for telecommunication and is a new tool for earthquake location, for crustal exploration using unexpected sources and provides key records for understanding earthquake and fault structure and behavior. Extending recently distributed acoustic sensing (DAS) studies, we provide spatially un-aliased broadband nano-strain data. We record seismic signals from natural and man-made sources with 4-m spacing along a 15-km-long fibre-optic cable layout on Reykjanes Peninsula, SW Iceland. We identify with unprecedented resolution structural features like normal faults and volcanic dykes in the Reykjanes Oblique Rift, allowing us to infer new fault dynamic processes. Comparison with conventional seismometer recordings corroborates dynamic and stable spectral amplitudes between 0.1-100 Hz bandwidth. We explore sub-surface seismic properties using the weight of a car and the fibre optic telephone line along the road. The networks of fibre-optic telecommunication lines worldwide may be used as seismometers opening a new window for Earth hazard monitoring and exploration, and in particular volcanic hazard.

S01.04 Talk

Methods of automatic recognition of seismo-volcanic events: State-of-the-art and perspectives

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Modern volcano monitoring systems integrate a great number of sensors which produce continuously large amount of data. These observations must be analyzed and interpreted rapidly and efficiently in order to timely deliver early warning and eruption forecast in case of volcano unrest. Before most eruptions, the seismic activity increases and up to hundreds or thousands of events can be recorded in a few hours or days. This seismicity includes several types of events associated to different physical mechanisms at the source. Their interpretation requires the detection and the classification of individual events as well as specific data processing for each class. When carried out manually, the classification of seismic events is a time-consuming and tedious task which cannot be done in real-time in case of crisis.

The recent techniques of Machine Learning and automatic recognition are very promising for analyzing large databases and streams of information in real-time, especially for the recognition of seismic events. Several research groups have proposed applications and have developed prototypes for this purpose. Good results – 80 to 100 % of events correctly classified – are generally obtained using diverse methods such as Artificial Neural Networks, Hidden Markov Models, Random Forests, Self-Organizing Maps, or Support Vector Machines. Besides the algorithm used, the success rate of classification relies on the quality of the training databases, on the number and characteristics of the event classes, and on the features used to describe the signals.

In this contribution, we will present an overview of the methods of automatic recognition applied to the classification of seismo-volcanic signals. We will highlight examples of integration of these tools in monitoring systems and will draw some prospects of improvement based on novel methods, such as Deep Neural Networks, and on the sharing of large databases.

Seismo-acoustic wavefield of Strombolian explosions at Yasur volcano, Vanuatu using a broadband seismo-acoustic network and infrasonic sensors on a tethered aerostat

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Seismo-acoustic wavefields at volcanoes contain rich information on shallow magma transport and subaerial eruption processes and inform our understanding of how volcanoes work. We conducted a collaborative multiparametric field experiment at the active Yasur volcano, Tanna Island, Vanuatu from 26 July to 2 August 2016. Our observations include data from a temporary network of 11 broadband seismometers, 6 single infrasonic microphones, 7 small-aperture 3-element infrasound arrays, 2 infrasound sensor packages on tethered balloons (aerostats), an FTIR, a FLIR, 2 scanning Flyspecs, and various visual imaging data; scoria and ash samples were collected for petrological analyses. This unprecedented dataset should provide a unique window into processes operating in the shallow magma plumbing system and their relation to subaerial eruption dynamics.

Network-coincident STA/LTA automatic triggering indicates that the 6-day dataset contains over 8,400 infrasound explosions and over 10,400 seismic events. The infrasonic signatures of Yasur's Strombolian explosions consist of short-duration explosion waveforms with non- linear characteristics. The seismic signals are numerous repetitive long-period (LP) seismic events underlain by very-long-period (VLP) signals with periods of ~10 s. In addition to these dominant signal types, we also record a near-continuous broadband (~0.1–20 Hz) infrasonic tremor associated with the vigorous degassing activity. We observe strong variability in the synchronization of seismic and acoustic sources. Explosion events, clearly delineated by infrasonic waveforms, are underlain by seismic VLPs. However, strong seismic VLPs also occur with only a weak infrasonic expression. Our analyses include full seismic waveform inversion for a point-source moment-tensor and single force vector representation of the VLP source.

Features of Seismic Events Within the Lazufre Volcanic System, Northern Chile/Argentina

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The northern border of Chile and Argentina has an active volcanic complex with two volcanoes, Lastarria and Cordon del Azufre. An unusual inflation signature between the two volcanoes has been observed by InSAR data and modeled as an over-pressurized source at a depth of 7-15 km. A second, smaller deformation signal originating at ~1 km depth has been discovered near the summit of Lastarria. Current activity consists of extensive fumarole fields, seismic activity, and degassing. The degassing has changed in composition between 2009 and 2012, possibly indicating a transition from a hydrothermal to a magmatic system. The PLUTONS Project deployed 8 broadband seismic stations in the volcanic complex between November 2011 and March 2013. For events within 20 km of the network, we have so far identified five event types: Volcano-tectonic, long-period A (with dominant frequency of 5-8 Hz and depths shallower than 2 km), long-period B (with dominant frequency of 3-4 Hz and depths between 1 and 15 km), hybrid, and non-traditional hybrid events. The non- traditional events, which we call “reverse hybrid”, have a low-frequency onset and gradually increasing frequencies in the coda. All event types show no temporal correlation with the occurrence of distant large earthquakes and are of local origin, with the majority located near the summit of Lastarria. Preliminary manual review indicates about 5 locatable, local events per day, mostly at shallow depths less than 10 km below the surface. The volcano- tectonic, long period and hybrid events are similar to those found at other volcanoes. The reverse hybrid events, however, represent a new, so far un-recognized event type.

S01.04 Talk

Seismic anisotropy time variations at Mt. Etna

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The purpose of this work is to study the temporal variations in the seismic wavefield, associated with the stress changes in the dynamic features of the Mt. Etna volcanic activity. We used Shear Wave Splitting analysis on local earthquakes, in order to identify changes in stress field acting at Mt. Etna during the time interval from 2006 to 2011. This analysis allows us to obtain two parameters: the polarization direction of the faster split shear wave (j), that generally provides information about the anisotropic symmetry and stress direction, and the normalized time delay between the split shear waves (Tn), that provides information about the average crack density along the ray path. Based on our findings it is possible to divide Etna Volcano in three different sectors each one distinguished by typical fast wave polarization direction. We find that the western part of the volcano is controlled by the regional tectonic stress field having a EW and NS directions; the eastern part of the volcano is controlled by the local volcanic stress, particularly an EW local stress field in the NE sector (Pernicana), and a quasi NS local stress field in the SE sector (Timpe), where magnetotelluric surveys suggest a diffuse presence of hydrothermal activity and fluid circulation. Multiplets analysis regarding the temporal changes have shown that there is a direct link between the variations of the anisotropic parameters and the possible stress changes related to the eruptions. Before both summit and lateral eruptions stations exhibit significant variation in Tn, interpreted as due to a modification of the aligned fractures, and a 90°-flip of φ, which may be explained by over pressured fluids. This behaviour occurs when there is a change in the stress field, and it is probably related to the action of volcanic sources that influence the pore pressure.

S01.04 Poster

Innovative developments in the identification and forecasting of volcanic and volcano-tectonic activity: Experiences from different volcanoes

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Forecasting volcanic activity is a problem that has been addressed worldwide from different perspectives since the earliest stages of volcanology. Significant advances have been obtained after the development of complexity theory and the discovery of power-law distributions of different geophysical parameters. Particularly, frequency-magnitude power- laws evidence the scale-invariance and self-organization of seismicity. Furthermore, brittle fracture models illustrate that under certain conditions, a precursory evolution characterized by an accelerating strain rate or seismicity culminates in a catastrophic failure. These organizational features have allowed the development of several forecasting tools: precursory time evolution of VT earthquakes, their magnitude distribution, analysis of continuous seismic signals, analysis of seismic waveforms, and recognition of event families. Although manifestations precursory to eruptions have been reported for a long time too often are not recognized, misunderstood or simply ignored, conditions that may lead to a disaster. It is thus necessary to increase the reliability of the precursor's recognition and interpretation, and improve the communication of the hazards in order to enhance the confidence of the decision-makers. This task is not easy as the number of parameters involved in a volcanic process exceeds the number of measurable quantities that can be accurately measured at the surface. We present some examples of forecasting methods based on seismic observations from different volcanoes (Villarrica, Tungurahua, Teide, Stromboli, Popocatepetl, etc.), and how that experience has been used to improve the hardware and software developed for that purpose.

S01.04 Poster

The broadband seismic network KivuSNet in the Virunga Volcanic Province (D.R. Congo): seismicity catalogues and new fundamental seismological models

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Over the course of the past 5 years, the first dense real-time telemetered broadband seismic network in the Kivu Rift region (KivuSNet) was gradually deployed in the frame of several Belgo-Luxembourgish research projects (the most recent one being RESIST, funded by the Belgian Science Policy and Luxembourg National Research Fund). The Kivu Rift is located in the bordering region of the Democratic Republic of Congo and Rwanda, in the Western branch of the East African Rift. Here the active volcanoes Nyamulagira and Nyiragongo threaten the city of Goma and neighbouring agglomerations. For many years already, urbanisation in that region undergoes sustained rapid growth, and the region counts 1 million inhabitants today. In 1977 and 2002, eruptions of Nyiragongo caused major disasters. Destructive earthquakes can also affect the region, as was the case in 2002 in Kalehe (Mw 6.2) along the western shore of Lake Kivu, or in 2008 in Bukavu (Mw 5.9), south of Lake Kivu. While the first stations were already installed in 2012/2013, KivuSNet is fully operational with sufficient station coverage only since October 2015. Today, KivuSNet is composed of 17 stations delivering continuous real-time data, many of these installed under difficult conditions in a hostile environment. Many KivuSNet stations are co-located with GNSS KivuGNet stations, and three KivuSNet sites are in addition equipped with infrasound arrays. This contribution will present the lessons learned from these more than 2 years of continuous KivuSNet operation as well as the current status of seismological information as deduced from these data, including a robust 1D seismic velocity model and calibrated local magnitude scale for the Kivu Rift region. The complete seismicity catalogue (volcanic and tectonic events) has been relocated and a first ambient noise tomography has been carried out.

S01.04 Poster

Volcanic tremor source location based on seismic cross-correlations: application to synthetic tremor using volcano-tectonic earthquakes

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Determination of volcanic tremor source location has been a challenge in seismology due to the complexity of tremor waveforms and difficulties in reading P- and S-wave arrival times. We developed a location method for volcanic tremor recorded at a seismic network distributed over a small region. We combine the source-scanning algorithm (SSA) and seismic interferometry technique. Tremor records are preprocessed using seismic interferometry processing routine to obtain stacked cross-correlation functions (CCFs) for all station pairs, which are expected to show high amplitudes at the lapse time corresponding to the travel time difference. The CCF-based SSA maps the distribution of sources by amplitude summation at predicted travel time differences between stations. Our method does not require to read arrival times, compute synthetic values or provide initial hypocenter information. Reliability of the SSA is first assessed by locating volcano-tectonic (VT) events with accurate, known hypocenters. The uncertainty, calculated as the distance from the estimated source to the hypocenters, is less than 2 km at the frequency range of 8-16 Hz which contains the dominant frequencies of S-wave phase in the VT events. We further verified our method to locate the tremor source by stacking the CCFs of VTs occurred in a small region. The estimated source is determined approximately at the centroid of the VT hypocenters. Smaller region and larger number of events for stacking produce more accurate results. Finally, we apply our method to simulated volcanic tremors in which observed VT events are randomly superposed in time. The source locations are resolved with a spatial resolution of less than 2 km. Our tremor location method can be used as an alternative tool for volcano monitoring, especially to locate seismic events with long duration and no clear arrival times.

Automatic discrimination and fast wavefield decomposition of Volcano- Tectonic (VT) earthquakes by Independent Component Analysis: the case study of Campi Flegrei (Italy)

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A fundamental task in volcano-seismology is the characterization of the source of Volcano- Tectonic (VT) earthquakes; this passes through the discrimination of seismic events from the ambient background noise and the identification of the onset of the main phases, i.e. the body waves.

An automatic procedure based on the Independent Component Analysis (ICA) which successfully performs the blind source separation of convolutive mixtures, has been developed to have a prompt discrimination among the different sources in the seismic signals. Specifically, the ICA is adopted to obtain a clear separation among meteo-marine microseism, anthropogenic noise, and volcano-tectonic activity at Campi Flegrei. A coarse- grained variable, i.e. the frequency associated with the maximum amplitude of the power spectral density of the Independent Components (FMPSDA), is introduced. This parameter is sensitive to the variation in the frequency bands of interest (e.g. that corresponding to the corner frequencies of VT events) and can be used as marker of the insurgence of seismic activity.

In addition, the ICA also provides the wavefield decomposition of VT earthquakes into basic sources which are naturally polarized into the vertical and horizontal planes, thus allowing the identification and separation of the main seismic phases. On this basis, a novel approach, "ICA-based Polarization" (ICAP), which consists in the estimate of the polarization parameters directly from the Independent Components is introduced. The technique is suitable for directly retrieving polarization features of the seismic signals in a single step, avoiding a priori cumbersome segmentation and filtering procedures.

On the basis of the presented results, the application of the ICA to large massive seismic datasets represent an useful tool for fast pre-processing, thus efficiently supporting the volcano monitoring practice.

S01.04 Poster

Adaptive non-linear filtering for the detection of microearthquakes

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The detection of microearthquakes is an important task in various seismological applications as volcano seismology, induced seismicity, and mining safety. Together with improvements in the seismic network technologies (e.g. network densification, borehole installations) it can benefit from techniques of digital signals processing, aimed at enhancing signals related to microearthquakes from the background noise by improving the signal/noise ratio.

In this work we propose a novel technique based on a non-linear filtering procedure, which has shown to be more efficient, compared to traditional filtering, in enhancing signals related to small microarthquakes embedded in continuous recordings.

The implemented technique consists in a preliminary band-pass filtering of the signal followed by an adaptive spectral subtraction.

The spectral subtraction technique is a non-linear filtering which allows taking into account the actual noise spectrum shape. It allows achieving a good filtering even in cases where the signal and noise spectrum overlaps. In order to take into account of the temporal variation in the background noise spectrum, we designed an adaptive technique. We first cut the incoming signals into short temporal windows (1024 samples). Each windows is classified as “noise only” or “meaningful signal” (which can be either a microearthquake or any other relevant transient signal) using different features as the signal energy and the zero-crossing rate. Windows recognized to consist of noise only are continuously accumulated in a dynamic buffer which allows the average noise spectrum to be estimated and updated in an adaptive manner.

We applied this procedure to some seismic swarms recorded by Red Sísmica Canaria, managed by Instituto Volcanológico de Canarias (INVOLCAN), on Tenerife and La Palma islands, comparing results from the proposed detection algorithm with standard approaches.

S01.04 Poster

Locations of families of repeating events at Telica Volcano, Nicaragua

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Telica Volcano, Nicaragua is a persistently restless volcano with very high rates of seismicity and frequent small explosions. Locating events at Telica is difficult due to the typically low-amplitude and emergent nature of the low-frequency waveforms. Telica Volcano has a high rate of multiplet occurrence: of the >200,000 earthquakes recorded on the TESAND network between 2010-2013, ~51,000 were found to be correlated at a cross- correlation threshold of 0.8 or above. In previous analysis of the 2010-2013 data, cross-correlation of all >200,000 waveforms was carried out at a single station using '*Peakmatch*' - a fast-approximation tool for rapid cross-correlation of large datasets. In this study we investigate some of the most pervasive multiplets at Telica during this period and trace these multiplets across all stations in the seismic network. We identify a subset of events that are all correlated with each other at each station. We then stack those events by station to improve signal-to-noise ratios of the multiplet. First arrival picks of individual events within the multiplet are greatly improved from correlation with the stack and then used to locate events. We use the locations of individual events within the multiplet to investigate the source volume variation within a multiplet, and we compare locations across different multiplets. The workflow and code has been developed in the GISMO toolbox framework - a seismic data analysis toolbox for MATLAB. The code developed here will be added to the growing repository of GISMO contributed code.

S01.04 Poster

Multiscale analysis of geophysical signals using financial markets tools

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Financial markets specialists often use multiscale analysis on different kind of time series. Many tools have been developed for these task. Two of them, widely used, are: candlestick charts and technical indicators. Our approach consists in using both tools to analyze geophysical time series, with special reference to seismic data.

We first represent the energy of the signal using candlesticks at user selected time scales. In out case we use four summary quantities of the signal: the energy of the first sample, the maximum energy within the candle, the minimum energy and the energy of the last sample used in the candle. We found convenient representing, together with the candlesticks, the average signal energy and the zero-crossing rate for each considered time interval. We show how the graphical candlestick representation alone is able to emphasize representative changed within the time-series.

On the other hand, many technical indicators have been defined to extract further information from such type of charts. As an example is the STA/LTA method, which is similar to the well know algorithm to detect the arrival time of seismic phases on seismograms. However this algorithm, applied on candlestick data, is able to operate in a multiscale fashion.

Furthermore, since the candlestick analysis highly reduces the number of samples, providing only the relevant information about a time-series, it is highly suitable to investigate correlations between very different type of data (e.g. seismicity, gas flux rates, etc.). This feature is particularly useful when comparing time-series having highly different sampling rates.
We apply candlestick analysis to seismological and geochemical datasets, recorded by Instituto Volcanológico de Canarias in the past years, in particular we show example application to recent unrests on the volcanic islands of Tenerife and La Palma.

Monitoring volcanoes using seismic anisotropy

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Seismic anisotropy is used as a tool to determine the stress state of the crust, and changes in anisotropy around volcanoes have been interpreted to be caused by magmatic activity. We test this on 13 volcanoes from Japan (Fuji, Unzen, Sakurajima, Aso, Asama, Kirishima, Ontake), New Zealand (Ruapehu, Te Maari), and ocean islands (Soufriere Hills, Kilauea, Okmok, Piton de la Fournaise) by comparing measured changes in shear wave splitting to other indicators of stress or volcanic activity. Shear wave splitting is measured with an objective automatic code, MFAST. The parameters fast polarization (phi) and delay time (dt) respectively give estimates of anisotropy orientation (which may be a proxy for stress direction) and of the product of path length and strength of anisotropy. We have not measured every variable on every volcano, but we found changes in phi or dt associated with eruptions at nine volcanoes, seismicity rate at three, GPS or tilt at three, Vp/Vs ratio at three, focal mechanisms at two, and b-values or isotropic velocity change or gas flux at one volcano each. To rule out the possibility that the changes are caused by earthquake travel paths going through different regions with different earthquake sources, we using fixed sources where possible. We also test whether random scatterers can cause apparent splitting in isotropic media. Stress changes can explain some of the observed variations in parameters. But at others, changes in gas or liquid content in cracks appears to be a likely cause of the changing parameters.

Detecting hidden seismo-volcanic events through the seismic network covariance matrix analysis

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New seismic methods for volcano monitoring face different challenges. For instance, they must be able to characterize low energetic events that are too weak to be detected by traditional approaches based on manually picking phase arrivals. Furthermore, because the long-period seismicity constitutes an important feature for volcanic unrest, new methods must be adapted to detect and locate long-period events and volcanic tremor. Moreover, the continuously growing monitoring networks and consequently the increasing data fluxes, require that new methods to be capable of performing data-intensive automatic analysis. The seismic network covariance matrix method, used in this work, fulfills all those requirements.

The method is designed to automatically detect and locate all kind of seismo-volcanic events, from impulsive volcano-tectonic earthquakes to emergent long-period events and continuous volcanic tremor. It is based on the analysis of eigenvalues and eigenvectors of the seismic network covariance matrix. Events are detected through the time evolution of the width of the distribution of the eigenvalues of the network covariance matrix, which is a proxy of the number of acting sources. Each detected event is then located through a cross- correlations based location method using the corresponding first eigenvector of the covariance matrix. We applied this method to one year (2017) of continuous data recorded by 15 permanent broadband seismic stations operated by the Instituto Volcanológico de Canarias (INVOLCAN) on the island of Tenerife (Canary Islands). The aim is to improve the catalog of seismo-volcanic events by adding hidden events not detected by manual picking.

Real-time analysis for rapid assessment of driving forces associated with seismic swarms

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Volcanic eruptions are often heralded by magma movement, thus it is important for observatories to detect and characterise such motion, and as early as possible. Here we present a real-time monitoring tool to track seismic migration which is a good proxy for magma migration as it reflects the stress perturbations induced by the migrating magma. This can be done using Seismic Amplitude Ratio Analysis (SARA), a simple method which tracks the time evolution of the ratios of seismic amplitudes recorded at different seismic stations in a network in real time. Changes in amplitude ratios signify changes in location of the seismic activity, which could be interpreted in terms of magma movement. To quantitatively determine whether amplitude ratios are changing, we use the Mann-Kendall trend test which is based on Kendall's correlation coefficient. Using this method, we are able to accurately pick up subtle amplitude ratio changes across different time scales. Building upon the success of the method applied on synthetic seismograms generated from a variety of scenarios, we moved on to tailor the method for practical application on real seismic data. At some locations, it is inevitable for the seismometers to record the background noise contributed by diurnal cycles. Real changes in the computed amplitude ratios reflecting seismic migration will be masked if this is not taken into account, especially if the migration duration is shorter than the diurnal cycle. To isolate the seismic activity from the noise, we developed steps to remove the background noise, and our results show that migration episodes are more clearly highlighted after background noise removal. We applied SARA on different seismic swarms recorded at different volcanoes. The results obtained demonstrate the ability of SARA to distinguish between bursts of seismicity with or without associated migration.

The seismic monitoring network and the seismicity of Ischia island

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The modern seismic monitoring network of Ischia island (southern Italy) started with a single station in 1970 installed in the Casamicciola Terme Geophysical Observatory. In the following years, the network was gradually improved until the actual configuration that includes 4 stations with real time data transmission and 6 mobile stations with local data acquisition. The current network configuration is able to locate shallow events with M≥1.0 and to detect smaller earthquakes or other types of natural and artificial events (e.g. blast fishing).

This system is in charge of Osservatorio Vesuviano (INGV), which is the scientific institution that performs the geophysical monitoring of the Neapolitan volcanic areas. An accurate catalog of the earthquakes recorded by the modern seismic network of Ischia is available starting from 1999. The seismic history of the island is dominated by the earthquake of 1883, which caused serious damage and many fatalities in Casamicciola Terme. More recently, the earthquake that hit the island more severely occurred on 21st August 2017 and caused the collapse of some houses and two victims. Before this event, the seismicity of Ischia has been characterized by low magnitude (Md≤2.3) earthquakes located in the northern part of the island, mostly beneath the town of Casamicciola Terme at very shallow depths. This area coincides with that where the devastating event of 1883 occurred and where the small magnitude seismicity recorded between 1927-1936 was located. Also the 21st August 2017 earthquake and its aftershocks affected the same area. The historical studies and the geophysical data collected by the seismic monitoring network in recent decades show that the northern slope of Mount Epomeo, where the upper part of Casamicciola Terme lays, coincides with the main seismogenic zone of the island. Here very shallow earthquakes with high epicentral intensity and relatively low magnitude are usually recorded.

Automatic Relative reLocation of microseismicity at active volcanoes in Vatnajökull glacier, Iceland

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Real time monitoring and analysis of signals reflecting volcanic unrest are critical to enable quick interpretation of escalation in activity and allow eruption early warning to be issued. Seismic activity in volcanoes is an important indicator of unrest and sudden escalation in seismicity is a common precursor to volcanic eruptions. Automatic, real-time Relative reLocations (ARL) of microearthquakes in volcanoes therefore has the potential to not only improve location accuracy and ability to monitor magma movements in the subsurface, but also to indicate when magma starts to move towards the surface before an eruption.

At the Icelandic Meteorological Office ARL has for several years been running successfully on microseismicity in the South Iceland Seismic Zone, where the process can map activity on the main faults of the transform zone with high precision in near-real time. But ARL has also been applied in volcanic environments with some success. In 2014, within the FP7 FUTUREVOLC project ARL processing of microearthquakes was implemented for sources in the dyke intrusion, which extended 45 km from Bárdarbunga volcano to the eruption site in Holuhraun. After the eruption ended in February 2015, some activity has persisted in the dyke as well as in a cluster below the dyke, extending down to 23 km depth. To monitor this activity we recently added additional sources from the deep cluster to the ARL process. Future development of the process will include modifications of the workflow to speed up the processing, and extensions to (i) the Bárdarbunga caldera where, significant seismic activity continues and relative relocations have had some success in mapping the activity on the caldera ring fault, and (ii) the Öræfajökull volcano, which has recently shown signs of unrest and where relative relocations have been quite successful in mapping activity on the ring fault of the small caldera.

S01.04 Talk

6C ground motion observations on volcanoes: opportunities, experiments, observations

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The observation of the complete ground motion (i.e., three components of displacements or velocities with standard seismometers, and three components of rotations) is gaining increasing attention, given the wide spectrum of benefits in particular for volcanic environments. These benefits include: 1) the removal of the tilt-displacement ambiguity by directly measuring rotational motions and correcting for them; 2) array-like processing of the colocated 6C measurements to obtain information on propagation directions of signal, shallow local phase velocities (structural information); 3) opportunities to better estimate full moment tensors. This emerging area of investigation is being made possible with the advent of a first broadband rotation sensor adapted for seismology. This sensor - blueSeis - developed by the French company iXblue is a fibre-optic gyro recording with a flat response function in the frequency range from 0.01 to 100 Hz. Experiments have been carried out at Stromboli volcano and very recently on an active volcano on the Galapagos Islands. We will present some fundamental concepts of 6C ground motion analysis, experimental setups and observations.

Seismic velocity changes at White Island volcano, New Zealand, using ten years of ambient noise interferometry

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Recent advances in seismology have brought significant improvements towards detecting small velocity changes by cross-correlating ambient seismic noise. At volcanoes, temporal velocity perturbations carry information about stresses and fluids present within hydrothermal and magmatic systems. White Island volcano represents an excellent case study for ambient noise monitoring, with multiple well-documented eruptions within the past six years. We monitor this volcano from 2007 - 2017 by cross-correlating the different components of individual seismic stations. White Island is well suited for this approach, with only one permanent station active throughout eruptive activity. We also process seismic stations located onshore to investigate background regional changes.

Velocity increases 0.1% at the volcano in the months preceding an explosive eruption in April 2016 and increases 0.05% during eruptive activity in 2012 - 2013. These correlate well with heightened levels of volcano-seismicity and are interpreted to reflect cracks closing under increased pressure beneath the volcano. We also detect clear co-seismic velocity decreases associated with a M_W 5.2 and M_W 7.1 earthquake. This likely reflects dynamic tress changes as a result of passing seismic waves, with the larger earthquake interpreted to have triggered an eruption in the two weeks following. Finally, annual variations recorded by onshore stations are also partially present at the volcano, suggesting an environmental influence. Velocity changes at White Island therefore represent a complex interaction of volcanic and non-volcanic processes, highlighting the need for improved understanding of the underlying sources of background velocity changes.

S01.04 Talk

Noise-based seismic monitoring of the Campi Flegrei caldera

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The Campi Flegrei caldera is one of the highest risk volcanic fields worldwide, because of its eruptive history and the large population hosted within the caldera. It experiences bradiseismic crises: sudden uplift with low energetic seismic swarm occurrences. No seismicity is recorded out of these deformation rate changes. Therefore, a continuous seismic monitoring of the caldera is possible only by means of the ambient seismic noise. We apply a noise-based seismic monitoring technique to the cross correlations of the seismic recordings coming from 15 stations along 5 years (2010-2014). The resulting relative velocity variations are compared to the temporal behavior of the geophysical (uplift measurements, and shear wave splitting results), and geochemical observations routinely sampled at Campi Flegrei. We could thus discriminate between two kinds of crustal stress field variations acting at different timescales, and we speculate they are related to a possible magmatic intrusion and to the gradual heating of the hydrothermal system, respectively. This study sets up the basis for future volcano monitoring strategies.

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S01.05 - Geomatics and volcanic areas monitoring applications and developments for hazard mitigation

Monitoring Volcanic Unrest through InSAR data using Deep Learning

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Recent improvements in the frequency, type and availability of satellite images mean it is now feasible to routinely monitor volcanoes in both urban and remote areas. In particular, Interferometric Synthetic Aperture Radar (InSAR) data can detect surface deformation, which has a strong statistical link to eruption. However, the datasets produced by modern satellites are too large to be manually analysed on a global basis. In this study, we systematically process >30,000 interferograms acquired by Sentinel-1 covering over 900 volcanoes in 2016-2017. Then we apply machine learning algorithms to automatically detect volcanic ground deformation. The proposed method works on 'wrapped' interferograms with no atmospheric corrections. The ground deformations display as fringes representing a set amount of displacement. These fringes provide strong low-level visual features for image classification. Here, we extract the spatial characteristics of the interferograms using deep convolutional neural networks (CNN) and initially train the model with Envisat data. The algorithm provides a probability that a given interferogram contains surface deformation. The positive results (probability >0.5) are checked by an expert and fed back for model updating. Following training with a combination of both positive and negative examples of Sentinel-1 data, this method reduced the number of interferograms to approximately 100 which required further inspection, of which at least 39 are considered 'true positives'. We demonstrate that machine learning can efficiently detect large, rapid deformation signals in wrapped interferograms, but further development is required to detect slow or small deformation patterns which do not generate multiple fringes in short duration interferograms. This study is the first to use machine learning approaches for detecting volcanic deformation in large datasets and demonstrates the potential of such techniques for developing volcanic unrest alert systems based on satellite imagery.

S01.05 Poster

3D modeling around Aso crater with SfM of UAV

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Field survey around the crater is very important to understand damage survey and volcanic activity measurement, especially after an eruption. However, it is dangerous for risk of death, even though manned flight. Considering the safety, UAV is a powerful tool near the future for volcanic study to survey without approaching to the crater. We surveyed at Mt. Aso where located in the middle of Kyusyu island, with UAV in low-altitude-flight. We introduce the result made SfM 3D model shown topographical change and spout amount of crater and its surroundings. This survey was conducted as part of the MEXT's next- generation volcano research and human resource development comprehensive project. Also, we cooperated the project with Aso volcano disaster prevention conference council, Kyoto University volcano research center, and JMA.

Mt. Aso erupted on October 6, 2016. The eruption column reached 8000 m and ash falls more than 200km. Tourist facilities beside the crater were buried in ash and got some holes in the roof with ballistic projectiles. We operated UAV at 2 km far from the crater on December 8, 2016. The flight was 1.5 km distance for 15 minutes due to the battery limitation.

A 3D model was constructed from 1,000 photographs with SfM structure. DSM data and orthophoto were created, and topographic interpretation was performed with the RRIM (red relief image map). The result of RRIM images indicated the deposition of ballistic projectiles near the crater, pyroclastic density current/ lahar outside the crater.

We operated UAV to understand the topographic features at Mt. Aso erupted 2 months later. After processing 3D data, it was compared with DEM data taken before the eruption by aerial LiDAR. As a result, it was found the maximum layer thickness reached 16 m and volume of deposit about 100,000 m3.

New approaches in lava flow mapping and DEM updating employing innovative technologies

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Etna is one of the most active volcanoes on the Earth, considering the huge amount of people living on his flanks, visiting the volcano every year the lava flow monitoring for risk mitigation and Civil Protection purposes is one of the fundamental task of the Cartographic Laboratory of the INGV-OE. The continuous request of detailed information regarding an ongoing effusive event pushed us to look toward new tools useful to quickly obtain the expected results from the "decision maker". The peculiarities of the approach we present are quick planning and carrying out of surveys, low cost as well as the usage of different sensors. In particular, in the last year we tested the simultaneous use of UAV, high precision GPS, high-resolution camera with GPS integrated, a backpack composed by a reality capture sensor platform combines imagery and point cloud and a portable imaging laser scanner. This new tools were tested on the summit crater of Etna and in a lava tube. The different point clouds obtained after each surveys were elaborated with a custom software that allow their management and overlap. This experiment exhibit the possibility to obtain high-precision 3D model through the homogenization of point clouds derived from different sensor, taking into account the survey goals, the operational requirements and the availability of the tools to be used. This new photogrammetry approach can be applied in any environment where 3D reconstruction is required to update the morphological changes and to evaluate volcanological parameters such as area and lava volume and effusion rate.

Assessing ballistic hazard using a UAV: Yasur Volcano, Vanuatu

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Recent eruptions around the world have highlighted the threat volcanic ballistics pose to the growing number of volcano tourists and climbers. To better understand and mitigate ballistic hazard we need to improve our knowledge of its extent and distribution characteristics. Thousands of ballistics can be ejected in an eruption and be deposited over large areas, making mapping in the field difficult. Additionally, identifying individual eruption deposits at persistently erupting volcanoes is challenging. UAVs make aerial mapping an accessible option for scientists and hazard and risk managers, providing an overview of the entire ballistic field in high enough resolution to map individual ballistics. We used a UAV to image the ballistic field at Yasur Volcano, Vanuatu on two occasions in 2016, spaced two months apart. Structure from Motion software was then used alongside RTK GNSS measurements to create two sets of orthophotos and DEMs from which spatial extent and distribution were analysed. Over 5000 ballistics were mapped from 32 400m^2 areas spaced every 100m radiating away from the vent along transects every 22.5°. Higher spatial densities along the mapped SSE transect indicate that this was a preferential eruption direction during the two-month period between data collection trips. UAV and GoPro video, infrasound data and visual observations collected during these visits allowed us to analyse eruption frequency and supplemented the directionality data found from the mapped deposits. Combining these datasets, we present a ballistic hazard assessment for Yasur Volcano comparing the longer term ballistic hazard to that from the two-month period between data collection trips.

SAFETY as a hazard assesment tool to monitor volcanic deformation

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"Sentinel-1 for Geohazard Prevention and Forecasting" (SAFETY) was a two year project, funded by European Commission (Ref. ECHO/SUB/2015/718679/Prev02-SAFETY) which aims at providing Civil Protection Authorities (CPA) with the capability of periodically evaluating and assessing the potential impact of geohazards on urban areas. It finished in December 2017. Main reached objectives were the creation of useful products and tools, which exploit Sentinel1 data, and the design of a sustainable long-term infrastructure involving CPAs and Public Organizations (PO) responsible for the monitoring of the particular geohazards.

National Geographic Institute of Spain (IGN) is the public institution in charge of volcanic monitoring and alert communication to CPAs. It operates a real time volcanic monitoring system (VMS) based mainly on seismic, geochemical and deformation data. At SAFETY context main task of IGN were the implementation of SAFETY tools into the VMS and the validation of the generated deformation maps, based on Sentinel1 images, using other geodetic techniques.

We show the automatization and implementation of SAFETY tools performed at IGN to generate deformation products, which can be integrated in VMS to reinforce alert generation capabilities to CPAs. We also analyse validation procedures developed and applied to Sentinel1 based deformation maps making use of GNSS data, which showed the methodology involved at SAFETY is suitable to detect milimetric to centimetric deformations likely related to volcanic activity.

Further efforts will be done in the context of "Geohazard Impact Assessment for Urban Areas" project (U-Geohaz) also funded by the European Commission which will fully exploit the results obtained by SAFETY in the next two years.

S01.05 Poster

VolGIS: a new volcano-oriented GIS for multidisciplinary volcano analysis

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VolGIS is a new volcano-oriented Geographic Information System that makes possible to model and visualize different volcano-related available data in a user-friendly high- resolution visualization environment. The goal of this project is to create an open-source freeware platform where the user can apply a set of analysis tools to a specific volcanic dataset, or implement others algorithms to make new analyses, in an interactive 3D georeferenced and *queryable* environment. Here we present the prototype of VolGIS and its application to a 16-years earthquakes dataset of Mt. Etna. VolGIS allows making a tridimensional earthquakes density analysis at a customizable cell size resolution. It generates 3D isosurfaces that constrain volumes of high earthquakes concentration using the Marching Cubes algorithm. Each analysis can be performed both on the entire area or in a specific zone inside it. VolGIS integrates the possibility to import any map in the system and easily switch from a perspective to an orthographic view, enhancing interpretation.

While at this stage the time analysis is not implemented, we are planning a 4D environment, more suitable to assist volcano monitoring. VolGIS will then be integrated with online available tomographic codes such as LOTOS (for velocity tomography) and MuRAT (for attenuation and scattering tomography) to enhance the ability of users to interpret their results. We believe that this tool could sharply increase the ability to understand and communicate volcanological phenomena to different end-users such as media, decision and policy makers or the general public.

The emplacement of the lava dome at Nevados de Chillán in 2017-2018 using structure from motion (SfM) photogrammetry

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Lava dome-building volcanoes are among the most unpredictable and hazardous volcanic phenomena, where the associated activity includes effusive activity that may persist for years to decades, and may be punctuated by periods of repose and sudden explosive activity.
Thus, lava dome morphology and their growth rate are important to quantify for the purposes of hazard assessment. After almost two years of successive pulsatory explosive activity which formed a elongated crater of ~210 m diameter called Nicanor, an effusive eruption at Nevados de Chillán Volcanic Complex in Chile began in 20th December 2017, forming a lava dome inside the new crater, that volcanic activity is ongoing. In this work, we applying the structure from motion (SfM) photogrammetric techniques to create high- resolution Digital Elevation Models (DEMs) and photomosaics of the lava dome, from aerial photography acquired during observation overflight of Nicanor's crater between one day after the extrusion and the first months of 2018. The comparison of the different DEMs allowed calculate the lava dome extrusion rates and document changes in surface morphology. We found that the lava dome has been emplaced from a NW-SE fissure trend developing a sharp crease structure which extends for ~90 m. From this structure, the magma diverges laterally at the surface, forming different brittle fractures related to the viscous behavior of the dome. In plan view the lava dome have a semi-circular morphology controlled mainly by the topography of the crater. On first days of Abril 2018, the lava dome had a volume of ~0,2 x 106m^3, leading to an estimated low effusion rates of ~0,02 m^3/s for the entire effusive cycle.
The results presented here demonstrate that photogrammetric monitoring provides both an effective and systematic method of repeatedly measuring lava dome growth and a useful dataset for risk forecasting.

Analyses of volcanic sites by multiscale hyperspectral spectroscopy

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The Space Italian Agency (ASI) is going to launch the new space mission PRISMA (PRecursore IperSpettrale della Missione Applicativa). The mission is aimed to spectrally characterize the Earth surface through the combination of data acquired by hyperspectral and panchromatic sensors.

In this context, one of the mission objectives is represented by hazard mitigation and risk management and Mt Etna volcano has been selected as a calibration and validation test site. An airborne and ground measurement campaigns were carried on at Mt Etna and data were acquired by Hyperion satellite, Geocart airborne hyperspectral system and by a ground field spectroradiometer.

The hyperspectral data allow to characterize the composition of volcanic surface deposits, aerosol and gas emissions.

In order to handle, radiometrically calibrate and compare different kind of hyperspectral data, an IDL library software package has been implemented to be customizable for different type of hyperspectral systems.

This software provides a range of tools and applications for radiometric calibration, striping correction, horizontal and vertical banding, spectral and spatial spiking. In this work the IDL software is presented as well as the results of hyperspectral surface characterization obtained on Mt Etna test site.

Deriving digital elevation models using high-resolution satellite imagery in high relief volcanic areas

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Nowadays, optical satellites can collect high-resolution stereo imagery over large areas that should ensure good accuracy and reliability of the derived elevation data. To test this, two pairs of stereo Pleiades imagery collected in July 2015 over Mt. Etna volcanic area (Italy) were used and processed with the automated, open source NASA AMES Stereo Pipeline (ASP) to generate several versions of a digital elevation model (DEM). Each pair of stereo satellite imagery was run with two algorithms, one using a local search window (LSW), and the other using a more global matching (MGM) methodology, a modification of the semi- global matching (SGM) algorithm. The first algorithm estimates the apparent motion of the scene points, or disparity, by comparing local windows around each pixel in the stereo pair. This method is computationally quick, but cannot cope with ambiguities if the texture is lacking or the pattern is repetitive in the chosen window. The second algorithm compensates for ambiguities by using the smoothness of the disparity map and reducing the two-dimensional smoothness constraint to the average of the one-dimensional line optimization problem with the addition that the values of any given pixel are influenced by the values in the entire upper-left quadrant window. The results were exported as 3D point clouds and later processed using a USGS open source script to derive elevation matrices with a 2-meter spatial resolution.

Validation of processed DEMs was performed using a LiDAR derived DEM from 2005. The ellipsoidal elevation values derived from the Pleiades stereo imagery have been converted into orthometric heights using the CGR tool and the geoid ITALGEO 95. The planimetric validation RMSE is between 1 and 2 pixels, while the vertical validation RMSE is between 1 and 3.5 pixels, with MGM algorithm results consistently performing better than LSW.

Lidar imaging and GIS analysis of ignimbrite surface morphology and postglacial faulting at Crater Lake, Cascade Range, U.S.A.

Joel Robinson, Charles Bacon

U.S. Geological Survey, USA

Lidar collected during summer 2010 reveals, in unprecedented detail despite forest cover, the well-preserved surface of the ca. 7.6 ka climactic ignimbrite and related deposits surrounding Mount Mazama and Crater Lake caldera, Cascade Range, USA. Analysis of the ±1 m lateral and ±4 cm vertical resolution lidar in a GIS and creation of shaded-relief and slope maps, along with elevation profiles, allow ignimbrite surface morphologies to be recognized and a set of normal faults to be newly identified.

Ignimbrite surface morphologies reflect internal depositional processes. Nine morphologies were identified including furrow-ridge sets and wedge-shaped mounds eroded by pyroclastic flows, flow-parallel ridges and perched benches from passage of multiple more-mobile pyroclastic-flow cores, headwall scarps indicating ignimbrite remobilization, fields of closely-spaced pits caused by phreatic explosions, and extensional fractures due to differential compaction of ignimbrite. These morphologies illustrate a dynamic environment that varied spatially and temporally during eruption, and show that multiple processes modified the ignimbrite during and after deposition.
Mount Mazama is adjacent to the West Klamath Lake fault zone (WKLFZ), a series of mainly down-to-the-east arc-parallel normal faults. The lidar survey reveals several previously unrecognized faults in the heavily forested terrain west of the caldera. Postglacial surface rupture lengths of individual faults suggest earthquakes of Mw5.9–6.5, or Mw7.0 if several faults ruptured during a single event. Scarps 5–12 m high, developed over ~8 kyr, imply vertical slip rates of 0.6–1.5 mm/yr for the zone west of Crater Lake, higher than the ~0.3 mm/yr rate for the WKLFZ. Also evident are widespread west-northwest and north- northwest topographic lineaments that suggest distributed dextral and sinistral shear consistent with GPS vectors and recent models of clockwise rotation of the Oregon forearc block.

S01.05 Talk

Unmanned Aerial Vehicles and their application on the study of Volcano- sedimentary pyroclastic deposits: A perfect platform for Textural Quantitative Analysis

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Recently Unmanned Aerial Vehicles (UAV) are transforming the way we sense and interact with the environment. The decrease in cost, the increase in the payload, combined with the availability of smaller cameras with better resolution, has contributed to its diffusion in different fields of geology. This technology could have some other applications in geoscience such as Volcanology. Nowadays the advantage of using UAVs in volcanology is significant: to avoid the risk of researchers and to obtain data from unapproachable locations such as a dense plume, an active crater or a high outcrop where sampling using rappel techniques are the only way to obtain quantitative data.

This work presents a new way to obtain quantitative data for study of pyroclastic deposits by using UAVs. We use a hexacopter vehicle mod. DJI 900, equipped with two cameras of different resolution and apparent field. The method consists of projecting to the outcrop wall two laser beans parallel each other. The lasers dots act as a scale, and provide scaled images suitable for image analysis. Videos obtained by a GoPro Hero 4 camera, with a wide field rectified lens, are used for the 3D model reconstruction, photogrammetric purposes and to analyze the coarsest fraction of the outcrops. A Sony hdrcx455/B camera is used for high resolution imaging in order to obtain the best resolution for optical granulometric analysis of millimeter to centimeter-sized clasts. Videos are processed to obtain images and are analyzed using image analysis software designed in our labs.

The results obtained are promising and comparable with results obtained by other texture analysis methods. The resolution we obtain allows the measurement of particles on the order of 1 mm in size. This method, developed for volcano-sedimentology purposes, can also be useful in other sedimentary research, structural geology and geotechnical applications.

Use of Sentinel-1 data to characterize erosion and deposition processes due to lahars at Volcán de Colima, Mexico

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Lahar events are considered one of the most dangerous secondary hazard in volcanic environments. The hazard potential is enhanced in tropical environments, where the annual precipitation amount and intensity play a crucial role in the remobilization of loose volcanic deposits. Volcán de Colima (VdC), Mexico, is a peculiar example. There, annual precipitation reach ~1500 mm, with maximum peaks during July. The presence of loose block and ash flow deposits, which are easily remobilized, favour lahar formation with about 20 events per rainy season. In this scenario, remobilized materials may reach distances up to 15 km from the cone. Studying the erosion and deposition processes caused by lahars at VdC might help in understanding these phenomena and in defining hazard mitigation strategies. For this purpose, remote sensing data, and especially satellite based imagery, can be of great advantage. In this work, we study lahars with the use of different remote sensing datasets in the Montegrande ravine, located in the south portions of the VdC complex. We aim at identifying the capabilities and limitations of synthetic aperture radar (SAR) imagery acquired from the SENTINEL-1 satellite to surface changes along the Montegrande ravine. Moreover, we use additional remote sensing techniques, such as multitemporal DEM generated from airborne UAV and multitemporal optical imagery from terrestrial cameras, to validate our results. We focussed our investigation in the period between June and July 2017, when several sediment-laden flow events have been detected by the UNAM monitoring station, composed of a geophone and an infrasound sensor. Preliminary results show that we can map SAR coherence changes along the Montegrande channel, with significant peaks at specific locations. The results of this are of great relevance to define the current capacity SENTINEL-1 imagery to identify and map changes associated to surface processes in volcanic environments.

S01.05 Poster

Photogrammetric study of the Avachinsky volcano: The current cone morphology as a source of potential hazard

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The Avachinsky volcano is an active andesitic stratovolcano located in southern Kamchatka, 25 km northeast of the Petropavlovsk-Kamchatsky city. During the eruption spanning from January 13 to 18 in 1991, the volcano's crater, which is 185 m in depth and 370 m in diameter, was filled with lava. After the eruption, the excess lava poured out through the lower part of the crater's rim to the south-southeast slopes and formed a blocky lava flow that is 1,850 m in length. The volume of the lava, which plugs the crater, is 8,400,000 m3. The volume of the lava flow is 4,300,000 m3. The aerial survey of the Avachinsky volcano on November 11, 2001, revealed a system of new fractures on the lava surface in the crater and on the adjacent sectors of the slopes. The most noticeable is a fissure – which is 280 m long, up to 20 m wide, and up to 17 m deep – that was formed as a result of phreatic explosions of merged explosive funnels. Comparing the 1991 and 2001 DEMs of the cone, we identified horizontal displacements in the south-southwestern sector of the lava plug. We measured the distances between certain points on the lava plug's surface, which were located on both sides of the fissure. The measurements from the 2001 DEM showed, on average, a 1.4-m increase in the distances that reflects the width of the fractures on the slopes of the cone. We suggest that the weakening of the upper part of the Avachinsky cone due to the fractures and deformations will contribute to its collapse during the next unrest. The next eruption could be catastrophic due also to the massive lava plug in the crater that blocks the vent. Therefore, Petropavlovsk-Kamchatsky and its surroundings are under threat of volcanic hazard.

S01.05 Talk

Multi-resolution thermal infrared remote sensing of Mount Hasan Stratovolcano (Central Anatolia, Turkey)

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Mount Hasan is a double-peaked stratovolcano located in the Central Anatolian Volcanic Province. While no recent steam activity have been observed inside the craters; fumaroles and water vapour have been observed at several vents on the western flank of the summit, between 2800 and 3000 meters (a.s.l.). The highest temperature and CO2 values measured in those vents are 68.7 °C and ~10000 ppm respectively. We used low to very-high resolution satellite and airborne thermal imagery to map the hydrothermal zone on the western flank of the volcano. Low-resolution (1 km/px) MODIS data acquired by Terra and Aqua platforms consisted of 4 daily images (daytime and nighttime) have been used to track the major thermal anomalies for a period of 17 years. ASTER nighttime thermal infrared imagery has also been used to map the thermal anomalies on the volcano at higher resolution (90 m/px). Surface temperature anomalies and relative radiative heat flux were calculated for 28 nighttime ASTER TIR imagery covering a period between 2001 and 2017. In order to investigate the structural features related to the thermal radiation in very-high resolution, airborne data have been collected using lightweight drones. By means of multi- view stereophotometry (SfM-MVS) very-high resolution surface elevation model (< 6 cm/px) of the summit area coupled with orthorectified photo (<3 cm/px) were constructed. Finally, the pre-dawn radiometric thermal imagery was acquired using a drone equipped with a thermal camera and the data were processed to map the thermal zone in <10 cm/px resolution.
This study was supported by The Scientific and Technological Research Council of Turkey (TÜBİTAK P. No: 116Y167).

S01.05 Poster

Assessing different scales of DEM spatial resolution for the morphological characterization of scoria cones: Applications to the Sierra Chichinautzin volcanic Field, central Mexico

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Morphological characterization of scoria cones provides useful information to infer properties of large monogenetic fields. Specifically, it has been suggested that it could be used to assess the degree of shape alteration of scoria cones to apprise the relative ages of the volcanoes.

Here, we compare 12 morphometric parameters (MP) calculated from the analysis of the elevation profiles of fifteen C14-dated scoria cones (ages <30kyBP) of the Sierra Chichinautzin Volcanic Field (SCVF) in Central Mexico using two separated DEMs with different horizontal and vertical resolutions: the TanDEM-X database, which is a SAR Digital Elevation Model provided by the German Aerospace Center (DLR), with a horizontal resolution about 12 m and a vertical accuracy of 2 to 4 m (depending on slope), and a higher resolution airborne LIDAR DEM (5 m horizontal, and 1 m. vertical resolutions) provided for a selected area of the SCVF by the Mexican National Institute of Geography and Statistics (INEGI).

The compared MP were: cone height, basal diameter, crater diameter, average cone slope angle, surrounding terrain slope, crater depth, crater off-set, ratio of height to basal diameter, ratio of crater diameter to basal diameter, volume of the cone, ratio of the crater depth to the cone's height, and cone horizontal elongation.

Calculations of the MP using both databases were found to be mutually consistent and equivalent for cones with volumes greater than 0.01 Km^3, regardless of their highly variable shapes. The only of those extensive MP rendering some weak correlation with the cone´s age was the average slope (r=0.6), remarking the need to explore new MP to assess the degradation state of young scoria cones targeted to set reliable volcanic morpho- chronologic criteria.

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S01.08 - Multi-method approaches to screen storage, activation, and transport in magmatic systems

The tip of the dike: crystals record the conduit opening and magma transport to the surface

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Monogenetic eruptions are typically fed by dikes. However, the processes and range of variables that control dike propagation and magma movement are still poorly known, especially those that occur at the tip of the dike. Numerical modeling and laboratory experiments suggest a very dynamic environment, with large temperature and pressure gradients, and a large amount of exsolved fluid. Here we report on the mineralogy and petrology of tephra erupted during the first month of the Paricutin monogenetic eruption (Mexico, 1943-1952), which appears to record the transition of the tip of the dike to more steady magma flow that fed this eruption.

Olivine crystals are typically < 250 micrometers and mainly skeletal. Those of the early tephra display a wide variety of zoning patterns in Mg/Fe, Ni, Mn, Ca, and P. Many crystals show cyclical and sharp Fo variation (=Mg/[Mg+Fe]) of up to 10 mol% in less than 50 micrometers. Such variations are mirrored by P zoning, indicating crystal growth with limited intra-crystal diffusion. These zoning patterns are likely recording the large variations of temperature, oxygen fugacity, other volatile pressures and associated melt evolution occurring at the tip of the dike. Preliminary modeling of the Fo variations at a range of temperatures is consistent with magma transport and dike propagation time scales. Such complex zoning patterns of the early tephra are absent from later erupted tephra and lava, which only contain normally zoned olivine. We believe that the crystal zoning patterns of the first explosive products record the transition from an early process of dike propagation and opening of a new volcanic conduit that involved large but local changes in magma composition and thermodynamic variables. Our results have implications for the understanding of dike initiation and magma transport in dikes as well as the early stages of monogenetic eruptions.

Temporal evolution of magma and mineral storage conditions in the Bárðarbunga-Veiðivötn volcanic system

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We have investigated three well-dated macrocryst-rich formations within the Bárðarbunga- Veiðivötn magmatic system in central Iceland in order to resolve the temporal evolution of magma storage conditions within one of Iceland's most productive volcanic systems. Studied formations are: Ljósufjöll (pillow lava, subglacial), Brandur, Fontur and Saxi (tephra cones, 8-9 ka) and Þjórsárdalshraun (lava flow, 3200 ka).

The samples from Þjórsárdalshraun and the tephra cones show similar melt-macrocryst relationships. Here, plagioclase rims (An_{69-80}) are in equilibrium with the carrier melt (Mg# 40-52), while plagioclase cores (An_{82-91}), olivine (Fo_{75-87}) and clinopyroxene (Mg# 75-87) macrocryst cores and rims are too primitive. On the other hand, the Ljósufjöll samples have more magnesian groundmass glass composition (Mg# 52-62), which is too primitive to be in equilibrium with the olivine (Fo_{75-77}), plagioclase (An_{65-72}) and clinopyroxene (Mg# 76-85) rims and too evolved to have crystallized the olivine (Fo_{84-87}), plagioclase (An_{87-90}) and clinopyroxene (Mg# 85-87) cores.

Clinopyroxene-melt equilibrium pressures were calculated using the clinopyroxene-liquid barometer of Neave and Putirka (2017) and equilibrium melt compositions were selected from a large database of Bárðarbunga glass compositions (Óladóttir et al. 2011 and unpublished data). Pyroxene from all localities records comparable crystallization pressures and temperatures (eq. 33 of Putirka 2008) of around 1.9 ± 1.4 kbar (6.9 ± 5 km) and 1188 ± 45 °C, respectively. Furthermore, using the pressure-dependence of the location of the olivine-plagioclase-augite-melt (OPAM) boundary (Yang et al. 1996), we calculate that melts erupted in the Bárðarbunga system last equilibrated with crystals at 2.2 ± 1.3 kbar (7.7 ± 4.6 km), in good agreement with clinopyroxene-melt equilibrium pressures.

Based on a comparison of our results to those obtained for the 2014-2015 Holuhraun eruption (Hartley et al. 2018), we conclude that magma and crystal storage conditions in this volcanic system did not change significantly during the Holocene.

Stochastic modelling of Krafla's magma bodies

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The Krafla volcanic system in NE Iceland exhibits active bimodal basic and acidic magmatism, with high-temperature geothermal resources that have been exploited since 1977. Deep wells provide a unique insight into Krafla's geological structure, including two intersections of acidic magma. It is thought that shallow magma bodies play a significant role in heating the geothermal system, as well as being a volcanic hazard. The study evaluates available geoscience and engineering data; generating several conceptual models for the locations and morphology of current magma bodies. These include various combinations of dykes, sills, cone sheets, and magma chambers. Training images derived from these models form the basis for further stochastic simulation of the bodies using the DeeSse multiple point geostatistics algorithm. A supervised machine learning classification model was used to predict magma occurrence based on exhaustive geophysics data, with the aim of guiding local target probability in the simulations. Unfortunately, the data was inadequate to train a robust model, and excessive processing times also resulted when using a local target probability in DeeSse. The resulting realisations are therefore unconstrained by geophysics and quantities of magma in the models remain arbitrary. When analysed for uncertainty using information entropy, phi, and distance clustering – the simulations show that magma probability is defined mostly by body geometry and large-scale patterns constrained by the limited hard data. The study demonstrates the potential for DeeSse to reproduce complex geological patterns, as well as the difficulty in providing appropriate training images.

S01.08 Talk

Pre-eruptive dynamics and geometry of the feeding system during the initial stages of Monte dei Porri volcano (Salina, Aeolian Islands)

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Pre-eruptive dynamics and the geometry of the feeding system of the initial stages of Monte dei Porri volcano, located in the western part of Salina (Aeolian Islands), were investigated through textural and compositional analyses on plagioclase crystals. We studied the Punta di Megna lava flow, which present structures related to mingling between two magmas having different geochemical compositions, with a minor dark portion which intrudes a lighter one. Four main plagioclase textures were recognized, namely:

1) Oscillatory zoning, with constant FeO and small variations in the An content, suggesting quiet crystallization;
2) Dissolved core, with An contents abruptly decreasing, related to rapid magma ascent;
3) Sieve-textured rims with an increase of An and FeO contents, suggesting magma mixing;
4) Coarse-sieve textures, with glass pockets randomly distributed in the crystal superimposed to oscillatory zoning, which suggest a slower magma ascent.

All the four textures are ubiquitously present in all the analyzed samples, but sieve-textured rims plagioclase are the most frequent in the lighter (and main) portion of the lava flows, confirming that they are the result of magma mixing between two magmas at different composition and temperature. Nonetheless, the dark, and more basic, portion of the lava flow has a predominance of plagioclase with dissolved cores, suggesting that chemical-physical variations during magma ascent played a major role. So, we propose a feeding system including two reservoirs, at least for the initial stages of Monte dei Porri volcano. Magma from a hotter, more mafic and deeper (10 km) magma chamber would have rose quickly, forming dissolved cores and sieve-textured rims, and reached a shallower (3 km) reservoir with a magma that was crystallizing. The simultaneous occurrence of dissolved cores and coarse sieve-textures in the same samples would indicates that magmas rose up with a variable rate at water- undersaturated conditions.

S01.08 Poster

Understanding the origin of magmatic necks: insights from Etna and analogue models

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Magmatic necks are commonly found in volcanic areas often showing a homogeneous structure with cylindrical shape and diameter of up to several hundreds of metres. Their massive and uniform structure poses a space problem for their emplacement in the brittle crust. We use field data and analogue models to investigate how necks may emplace at shallow levels, contributing to the solution of the space problem. Field analysis investigates in detail the geometric, structural and magmatic features of two necks outcropping in the eroded portions of Mt. Etna. These are homogeneous and massive intrusive bodies, related to a single episode of emplacement at a paleodepth of 500-700 m. Their possible emplacement mechanism has been further investigated through analogue models, injecting vegetable oil (magma analogue) within sand (upper crust analogue). The models suggest that necks may form from the upward propagation of dikes if a topographic relief (as a volcanic edifice) is present. Such a relief promotes, due to its gravitational forces, the thickening of the intrusion towards the surface. The similarity of the Etna necks with other known worldwide cases suggests a general applicability of our gravity-driven model in the development of shallow magmatic necks.

Key words: neck, magma, dike, volcanic edifice, Etna

Defining rates of magma ascent and degassing at open-conduit volcanoes: clues to re-evaluating the hazard associated to violent paroxysmal eruptions

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Magma ascent velocity during explosive eruptions is often too rapid to be recorded by diffusion of most major and trace elements. Only elements with very high diffusivity, such as Li in plagioclase or the melt-bubble exchange of fast-diffusing volatile species can provide direct measurements of such short-lived processes. We are using two different modeling approaches that benefit from the diffusion of volatiles (H_2O, CO_2 and S) in partially-opened melt inclusions and tubes in olivine and the fast diffusive relaxation of Li zoning in plagioclase to recover timescales of magma ascent and degassing during unusual explosive eruptions at open-conduit volcanoes. Some relevant explosive episodes with different intensity, which occurred at Mt. Etna between 2011 and 2016, have been individuated and selected as case study. Modeling the diffusion of volatile species along olivine melt tubes leads us to recover timescales over which volatiles have been exchanged by diffusion with the external melt, and to determine the duration of magma ascent over a wide range of depth. Open-system separation of the gas phase upon eruption produces Li depletion from the melt, due to preferential and rapid transport of Li into the exsolved fluid phase. This process induces outward decrease of Li concentration in plagioclase, enabling to derive timescales of magma ascent and degassing just before the emission. Results evidence that processes of gas flushing are responsible for the re-activation of the magmatic system and the generation of some highly energetic eruptions, which occurred over unusually short timescales. The choice of eruptions characterized by different intensity of the explosive activity leads us to produce an array of ascent rates for a wide range of possible eruptions at open-conduit systems erupting low-viscosity basic magmas, which revealed to have important hazard associated.

S01.08 Poster

Diffusion of trace elements during mixing of mafic and silicic magmas: implications for timescales of magma mixing

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Chemical diffusion controls mass exchange rates in magma mixing events and represents a source of timescales for pre-eruptive magma mixing. We experimentally studied the diffusive mass exchange of 30 trace elements between melts of natural shoshonitic and rhyolitic composition from Vulcano Island, Italy. A set of 13 diffusion couple experiments was run in an Internally Heated Pressure Vessel at 1200 °C, pressure from 50 to 500 MPa, and both dry and hydrous (1 wt.% and 2 wt.% added H_2O) conditions. Concentration profiles were measured by LA-ICP-MS.

A group of 13 elements show normal diffusion profiles, and hence diffusion coefficients were calculated using a concentration-dependent method. We find that water content is the main conditioning factor of diffusion in our experimental setup. The addition of 2 wt.% water results in a diffusivity increase between 1.0 and 1.4 orders of magnitude, with the highest values corresponding to LILE (Ba, Cs, Rb and Sr) and the lowest to transition elements (Ta, Cr). Diffusivities increase smoothly from rhyolitic to shoshonitic melts, except for Ba and Sr, which are insensitive to melt composition. Evidence of coupling to SiO_2 and variable decoupling with melt viscosity at high viscosity values are present.

A second group of elements comprising Y, Zr, Nb, Pb and, most notably, REE (except Eu) display prominent uphill diffusion in the form of very deep minima in the rhyolitic side coupled to wide maxima in the shoshonitic side. This behaviour implies that diffusion is affected by activity gradients induced by the strong SiO_2 contrast, resulting in a transient melt-melt partitioning in favour of the less polymerized shoshonitic melt.

These results indicate that dissolved water is capable of notably accelerating mass exchange, therefore affecting derived timescales, and that some elements can effectively increase their compositional variability during early stages of mixing.

S01.08 Poster

Constraining the P-T-X-t paths of magma storage and migration in the Snæfellsnes Volcanic Belt, W-Iceland

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Tracking the crustal storage and transfer of magmas on their way to an eruption is an important goal in volcanology. To this end, we apply an integrated method, linking Systems Analysis, a time-integrated study of zoned olivine populations [1-4], melt inclusion geochemistry and thermobarometry. This enables us to constrain the pressure-temperature- composition-time (P-T-X-t) paths for sub-surface magma storage, evolution and migration in the Snæfellsnes volcanic belt (SVB), in W-Iceland. We have investigated 110 olivine and 58 clinopyroxene macrocrysts contained in two postglacial lava flows from the Snæfellsjökull (*Búðahraun*, *Búð; ~5.0-8.0 ka* [5]) and Ljósufjöll volcanic systems (*Berserkjahraun*, *Bers*; ~4.0 ka [5]). Olivine macrocrysts from *Búð* and *Bers* show simple *normal* and complex, *reverse* zonation.
The core (Fo_{73-91}) and rim (Fo_{71-80}) compositions of the olivine macrocrysts are bimodal, with peaks at Fo_{82} and Fo_{88} (cores) and at Fo_{74} and Fo_{77} (rims). Clinopyroxene macrocryst compositions range from Mg# 62 to 93, with peaks at Mg# 83 (*Búð*) and Mg# 78 and 84 (*Bers).* The Al-, Ti- and Cr-contents range from 2.5 to 8.3 wt% (Al_2O_3), 0.5-4.4 wt% (TiO_2) and up to 1.4 wt% (Cr_2O_3). Crystallization pressures and temperatures have been calculated using the clinopyroxene-liquid thermobarometer of [6]. Clinopyroxenes from *Búðahraun* with Mg-number 81±2 reveal pressures of 5.4±0.9 kbar and temperatures of 1193±11°C. We assume that these clinopyroxene compositions have been in equilibrium with olivines of similar forsterite contents.

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Using volatile contents to infer the emplacement mechanism of silicic lava flows: An FTIR study of Obsidian Dome, CA

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Texture, composition, thermal history, and volatile content control the rheology of silicic lava flows and therefore, the dynamics of silicic lava emplacement. There are two end- member models for the growth of silicic lava flows. Endogenous growth is characterized by the formation of a firm carapace, which inflates as new lava erupts. During exogenous growth the carapace is more mobile, and movement is accommodated by younger lava cascading down the lava flow front. These two emplacement models predict different spatial trends in volatile content within the lava flow. We are testing emplacement style by measuring the volatile content of 135 samples from Obsidian Dome, Mono-Inyo Craters, CA using Fourier transform infrared (FTIR). We collected samples along seven different one- dimensional (1D) transects of outcrops and drill core. All samples are rhyolite (74 wt.% SiO_2), but texture varies and includes dense glass, fine vesicular pumice, and coarse vesicular pumice. Water contents from the drill core proximal and distal to the vent range from 0.13 to 0.63 wt.% and 0.05 to 0.30 wt.%, respectively. Outcrop samples collected on the western margin of the flow have water contents ranging from 0.05 to 0.35 wt.%. Water speciation cannot be determined for samples with such low water contents, thus we measured the H_2O_{total} absorbance at 3500 cm-1. Carbon dioxide is not detected in any sample. We find that H_2O_{total} values show no systematic variation along any of the 1D transects, and no correlation with different textures. The H_2O_{total} values are also consistently below predicted solubility limits for water in rhyolite glasses. Together, our data suggest that most of the rhyolite outgassed to atmospheric conditions during emplacement, supporting the model of exogenous growth. Future work will characterize the thermal history and measure the viscosity of samples from Obsidian Dome, to further constrain the rheology of silicic lava flows.

S01.08 Poster

Paricutin volcano mineral assemblage suggests magmatic evolution controlled by fractionation without significant crustal assimilation

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Paricutin volcano is the youngest monogenetic cone from the Michoacán-Guanajuato volcanic field (central Mexico), with an excellent historical record of the eruption from February 1943 to March 1952. It has been considered a classical example of magma differentiation controlled by crustal assimilation combined with fractional crystallization. However, whole-rock major and trace element data, together with multi-isotopic studies of its volcanic products, point to mantle source heterogeneity and fractional crystallization as the key processes involved in the origin and differentiation of the magmas.
We present a detailed study of the phenocrysts (olivine, Cr-spinel and pyroxenes) in the tephra deposits and lavas that span the entire duration of the eruption, to clarify the processes that lead to the chemically zoned eruption. All eruptive products have low phenocryst contents (< 10 wt.%). The early tephras, erupted within the first weeks/month, are basaltic andesites with oscillatory zoned olivine, zoned Cr-spinel and rare xenocrysts of reversely zoned orthopyroxene and clinopyroxene. This complex suite of crystals is probably related to the opening of the conduit. In contrast, the rest of the tephras (after March 1943) and lavas erupted throughout the nine years are andesites with normally zoned olivines, Cr- spinel in equilibrium with their host olivine, and frequent orthopyroxene with minor chemical zoning, suggesting mild fractionation and mafic recharge with melts of similar compositions. We don't find mineralogical evidence of assimilation of granodiorites, which was previously postulated on geochemical grounds and the presence of xenoliths in the early lavas.
Together, whole-rock and mineral chemistry data suggest rapid fractionation and subtle magma recharge events as the main magmatic processes controlling the evolution of Paricutin magmas, with limited to no crustal assimilation involved.

S01.08 Poster

Triggering Mount Etna's most destructive historic eruption. Cryptic magma mixing recorded in clinopyroxene megacrysts

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The 1669 flank eruption of Mount Etna (Sicily, Italy) was one of the most voluminous and destructive in its recorded history (Branca et al., 2013, Corsaro et al., 1996). This study focuses on cm-sized megacrysts of clinopyroxene, found in the 1669 scoria deposits. We present a multi-method approach to reconstruct magma dynamics in the plumbing system preceding the eruption. Petrological observations in combination with laser ablation ICP-MS mapping (Ubide et al., 2015) reveal sharp compositional zoning of the megacrysts, not seen in major element transects. Trace element data, including Cr, Zr and REE's, show that core, mantle and rim zones originated in distinct magmatic environments. Chromium-rich cores (300 ppm on average) are in disequilibrium with the glassy to microcrystalline host groundmass and indicate crystal inheritance from a primitive magma source. Oscillatory zoning in the mantle of the crystals suggests a sustained period of magma replenishment and crystallisation. Finally, ubiquitous Cr-rich (180-300 ppm) rims are in equilibrium with the groundmass and rich in melt inclusions, suggesting a final recharge event inducing rapid crystal growth and eruption. Chromium enrichments are not coupled with increases in MgO suggesting a cryptic mixing, involving two melts of similar composition. While historical accounts report that only two weeks of intense seismic activity preceded the eruption, pyroxene growth rates and olivine diffusion chronometry (Kahl *et al.*, 2017) indicate that recharge began much earlier. Temperatures of 1080-1180°C and pressures of 3-6 kbar have been calculated for the three magmatic environments based on clinopyroxene composition at 2 wt.% H_2O (Neave & Putirka, 2017), to constrain the conditions of magma storage and mixing. The clinopyroxene data from this study are combined with olivine data from Kahl *et al.*, (2017) to present a comprehensive model for pre-eruptive magma dynamics and eruption triggering mechanisms at Mt Etna.

Multi-stage crystallisation and magma mixing at Popocatépetl volcano, Mexico

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Popocatépetl (Popo) is an active arc volcano in the densely populated metropolitan area of Mexico City. Since 1994, dome emplacement and destruction cycles have caused several evacuations, however current activity is minor compared to Popo's eruptive history, including two Plinian events in the last ~2000 years and several large effusive eruptions.

We present a detailed mineralogical characterisation of lavas and pumices erupted during the last ~14.1 ka, with key implications on the architecture and dynamics of Popo's plumbing system. Lower crustal magmas fractionating ol (Fo_{89-82}) + chr + aug (≤6 wt % Al_2O_3) feed a shallow mafic magma reservoir (≤3 kbar), which crystallises opx (Mg# 90 - 79) + cpx (Mg# 91 - 82) + chr ± sulf over a temperature range of 1000 - 1115°C. This shallow mafic endmember is periodically injected into a more evolved reservoir, producing transient hybrid melts at 960 - 1030 °C that facilitate the onset of pl crystallisation (An_{65-50}) as well as a peak in opx (Mg# 78 - 71) + cpx (Mg# 83 - 79) ± sulf crystallisation. Following this initial hybridisation stage, the evolved reservoir cools to long-term storage temperatures of ~960°C, and ap, ilm and mag start to crystallise together with evolved pl (An_{50-28}), opx (Mg# 71 - 56) and cpx (Mg# 64 - 79).

This dynamics is of a cyclical nature, as mafic magmas are repeatedly injected into the evolved reservoir. Multiple generations of phenocrysts with different histories are stored in a heterogeneous crystal mush in the evolved reservoir, which gets periodically remobilised by mafic injections. These results suggest that the plumbing system of Popocatépetl is characterised by interconnected magma reservoirs on multiple levels. Magma injections from depth may propagate upwards and eventually lead to effusive and explosive eruptions of a mixed and hybridised andesite.

S01.08 Poster

Toward a new concept for magma ascent dynamics at monogenic volcanic fields: the archetype of the northern Main Ethiopian Rift

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Monogenic volcanic fields are made up of tens-to-thousands small monogenic eruptive centers. They are frequent in some "complex" geodynamic frameworks, like the Trans- Mexican Volcanic Belt and the Central Kamtchatka Depression, and in some extensional settings such as the Northern Main Ethiopian Rift (NMER). This area is characterized by an oblique en-echèelon system of active faults at the floor of the Rift Valley (the Wonji Faults Belt), which actually accommodates all the extension of the NMER and is the main site of volcanic activity. Here, volcanism is characterized by central volcanoes, eruptive fissures with lengths of several kilometers and small basaltic monogenic scoria cones (MSC, >200) with associated minor lava flows, aligned along the Wonji segments.

Fissural products have trachybasaltic composition and are aphyric (P.I. <1-2vol%), whereas MSC are basalts with P.I. of 15-30vol%, with plagioclase phenocrysts as the dominant phase. Mass balance calculations showed a same parental magma for all these products, but different crystallization histories. MSC products derive from the shallow fractionation of ca. 15vol% of crystals (Ol, Cpx, Ox, Opx) plus cumulus of 30-40vol% of plagioclase. Fissural magmas underwent more extensive fractionation (35vol%) of the same mafic phases.

We put forward the idea that:

1) fissural trachybasaltic magmas reside at the Moho, where they fractionate mafic phases: when eruption is triggered (probably for tectonic reasons), they rise directly to the surface through fault systems;
2) MSC basaltic products derive from low-pressure crystal fractionation (<10-12 km) of a magma which rose up from the Moho through the lithospheric Wonji faults, later was stored at shallower depths (elongated along the main fault system) and crystallized.

In this view, monogenic volcanic fields are generated from a slow ascent (mainly depending from density contrast) from this low- pressure magma reservoir of several small-volume blobs of magma, from which every MSC is generated.

Pre-eruptive magmatic processes and their timescales at Vulcano island (southern Italy) during the last 1000 years

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Volcanic products emitted at Vulcano (Aeolian Islands, Italy) over the last 1000 years have been investigated through an integrated textural and micro-analytical study on plagioclase crystals, which allowed us to draw a detailed model of the internal structure of the magmatic system. Two centers have been active during hystorical times in Vulcano: Vulcanello, where poorly evolved magmas were mainly erupted and La Fossa Cone, which erupted more differentiated products.

We found that magma storage and mixing occur into an articulated plumbing system developed from the mantle-crust boundary to the surface. A basaltic-shoshonitic reservoir, probably located at the depth of the Moho, fed the activity of both centers. Starting from Moho depth, our data indicate the presence of three main magma levels beneath La Fossa Cone, which were variously reactivated over the whole period of activity. Plagioclase crystals registered the ascent and continuous episodes of magma recharge plus mixing that affected the shallower reservoirs. The first stages of activity at Vulcanello were fed by poorly differentiated melts that directly rose from the deep basaltic-shoshonitic reservoir, residing for a short period of time into the crust before the eruption. Indeed, Sr diffusion modeling in plagioclase indicates limited residence times (<2 years) for crystals erupted at Vulcanello if compared to those of the La Fossa Cone eruptions (2-10 years). Our time estimations suggest that magma feeding the activity at La Fossa have been stored for most of the time in reservoirs located below the plagioclase nucleation depth (~11 km of depth), intruding at shallower levels only few years before the eruption onset.
According to our model, magmatic eruptions at Vulcano could be related to the ascent of deep basic magma that triggers a sort of "reaction chain" through subsequent episodes of recharge and mixing toward the upper magmatic reservoirs.

Dynamic interaction between shallow reservoir and deep chamber inside Aso volcano, Japan

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In the southwest Japan, long-period tremors (LPTs), have been observed at Aso volcano since the pioneering work by Sassa (1935). LPTs typically have a resonant period of ~15 seconds and they are repetitive and appear time-invariant in their location and mechanism. It is considered that LPTs represent the resonance of a crack-like volcanic conduit located close to the active first crater, with a source depth close to the sea level. In this study, we aim to clarify possible response/feedback between shallow conduit of the LPT source and the magma chamber. Previously, we constructed LPT catalog between 2011 and 2016 and identified diverse LPTs with opposite waveform polarities (Niu and Song, 2018, EGU/JpGU). Through waveform stacking of broadband displacement and horizontal tilt borehole recordings, we find that LPT stacked waveforms are accompanied by a very weak (e.g, vertical displacement of ~ 1 μm and horizontal tilt of < 1 nrad), but detectable static offset, with a rise time on the order of ~100 seconds. The displacement ratio and tilt ratio of static offsets among different station or/and different channel do not show appreciable change over the 6-year period, and they are distinct from those measured against LPT, suggesting a repetitive, but non-destructive source located away from the LPT source. Joint inversion of tilt and displacement vectors of static offsets put the source close to previously inferred magma chamber of ~ 4 km, a few kilometres southwest of the first crater and the LPT source. This observation demonstrates that the LPT source and static-offset source occur almost concurrently beneath Aso volcano, indicating a causal interaction between the shallow conduit and the magma chamber.

S01.08 Talk

Combining petrologic and seismic studies to constrain magma storage conditions beneath Marapi volcano, West Sumatra, Indonesia

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Marapi is characterized by frequent gas bursts and small eruptions (VEI 1–2) and in the past four years, the volcano has been erupting every year. Despite its frequent activities, the eruption mechanisms, and the processes of magma storage and transport at this volcano are still lacking of study. The large number of fresh-looking volcanic bombs and the presence of eight seismic stations lead us to reconstruct the plumbing system of the volcano through an interdisciplinary study. A petrologic study of the summit bombs uses pyroxene, plagioclase and glass compositions to obtain pressures and temperatures of magma storage as well as magma evolution. Two-pyroxene geothermobarometry reveals that the magma is stored at pressures of 300 – 600 MPa (11 – 22 km depth) and temperatures of 900 - 950°C. In order to further image the magma reservoir, we performed teleseismic receiver function analysis of the seismic data. In the radial component of receiver functions, all stations show consistent negative polarity at 2-3 seconds, which indicates a transition to lower velocities. This low velocity zone at depths of 8 – 15 km could indicate current magma storage and we observed that the low velocity zone appears to be extending to the west towards the neighboring volcanoes Singgalang and Tandikat. The low velocity zone from the seismic study overlaps with the depth of magma storage estimated from petrology. To better link our understanding of the plumbing system with immediately pre-eruptive magma dynamics, we apply (1) geothermobarometry to the most recently erupted bombs (June 2017), (2) diffusion modeling of orthopyroxene rims to investigate the time scales of eruption triggering, and (3) receiver function inversion to better constrain the velocity structure beneath the volcano. Such combined interdisciplinary studies will be informative for future periods of unrest and for volcanic hazard assessment.

S01.08 Poster

Insights into magma storage and fault- magma interactions in an early-stage continental rift from active deformation and kinematic modelling studies

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A volcanic eruption triggered by a dike intrusion sourced from another magma chamber has been documented in the Afar region, and inferred in an early stage rift, the Magadi-Natron area, East Africa. We use new seismic data, discussed in the context of new geochemical and geological data, to unravel the changing stress-state and role of magma intrusion in the Magadi-Natron region, a seismically and magmatically active sector of the Eastern rift. In 2007, the Oldoinyo Lengai-Naibor Soito-Gelai (OL-NS-Gelai) magmatic complex in the south Natron basin was the site of an earthquake swarm and a large volume dike intrusion beneath the NS monogenetic cone complex, and followed by an eruption at the carbonatitic OL volcano. Yet, the source of magmas and the mechanism for triggering a nearby eruption remained elusive, owing to the lack of crustal imaging and fault kinematic data. Since then, new datasets have allowed detailed studies of earthquake locations, receiver functions, tomographic imaging, gravity modeling, field geology, fault geometry, and gas emissions in the Magadi-Natron area. In this study, full moment tensor inversion via waveform modeling of earthquakes M>3.4 reveals source mechanisms with significant dilatation components, implying magma intrusion and gas expansion as the cause of the volume change. We interpret the crack-type seismic sources as evidence for magma-involved faulting where faults serve as pathways for volatile emission. Waveform analysis on the nearest permanent seismic station just outside Nairobi (KMBO) indicates similar rupture processes occur over eruptive and inter-eruptive cycles. We hypothesize that these magma-related earthquakes occur on multiple faults above a sill complex previously imaged using seismicity and joint gravity-seismic tomography. These results are discussed in the context of the growing database of complementary geophysical, geochemical, and geological studies in the area, as we seek to understand the structure and implications of this early-stage rift magmatic system.

S01.08 Talk

Insights from 17 years of geodetic and petrological observations at Mt. Etna volcano (Italy): definition of a long-term pattern of magma transport and storage

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During the last two decades, a number of large eruptive events (e.g., 2001, 2002-03, 2004-05, 2006, 2008) as well as more than 100 paroxysmal events (from moderate to intense and impulsive explosive activity, coupled sometime to voluminous lava flows) occurred at Mt. Etna volcano. These events involved the upper sector of the northern and southern flanks of the volcano, along with the summit craters. By careful inspecting the daily displacement on selected continuous GPS stations installed on the upper part of the volcano edifice, we proposed an unprecedented and detailed resolution of different deformative episodes occurring at Mt. Etna. The surface deformation for each detected stage was used to constrain isotropic half-space elastic inversion models. In addition, a number of petrological observations on volcanic rocks (lavas and tephra), which were collected on the field during the on-going eruptive activity, provided relevant constraints on the timescales of magma storage and transfer at various levels of the volcano plumbing system. The joint interpretation of constraints coming from geodetic data and petrological observations allowed us to provide an updated model of the magma ascent history and of the complex interactions that affected various magma batches during the whole investigated period.

Explosive volcanic eruptions: can we anticipate their size and impact?

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Understanding the conditions under which large volcanic eruptions, up to caldera-forming eruptions, can develop, is clearly one major issue for both basic volcano science and volcanic hazard forecasts. The recently uncovered relative frequency of explosive volcanic eruptions at the global scale suggests the hypothesis that the magnitude of volcanic eruptions with VEI greater than 2 is controlled by exceedingly complex short-range interactions, resulting in the practical impossibility of deterministic predictions on the eruption magnitude. Accordingly, the current lack of a general reference to forecast the eruption size based on unrest dynamics may reflect an intrinsic character of explosive eruptions, rather than a defect in understanding. Here we employ a numerical modelling approach to analyze the conditions leading to eruptions with different intensity, magnitude and duration. Our approach takes into consideration a system made of a large, deep magma chamber connected through a dyke to a smaller and shallow chamber, in turn communicating with the surface through a vertical conduit. The system hosts magmas with different degrees of chemical evolution and different volatile contents. System evolution, described as a succession of steady flow phases, shows that the scale of the eruption is largely controlled by elements that have negligible relevance in determining the unrest dynamics. Large caldera collapse, related to a pressure drop in the deep magmatic system below the tensile strength of surrounding rocks, is restricted to cases with very high eruption intensity, whereas mid or low intensity cases invariably lead to eruption closure following a pressure drop at shallow levels. These results are consistent with current observations and knowledge, and concur to depict a situation where the size and impact of a next explosive eruption cannot be anticipated based on pre-eruptive observations and measurements.

Pyroxene residence time of two contrasting Plinian eruptions at Popocatèpetl volcano (Mexico)

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Popocatèpetl volcano in Mexico is one of the most active volcanoes on Earth and it also ranks very high in term of threatened population, with more than 20 million people living within 70 km from the crater. The ~14.1 ka Pumice with Andesite Plinian eruption (PwA) was the most powerful on record at Popocatèpetl. The ~23.5 ka Tochimilco Plinian eruption marked the transition from the old Ventorillo volcanic edifice to the modern Popocatèpetl cone. Plinian events are punctuated by periods of quiescence and present-day like effusive interplinian activity.

Both pumices and lavas are andesite to dacites with a mineralogical assemblage of plagioclase > pyroxene > Fe-Ti oxides ±amphibole. The pyroxene population is characterised by complex zoning and frequent disequilibrium textures testify magma mixing and hybrdisation processes between a mafic end-member, dominated by olivine + Cr-spinel
+ pyroxene ±plagioclase, and an evolved end-member characterised by plagioclase + pyroxene + Fe-Ti oxide + apatite.

Fe-Mg elemental diffusion modelling on orthopyroxene indicates pre-eruptive crystal residence time ranging from few days to hundred years. However, the Tochimilco pumice is characterised by high frequency of mafic injections < 6 months before eruption. On the contrary, pyroxenes of PwA have longer residence times (decades) with very few crystals recording shorter timescales (few years). Effusive events record injection events in the months-years before the eruption.

Two distinct triggering mechanisms can be identified for the Plinian eruptions. Pressurisation by volatile associated with melt replenishments, possible closure of the system and extensive crystal cargo remobilisation characterise the PwA explosive eruption. A direct causal link between mafic injections and eruption is evident for the Tochimilco pumice: magma injections in the days-months before the eruption possibly associated with failure of the flank of the edifice can be invoked as eruption triggering mechanism.

What controls the arrival of magma at the surface? Interplay between buoyancy and crustal stress field

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The last phase of magma transport towards the surface occurs by magma flow through induced crustal fractures. These are either referred to as dykes or sills, depending on their orientation relative to lithologic layers. This propagation phase of an intrusion starts with the failure of the magma storage zone and potentially lead to an eruption but this is not always the case. It usually occurs on a short time scale (hours to days) and generates both seismicity and surface displacements. In a perspective of hazard assessment and risk mitigation, it is essential to have rapid clues enabling to address the following key questions: will the magma make it to the surface, initiating an eruptive event? And if yes, where and when will it reach the surface? Inherited structures are often evocated to explain magma paths. Here, based on both 2D numerical approaches and 3D analogue experiments, we show that magma transport through the upper crust is mainly controlled by the relative influence of magma driving forces (buoyancy, overpressure, dyke extension) and the local stress field. We will illustrate this interplay using observations in different geological settings. At Etna and Piton de la Fournaise volcanoes, specific eruptive crisis will be examined. We will also use evidence of magma eruption or intrusion within impact craters of different radius on the Moon. We will then propose efficient strategies to forecast magma path and propagation timing.

S01.08 Talk

The link between magmatic water content and geophysically determined magma storage depth

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Magma storage depths help shape our understanding of volcanic hazards, crustal structure, and continent formation. However, controls on the depth of magma stagnation are poorly understood. Some have argued for the importance of intrinsic (e.g., buoyancy, viscosity) controls [a], while others have emphasized the importance of extrinsic (e.g., crustal structure) controls [b]. We investigate the role of magmatic water content, a key intrinsic variable that drives changes in magma physicochemical properties. We target 22 arc volcanoes worldwide, focusing on mafic-intermediate systems. Reservoir depths, mostly based on geodetic or seismic observations, are compiled from the literature. Magmatic water contents are based on the maximum water content measured in large melt inclusion suites, which include new data for the Aleutians and previously published data. Storage depths (~2-15 km depth) correlate positively with maximum melt inclusion water contents (~2-7 wt.%), and, for select volcanoes with constraints on degassing style (open vs. closed), we find a strong agreement between storage depth and the depth at which water begins to degas. There are two possible explanations for these correlations: (1) magmatic water content controls magma stalling or (2) melt inclusion water re-equilibrates at the storage depth. If (2) were the dominant control, then melt inclusion water contents would not correlate with non-volatile trace elements (e.g., Nb/Ce and Ba/La), and yet they often do for the volcanoes studied here (our work in the Aleutians, [c], [d], [e]). Such systematics support (1), where intrinsically wetter magmas degas and crystallize deeper than dry magmas, resulting in deeper storage prior to eruption, and they demonstrate the global importance of intrinsic controls on the depth of reservoir formation.

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Zircon and apatite in host andesites and mafic enclaves: unravelling mixed magmatism at Soufrière Hills Volcano, Montserrat, Caribbean

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Soufrière Hills Volcano, a stratovolcano on the Caribbean island of Montserrat, is an active geological hazard. Its only historical eruption has had five discrete phases of extrusion between 1995-2010. Recent activity includes dome growth, vulcanian explosions and destructive pyroclastic density currents. Mafic magma remnants are preserved as mingled enclaves entrained in host andesites, how these coeval magmas interacted should shed light on eruptive processes.

Here we present field, petrological, mineralogical and geochemical data to investigate the mixed intermediate-mafic samples. Newly discovered metre-scale outcrops of medium- grained mafic rocks, from deep within the volcanic edifice, crop out in dome collapse block and ash deposits of the most recent eruptive phase, 2009-2010. These apparently represent the uneruptable cumulate plutonic component of the ubiquitous smaller-scale fine-grained erupted mafic enclaves.

We will undertake characterisation of zircon and apatite in standard petrographic thin sections of the mafic enclaves and host andesites. Intial observations indicate that zircon in the andesite are generally euhedral-subhedral suggesting it formed early in the crystallisation sequence. By contrast, zircons in the mafic enclave are subhedral-anhedral this, and the absence of zircon in the most mafic enclaves, suggests that it may have crystallised late, post mixing. Apatite has high Cl cores and lower Cl rims, from their uniform euhedral shape and lack of internal growth disjunctions the grains appear to be phenocrysts, with marked diffuse gradational zonation of volatile components.

New accessory mineral data will provide information about magma storage architecture, for example the potential eruptive volume. Accessory mineral core compositions from each eruption may reflect: different, isolated, magma batches - small pockets of magma; or, successive batches of the same magma - larger reservoir(s). In this way, the relationship between pre-eruptive evolution, eruptive triggers, timing and style, and so, potential future risk of the volcanic centre will be considered.

S01.08 Poster

Determining pre-eruptive volatile behaviour at Campi Flegrei (Italy): an integrated apatite and melt inclusion approach

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Volatile elements play an important role in controlling magma storage dynamics and eruptive processes in sub-volcanic systems. Melt inclusion analysis currently represents the most common petrological method for assessing magmatic volatile contents prior to past eruptions. However, recent studies have revealed significant potential for post-entrapment modification of melt inclusion volatile contents, which casts doubt on reliability of this record. Apatite is a common accessory mineral in terrestrial volcanic systems, which can incorporate all major magmatic volatiles (i.e. H_2O, CO^2, SO^2, Cl, F) into its crystal structure. The complexity of the apatite-melt volatile relationship has previously inhibited application of apatite as a magmatic volatile 'probe' but we have developed new thermodynamic models that permit interpretation of the apatite record for assessment of pre-eruptive magmatic volatile behaviour. In this study, we apply this technique to eight eruptions of the Campi Flegrei system (Italy), integrating our results with the melt inclusion record to obtain a comprehensive understanding of processes in the sub-volcanic system.
We find that clinopyroxene- and biotite-hosted apatite inclusions and the majority of apatite microphenocrysts preserve a record of volatile-undersaturated crystallisation. A subsidiary set of apatite microphenocrysts record cooling and volatile-saturated conditions. In contrast, clinopyroxene-hosted melt inclusions record volatile-saturated conditions at low pressures. This is interpreted as evidence for a multi-level magma system. The majority of erupted magmas are sourced from a deep storage region, which remains volatile-undersaturated until shortly before eruption. However, magmas also exist within small melt pockets at shallow crustal levels, which are entrained into ascending melts on eruption. Comparing apatite and melt inclusion records shows that Campi Flegrei melt inclusions are largely reset at shallow crustal levels.

S01.08 Talk

Groundmass microlite textures of 2014-2015 eruptive products at Sinabung volcano, Indonesia

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Pyroclastic flow events due to partial collapses of lava had continued at Sinabung volcano since Jan 2014. For a period from Jan 2014 to Jun 2015, we compared the crystallization condition recorded in groundmass plagioclase textures, with actual syneruptive magma ascent condition inferred from the lava effusion rate. The samples include, 1) co-ignimbrite ash, and 2) lava fragments included in the pyroclastic flow deposit (Jan 2014) and associated deposit of secondary explosion (Apr 2015). Gray and transparent lava particles are observed in ash. The ratio of the gray type once decreased from Oct 2014 to Apr 2015, and then increased. The average size and width/ length ratio of plagioclase microlites are smaller in and after Oct 2014 than in the earlier activity, regardless of the lava particle color. In addition, plagioclase microlite content in groundmass is smaller in and after Oct 2014. These changes are also recognized in microlites of lava fragments. Nakada *et al*. (2018) reported that the magma effusion rate continuously decreased from Jan 2014 to Jun 2015. If the diameter of the conduit is constant throughout the period, the ascent rate of magma in conduit should have decreased with time. The decreased rate of ascent leads to decrease of effective supercooling imposed on melt, resulting in growth-dominant crystallization. This is not consistent with our observation in the ejecta. We propose that the temporal change of microlite texture resulted from compositional change of melt. Shea and Hammer (2013) showed experimentally that growth rate is higher in less fractionated melt. The groundmass glass of the lava at Sinabung became more evolved in the later phase of the activity, supporting the idea for the temporal change of the microlite texture.

Eruption trigger mechanisms at arc volcanoes with century-long repose periods: A melt inclusion record of the 2015 - 2016 Momotombo eruption, Nicaragua

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Volcanoes that exhibit a repose period of 100-200 years between eruptions are common in the historical record and have the potential to be highly explosive and hazardous (e.g., a 136-year repose preceded the 1982 El Chichón VEI 5 eruption). The mechanisms that contribute to the reawakening of these systems can be deciphered by examining the eruptive products that record magma evolution. The expansion and overpressurization of a magma body leading up to eruption is most affected by the saturation and subsequent exsolution of a fluid phase. The composition and abundance of this fluid phase *and* how it might change over time is crucial in tracking expansion and contraction of a magma body. In this study, we aim to reconstruct the evolution of volatiles within the magma body that led to the 2015-2016 Momotombo eruption, Nicaragua, which occurred after 110 years of repose. This VEI 2 eruption produced basaltic andesite lava flows (bulk rock ~53.8 wt.% SiO_2) and ash with andesitic glass composition (~60.4 wt.% SiO_2), containing plagioclase, orthopyroxene, clinopyroxene, Fe–Ti oxide, and scarce olivine. Complexly zoned plagioclase crystals extracted from the ash typically contain multiple bubble-free, glassy melt inclusions in a single 2D core-to-rim section. We analyze H_2O, CO_2, F, S, and Cl concentrations in paired melt inclusions (hosted in the core and rim of crystals) by secondary ion mass spectrometry and incorporate volatile concentrations in preliminary thermodynamic models, including a mixed H_2O–CO_2 fluid phase, to track how overpressure may have evolved in the Momotombo magma during heat loss and crystallization. Our approach is designed to identify the possible role of mafic recharge (without mixing), magma mixing, CO_2 flushing, or (near) closed-system evolution in driving volatile behavior and volcanic unrest at Momotombo, with potential implications for similar volcanoes with centennial eruption recurrence intervals.

S01.08 Poster

Self-feeding rejuvenation of a volcano plumbing system following major explosive eruptions: evidence from the February-April 2017 eruptive activity at Etna

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After almost 8 months of quiescence, a new sequence of low-to-mild intensity eruptions characterized the activity of Etna volcano between January and April 2017. The activity started at a vent located between the old and the new cone of the South East Crater, and was characterized by moderate Strombolian eruptions accompanied by lava flows. The weak volcanic events of 2017 constitute a breakpoint in the post-2011 eruptive behavior of Etna, which had shown the most explosive eruptions of the last two decades. All erupted rocks are K-trachybasalts with compositions similar to those of other recently erupted products. However, whole rock data reveal some chemical differences of the 2017 magmas compared to post-2011 products. Major differences have been observed with respect to products of the 2011-13 paroxysmal sequence, especially concerning some major (Fe and Ca) and trace elements (Ba, Nb, Ta). Conversely, the 2017 whole rock compositions show affinities with the 2015-16 magmas emitted at Voragine.These data, together with variations of some incompatible trace element ratios (Zr/Nb, Ba/Ta), support the idea that the 2017 products can be the result of a different evolutionary path of magmas that have fed the activity before the 2015-16 eruptions at Voragine. Magma evolution could have been driven by progressive substitution of the residing magmas by recharge with new magma. Modeling of geodetic data suggests: i) recharging phase (June 2016 - early March 2017) by fresh magma occurring at depth of ~6.3 km bsl and ii) volcano-scale deflation in late March 2017 related to depressurization of a source located at depth of ~4.6 km bsl. All these observations suggest that the deep recharging magma progressively replaced (and mixed with) the residual one from the apical region of the reservoir, therefore lending credit to a self- feeding rejuvenation mechanism of the volcano plumbing system.

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S01.10 - Characterization and analysis of eruptive patterns

Data Mining applications on Mt. Etna monitoring system

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Mt. Etna shows persistent activity needing continuous monitoring, which implies the acquisition and storage of huge amounts of data over long time spans. The task of recognizing patterns (or motifs) from available data is a crucial step in developing systems for automatic detection of volcanic unrest, especially for civil protection purposes. To face this challenge, at INGV-Osservatorio Etneo several data mining tools have been developed.

We applied a brute-force algorithm for motif discovery, the Mueen-Keogh (MK) algorithm, to investigate recurrent patterns within the RMS (Root Mean Square) of seismic amplitude time series; RMS is one of the most used parameters to monitor volcanic activity, because it contains information about temporal variations of volcanic tremor, whose behaviour is connected to volcanic activity. By implementing optimization techniques, MK algorithm enabled us to discover patterns related to different phenomena, faster than conventional methods.

Considering RMS time series behaviour a stochastic process, we also tried to model the explosive activity system, assuming it to be a Markov process, by Hidden Markov Models (HMMs). HMMs analysis seeks to recover the sequence of hidden states, related to volcanic activity, from the observed emissions generated by the SAX (Symbolic Aggregate approximation) method, which maps RMS time series values with discrete literal emissions.

Besides seismological analysis, we developed a system based on infrasonic data. By extracting the main attributes of infrasonic events, we produced a 'feature space' constituted by three main clusters recognized by means of the DBSCAN (Density Based Spatial Clustering on Application with Noise) algorithm. Hence, we were able to associate each cluster to a particular source vent and/or a kind of volcanic activity. Clusters were used to train a classification model based on SVM (Support Vector Machine), allowing automatic event location without location algorithms and by using data from a single station only.

S01.10 Poster

Conduit geometry and evolution of effusion rate during basaltic effusive events: Insights from numerical modeling

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The dynamics of effusive events is controlled by the interplay between conduit geometry and source conditions. Dyke-like geometries have been commonly employed for describing conduits during effusive eruptions, but their depth-dependent and temporal modifications are largely unknown. Here we present a novel model that describes the evolution of conduit geometry during effusive eruptions by using a quasi-steady state approach based on a 1D conduit model and appropriate criteria to model the geometric evolution of the conduit due to fluid shear stress and elastic deformation. Such approach provides time-dependent trends for effusion rate, conduit geometry, exit velocity and gas flow, among other output variables. Fluid shear stress leads to upward widening conduits, whereas elastic deformation becomes relevant only during final phases of the eruptions. Since the model is able to reproduce different trends of effusion rate, it was employed for addressing the effects of magma source conditions and conduit properties on the main characteristics of the resulting effusive eruptions (e.g. duration, erupted mass, maximum effusion rate). We show that the total erupted mass is mainly controlled by magma reservoir dimensions and their conditions before the eruption (i.e., initial overpressure), whereas conduit processes and geometry are able to affect the magma withdrawal rate and thus the eruption duration and effusion rate. The resulting effusion rate trends were classified in different types, and associated to the curves described in the literature for different volcanic events. Results well reproduce these trends and provide new insights for interpreting them, highlighting the importance of reservoir overpressure and the initial dimensions of the feeding dyke on the resulting effusion rate curve.

S01.10 Talk

Multiple causes of dome collapse during the prolonged effusive eruption of Sinabung Volcano, Indonesia

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The collapse of unstable lava dome and flow structures, generating block-and-ash style pyroclastic flows, is the most dangerous hazard posed by the effusive eruption of more- viscous, higher-silica lavas. The size and frequency of these collapses can be difficult to predict, leading to difficult hazard assessments. This is especially problematic during prolonged eruptions, when residents may want to return home during periods of seemingly regular or low activity. This difficulty arises because the development of instabilities in erupted lava can be driven by multiple processes, such as changes in effusion rate, changes in flow advance rate, gas pressurization, hydrothermal alteration, and variations in underlying topography. Hazard assessment can thus be improved by better understanding the leading causes and characterization of observable precursors to collapse.

Utilizing multiple photogrammetry surveys and satellite remote sensing, we investigate the evolving morphology of erupted lava during the prolonged effusive eruption (2013-current) of Sinabung Volcano, Indonesia. We show that collapses during this eruption are caused by both surficial and sub-surface processes. During the initial phases of the effusive eruption (December 2013 – March 2014), high effusion and flow advance rates led to frequent collapses of variable size. After a period of relatively minor and infrequent collapse activity (April – September 2014), large collapse events in October 2014 and June 2015 were triggered by instabilities related to lava overtopping confining topography. Since the summer of 2015, vertical explosions have become common and are often associated with pyroclastic flows. This variation in activity suggests a change in shallow conduit processes that now allow gas pressure to build within the dome. While less frequent, pyroclastic flows associated with explosions can have lengths similar to the largest events from early 2014. Sinabung may appear less active in its current phase, but the extent of the hazard it poses remains high.

Insights into eruptive patterns using a coupled conduit-magma chamber model

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Eruptive cycles can have complex patterns in terms of the number and timing of individual eruptive episodes, the ratio of emitted lava versus pyroclastic material, and waxing – waning trends of the entire cycle. An eruption can start with the main eruptive episode shortly after the first signs of unrest, followed by a long waning phase and a shifting to an effusive phase. For example, Chaitén 2008-2009 and Cordón Caulle 2011-2012 eruptions in Southern Chile, started with 1 – 2 weeks of explosive activity followed by ~ 1 year of lava effusion. The lava/pyroclast ratio was roughly 1 in both cases. Other eruptions can start with a series of explosive and/or effusive events before the paroxysmal episode (e.g. Pinatubo, 1991). Other patterns include a series of sub-plinian events without a main event (Mount Spurr, 1992; Calbuco 2015) or long-lasted eruptions with alternated effusive/explosive activity (Unzen 1991-1995; Soufriere Hills, 1995-2010).

Here, a coupled magma chamber – conduit model is proposed to explain some of the patterns indicated before. The ascent of magma is modeled as a standard 1-D, homogeneous flow with gas loss due to permeability of the liquid – bubble mixture. Overpressure inside the magma chamber can be generated by injections of additional magma or vesiculation of volatile phases. Vesiculation was modeled by considering the time-dependent growth of bubbles and this disequilibrium process can cause complex behavior of the eruptive sequence. A parametrical analysis shows that the initial overpressure, volatile content, depth and size of the magma chamber are the main controls on the ratio of extruded lava versus pyroclastic material.

This work highlights the need of a conceptual framework to interpret the initial patterns of an eruptive crisis, predict the future behavior of the cycle and make a better hazard assessment. Supported by FONDAP Project 15090013.

Eruption cyclicity of at La Soufrière, St Vincent over the past 5000 years – defining cycles and constraining activity

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La Soufrière Volcano on the island of St Vincent, West Indies, has experienced four historical explosive eruptions of varying magnitude occurring in 1718, 1812, 1902 and 1979, which define a crude 80-100 year periodicity to the explosive activity. Recent fieldwork and extensive radiocarbon dating have established the stratigraphy of these historic as well as of two recent prehistoric events (that occurred in ~1440 and 1580 AD), showing that basaltic andesite scoria-rich pyroclastic density currents (PDCs) were typical in the last 600 years. Our radiocarbon dating shows that a similar broad periodicity of 80-140 years for explosive eruptions over the last 600 years, although there may have been a general decrease in magnitude and vigor of the more recent eruptions.

Products on the eastern flank represent two or three notable eruptions of scoria–rich PDC and radiocarbon dating indicate that these relate to two clusters of dates, one around ~2500 and another at ~4500 yr BP. These dates suggest that the broad cyclicity of the period between 1000 and 5000 yr BP was characterized by larger, less frequent, eruptions with relatively minor or no activity between these larger events. The spatial distribution of the products indicates that PDCs in the last 600 years were significantly controlled by the pre-existing crater topography, whereas the older events (2000-5000 yr BP) were not. This suggests that the eruptions between 2000 and 5000 were significantly larger and more vigorous than those in the last 1000 years. It is possible that the size and time scale of these different events results in a bias, with smaller events being missed or the time period studied is too short to completely capture longer-term cycles. Further geochronology will refine the nature of eruptive cyclicity.

Multiple chamber control on the evolution of sustained volcanic eruptions

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Explosive eruptions are the final result of the complex interplay between the dynamics occurring in different subdomains of a volcanic system, and comprising interconnected deeper and shallower magmatic reservoirs usually hosting magmas with different degree of chemical evolution, different volatile contents, and different properties. Satellite-radar observations, as well as stratigraphic reconstructions, show that in many cases the sustained eruption column phases are characterized by a short waxing phase (increase in column height) followed by a longer waning phase (decrease of column height). We simulate numerically the evolution of the eruption dynamics as a sequence of steady discharge phases in a domain constituted by two magma chambers connected through a dyke, and to the atmosphere by a volcanic conduit, by ensuring consistency between the steady flow assumption and the computed dynamics. The deep, larger system hosts less chemically evolved, volatile-rich magma, and we have considered two different conditions characterized by deep andesite and shallow dacite, or deep shoshonite and shallow phonolite. Our results show that in most cases a short (tens of minutes to one hour) phase of rapidly increasing eruption intensity (waxing phase) is followed by a longer (up to several hours) phase of slower eruption intensity decrease (waning phase). Such an evolutionary trend, which explains well the observations, is mostly controlled by the interplay between pressure evolution in the different magmatic domains, and balance between discharge into the atmosphere and recharge from a deeper magmatic reservoir.

Do compositional magmatic patterns match with the eruptive activity of the South- East Crater (Mt Etna) from 2011 to 2017?

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The petrological monitoring carried out in the last decades at Mt Etna has been aimed to regularly collect and analyze the volcanic products emitted during the main flank and summit eruptions. The compositions of rocks, glasses and minerals vary over the time and define regular or scatter patterns associated to a single eruption or multiple eruptive episodes that are characterized by different eruptive styles. Indeed, a wide spectrum of phenomena may occur, variable from explosions of different energy (Strombolian activity and lava fountains) to lava flows effusion. To investigate a possible correlation between compositional magmatic patterns and the characteristics of eruptive activity, we studied the activity of one of the summit craters of Mt Etna, i.e. the South-East Crater, from 2011 to 2017. In that period, 44 powerful paroxysms (2011-2013) were followed by discontinuous Strombolian activity and lava effusions up to 2017. The magmatic compositional patterns of the erupted products have been modeled to get insights into the pre-eruptive magmatic processes (i.e. magma mixing and fractional crystallization) responsible of magma differentiation. The integration of compositional magmatic patterns with geochemical and geophysical ones, available for the same time lapse (2011-2017), allowed to investigate the correlation between magmatic dynamics inside the volcano plumbing system and eruptive phenomena at the surface. Overall, the dynamics of the magma-gas mixture seems to influence the style of the eruptive activity. The integrated study of multidisciplinary patterns acquired during monitoring activity at Mt Etna is important to decipher possible evolution of eruptive dynamics of an ongoing eruption, contributing to assess the associated hazard.

Relation between alternating open/closed-conduit conditions and deformation patterns: an example from the Somma-Vesuvius volcano (southern Italy)

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We present the results of a meso-scale systematic structural analysis of fractures, faults and dykes exposed at the Somma-Vesuvius volcano (southern Italy). Observed fractures include: (i) radial and tangential (with respect the caldera axis), sub-metric to metric joints associated with the edifice load and volcano-tectonic activity (i.e. inflation, deflation and caldera collapse stages) and (ii) decameter-scale fractures related to volcano flank instabilities. For the Somma-Vesuvius volcano, preexisting radial joints were commonly reactivated as transfer faults during the caldera formation, allowing different blocks to move toward the center of the collapsing area. Dykes occur with different geometries, including en-echelon structures bounding structural depressions. The orientation analysis of all structures indicates that they are preferentially oriented. Furthermore, we provide a morphological lineament analysis using high-resolution Digital Terrain Models of Somma-Vesuvius. Azimuth and spatial distribution of dykes and morphological lineaments were analyzed for comparison with the old Somma Crater and Gran Cono axes, respectively. Results highlight the overprinting of radial and clustered strain patterns recorded in different volcano tectonic evolution stages. We suggest a possible deformation evolution model in which structures develop along either radial or preferential trends, highlighting different volcanic conditions: (i) where radial patterns occur, the structures developed during volcanic inflation cycles with a closed magmatic conduit condition whereas (ii) clustered patterns are probably associated with a regional strain field that overcomes the local deformation field, a situation typical in the case of open conduit activity.

Patterns of the ongoing lava dome eruption at Popocatépetl volcano, central Mexico: its consequences on the long- term assessment of volcanic hazard

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Popocatépetl volcano (central Mexico) is located in one of the most densely populated regions of the world. Its eruptive history ranges from low-intensity effusive episodes to major Plinian phases, the last one occurring around 1200 yBP. Since then, the activity of Popocatépetl has been characterized by moderate, mostly effusive eruptions. In the last 500 years, fifteen episodes of moderate activity can be identified. The current one, beginning in 1994, is a lava dome eruption that has emplaced, and subsequently destroyed, at least 40 distinct andesitic-dacitic lava domes. The whole episode has been accompanied by an outsized and persistent passive degassing. The analysis of this lava dome succession sheds some light on the underlying physical process controlling the eruption. The most critical parameters controlling the self-regulating process are the volatile content of magma, the geometry and dimensions of the main volcano conduit and the magma rate of ascent. A first result of the analysis is that the maximum volumes of the emplaced domes are exponentially distributed with a mean value around one million cubic metres, and a mean extrusion rate around 8 m3/s. Such distribution is interpreted in terms of a self-regulating process of equilibrium between the buoyancy force, driven by the volatiles concentration in the magma, and the capacity of the conduit system to release them, a condition that sets limits to the volume of the emplaced domes. Domes exceeding about 3.2 million cubic meters, or exceeding an extrusion rate of about 24 m3/s only have a 5% probability of occurring, and domes exceeding about 6 million cubic meters may indicate a disruption of the self- regulating character of the process. This is particularly relevant considering that about 20% of the major explosive eruptions worldwide have occurred during andesitic or dacitic lava dome eruptions (Ogburn et al., 2015).

S01.10 Talk

What tremor spectrum tells about eruptive sites: the 2015-2017 eruptions cycles at Piton de la Fournaise

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Effusion rate is one of the key parameters of volcanic activity. Piton de la Fournaise, with a mean of 1.7 eruptions per year since 1950 and an extended seismic monitoring network, is an optimal laboratory for researching new effusion rate measurement methods. Currently, at Piton de la Fournaise, they are estimated from gas or thermal proxies, which are influenced or blinded by bad weather conditions. Quantifying activity from tremor alone would enable to overcome this problem. However, tremor recording can also be influenced by eruption dynamics, gaz discharge and local eruptive site effects. In order to constrain how the effects related to eruptive site morphology affect the tremor, our team systematically followed up eruptions by photogrammetry and imagery. We compared 1/ the normalised cross spectral density of horizontal and vertical components of tremor at nearby seismic stations during recent eruptions (2015-2017) with 2/ photogrammetric reconstitutions of the eruptive cone structure and 3/ effusion rates estimated from SO2 fluxes and differential DEMs. We showed that the eruptive cone height, morphology and stability influence significantly the tremor source and can lead to overestimate effusion rates. When the eruptive cone tends to close, this manifests in a preponderance of co- frequencies around or lower than 2Hz. Preponderance of co-frequencies around 3-5 Hz indicates an open eruptive cone, and tremor intensity in this last case has a more direct relation to outflow rate alone. The investigation of this type of law between tremor, eruptive characteristics and effusion rates could improve measurement of key parameters in further research on other volcanoes.

S01.10 Talk

Coupled eruptions in a monogenetic basaltic volcanic field: are we underestimating the risk?

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Monogenetic basaltic volcanic fields are common across the globe and are of particular interest where they occur close to or coincident with cities, such as at Auckland, New Zealand. The term ‘monogenetic’ implies that the volcanic centres in the fields are active only once, and that the eruptions are discrete in both space and time, unlike ‘polygenetic’ where multiple eruptions occur from the same centre. However, many global studies investigating these volcanic fields have highlighted this understanding as too simplistic. For example, mixtures of polygenetic and monogenetic centres have been observed in single fields and flare-ups in activity are identified in many fields globally. Current hazard and risk models do not account for this complexity, and thus may be underestimating the threat posed by this type of volcanism.

Here we present evidence and detail of coupled eruptions identified in the Auckland Volcanic Field, New Zealand. Coupled eruptions are here defined as two centres within a field that vented closely together in both space (<1 km) and time (<1 ka). In the Auckland Volcanic Field, approximately 20 of the 53 documented centres show this dual venting. We present a detailed characterisation of these eruption couplets, and discuss their physical characteristics, temporal constraints, and geochemical compositions. We use geochemical data to highlight the relationships between these coupled centres, their mantle source(s), and magma ascent characteristics, showing a complex interplay between 1) mixing of heterogeneous sources, 2) fractional crystallisation and assimilation processes during ascent, and 3) relationships between edifice size and geochemical signatures. These characteristics allow us to comment on the eruptive patterns of the couplets, their frequency, and relationship with their sources.

Use of high-speed cameras to delineate contrasting but coeval styles of activity during fissure eruptions in 2011 and 2018 at Kilauea, Hawaii

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Observations using high-resolution video cameras of contrasting patterns of activity along the 2011 Kamoamoa and 2018 ‘Leilani Gardens’ fissures at Kīlauea help to delineate the boundaries between Strombolian explosions and Hawaiian fountaining eruptions. That demarcation has generally been articulated in terms of transient versus sustained activity, in turn, linked to mechanical decoupling versus partial coupling of exsolved volatiles.

In particular, the spectrum of activity included both (A) low unsteady fountains, and (B) rapid sequences of discrete bubble bursts plus spattering that fill much of the area between these extremes. The Kamoamoa eruption showed both contrasting eruption styles (A and B) simultaneously from adjacent fissure segments and, at the eastern and western extremities of the fissure, temporal shifts from activity resembling ‘rapid’ Strombolian explosions at Etna (style B) to sustained but low and unsteady Hawaiian fountaining (style A). The Leilani Gardens eruption, to-date, has shown similar contrasts from adjacent vents on single, short fissure segments, and also comparable temporal shifts.

Analysis of particle velocimetry and grain size from videos of the activity shows that both styles reflect the ascent of meter-wide large bubbles bursting through the magma free- surface and the contrast in styles is a function of the frequency and size of this large mechanically decoupled bubble population.

Stratigraphical and sedimentological study of the plinian tephra-fall deposit of the CE 1600 Huaynaputina eruption

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Huaynaputina volcano in southern Peru produced a large eruption (VEI 6) in CE 1600. Since 2016 the 'HUAYRURO' research project pursues three objectives: 1) tephrostratigraphy and physical characteristics of the Plinian fallout, 2) palaeoclimatic consequences and 3) catastrophic impacts on villages within a 20 km distance from the volcano. The erupted deposits encompass five tephra and PDC units, but we focuss on the stratigraphical, sedimentological and physical characteristics of the voluminous Plinian tephra-fall deposit.

The pumice-fall deposit shows three to six layers. A thin, inversely graded lapilli layer forms a sharp contact above the pre-existing soil. The crudely stratified pumice increase in size together with cm-sized lithics in the second and third layers, but decrease in size while lithics become scarce in the fourth layer. The fifth layer contains coarse ash with free crystals and scarce lithics. In proximal sections the uppermost, thinnest layer presents coarse pumice and small lithics. Oxidized lithics are scattered in all but the fifth and sixth layers. The grain-size distribution of 123 samples and the componentry of 101 samples was analysed in proximal, medial and distal areas.

Using pre-existing and new thickness measurements from 647 sections, we drew a revised isopach map and two isopleth maps. The 1cm-isopach map covers an area of 128,072 km^2 showing a dispersal axis oriented SW in the proximal zone < 32 km, W in medial areas between 32 and 78 km, and NW in distal areas >78 km. Using methods based on the exponential decrease of the deposit with respect to the distance of source, we calculated a volume of 8.60 - 9.93 km^3, i.e. increasing the previously published volume by 10 to 25%. Using Carey and Sparks' method, we estimated the total height of the column at 35$\pm$2 km, a value similar to the pre-existing estimates.

S01.10 Poster

Multidisciplinary Investigations of Phreatic Explosions at Telica Volcano, Nicaragua

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Telica is a basaltic-andesite stratovolcano located in the Maribios Range of the Central American volcanic arc in western Nicaragua. Historical eruptive activity of Telica has been characterized by low-explosivity (VEI 1-3) phreatic eruptions every few years. On decadal time scales, more explosive (VEI 2-3) eruptive episodes lasting several months occur. The oldest historically documented eruption was in 1527 (VEI 3), and the only historically documented lava flow, and magmatic eruption, was in 1529 (VEI 4). Telica is considered persistently active with high but variable rates of seismicity (<5 Hz <5 to >1200 events/d), high temperature fumaroles (>300ºC), and consistent flux of gasses (>250 T/d SO_2 & >800 T/d CO_2). We have been investigating Telica's persistent activity and phreatic explosions since 2009, when we installed the Telica Seismic and Deformation network and initiated collaborations with the Instituto Nicaraguense de Estudios Territoriales (INETER), the NOVAC gas monitoring project, and other regional colleagues and institutes. Here we report on temporal changes in seismicity, deformation, temperature, SO_2 emission, and visual observations in relation to the 2011 and 2015 eruption sequences, as well as geochemical analysis of the eruptive products. We interpret these data to define the style, explosivity and driving mechanisms of the eruptive episodes and improve our understanding of the processes leading to explosive activity at persistently restless volcanoes. Based on our observations, we have developed a conceptual model for the triggering mechanism for recent phreatic explosions, whereby sealing of the shallow (<2 km depth) hydrothermal system leads to phreatic explosions and re-opening of hydrothermal fluid pathways. These explosions pose direct hazards to the agricultural communities living and working the flanks of Telica, two major cities impacted by tephra dispersal and the ever-growing tourist market.

Long-term eruptive trends from space- based thermal and SO_2 emissions: a comparative analysis of Stromboli, Batu Tara and Tinakula volcanoes

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Batu Tara (Indonesia) and Tinakula (Solomon Island) are two poorly know volcanoes with morphologies and short-term eruptive activity very similar to Stromboli (Italy). However, information on their long-term eruptive behaviours is limited, making the parallelism with Stromboli volcano purely descriptive or based on short observations. Here, we use over a decade of satellite data to measure and compare the radiant flux (2000-2017) and the SO_2 emissions (2004-2017) of all the three volcanoes. The combined analysis of Volcanic Radiant Power (from MODIS data) and SO_2 burden (from OMI data) reveals different long-term eruptive trends and contrasting ratio of gas vs. thermal emissions. These data indicate that the eruptive mechanisms operating at each volcano are quite different. The persistent open- vent activity of Stromboli volcano is episodically interrupted by flank eruptions that drain degassed magma stored in the shallow portion of the central conduit. The long-lasting exponential decay of both thermal and gas emissions observed at Batu Tara is consistent with the eruption of undegassed magma from a deep, closed magma chamber. Finally, the Tinakula displays multiple yearly-long eruptive phases, characterised by evolving gas vs. thermal ratio and eruptive intensity increasing with time. Simple magma budget calculations for this volcano are consistent with the eruption from a volatile-zoned magma chamber, coupled with periods of gas/magma accumulations at depth. Our results suggest that the combined analysis of satellite thermal/gas data is a useful tool for decrypting the long-term volcanic dynamic that could remain hidden on a shorter time-scale.

Disaster Risk Reduction in the South Andes: Lanin-Villarrica volcanic region (Chile -GSNL)

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Within the Group of Earth Observations (GEO), Geohazard National Supersite (GSNL) of the South Andes area with the main volcanoes Lanin and Villarrica have been selected by the Committee of Earth Observations (CEOS), thanks also to INGV. In the GSNL South Andes region and locations nearby, there are several cities such as Pucon, Villarrica, and others, with a thriving touristic and agricultural economy and with many people who have learned to live with the risk of volcanic eruptions, lahars and earthquakes. The region has become a target for studies on disaster risk reduction according to the SENDAI framework.

The efforts that we describe here is happening to both at local level, with people at each municipality, academic (with the involvement of Universidad Tecnica Federico Santa Maria and other universities in the district of Araucania, Chile), and through institutions such as SERNAGEOMIN (http://www.sernageomin.cl/volcan-villarrica/). The effort is happening at local, national and international level with the presence of NASA as observation, and the International Charter (managed for disasters by ONEMI in Chile), Sat-Drones and other entities. Often, the experts are involved at personal level for the advancement of research purposes.

We present the assessment of what the needs to be done and what it is already done at local, then at national and international levels. We carried out flights of drones that we plan to connect with the satellites data in the region of GSNL. Preliminary results will be shown and discussed. Such the need for every municipalities under the volcanic risks to have specialized person who is trained for local emergencies. Furthermore, we are trying to reconcile the four level of hazards with the three level of hazards from the aerial industry in Chile, as well as other issues related to improve resilience to disasters at local and national levels.

S01.10 Poster

Understanding eruptive style changes at Fuego de Colima volcano (Mexico) by coupling numerical models and volcanological data

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The Fuego de Colima volcano (Mexico) shows a complex eruptive behaviour with periods of dome growth punctuated by mid- to high-intensity explosive eruptions. We investigated through physic-based numerical models two eruptive periods, as excellent examples of eruptive style transitions: the 1998-2015 activity and 1913 sub-Plinian eruption. The numerical simulations are constrained by subsurface data and independently inferred volcanological information (mass discharge rates, erupted volumes). Two types of geometries are inferred for the conduit feeding system, with the reservoir located within elastic rocks at 6 km depth or a conduit fed by two interconnected magma chambes located at 6 and 15 km depth. We demonstrated that the cyclic behaviour of dome growth during 1998-2015 eruptive cycle depends on the intensity of influx rate, volumes of the magma chambers and their degree of connectivity. The single magma chamber model provides a good match with the observed mid-term periodicity (weeks) of dome extrusion, while the dual magma chambers model better describes the long-term periodicity (years). Concerning the transition from extrusive to explosive activity that led to the 1913 sub-Plinian eruption, we found two main mechanisms may be claimed: i) an increase in magma chamber overpressure (magmatic trigger) or ii) a decrease of lithostatic stress acting on the volcano (non-magmatic trigger). The former implies arrival into the chamber of a magma batch, whereas the latter requires decompression-induced emptying of the magma column within the conduit-feeding system. A sudden jerk in lateral spreading is considered to be a reliable mechanism for unloading the upper conduit and driving fragmentation processes over a few hours. Although results are still not conclusive between a magmatic or non-magmatic trigger of observed eruptive style transitions, they highlight the control of the different investigated processes on close-to-equilibrium volcanic systems, opening new perspectives for comprehension about eruptive dynamics of calc-alkaline volcanoes.

Using a process-based model of pre- eruption seismicity patterns to forecast eruptions at dormant stratovolcanoes

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Long-term monitoring data and detailed eruptive histories are the most useful ways to forecast the size, timing and style of volcanic eruptions, yet such data are rarely available for many volcanoes. In these cases, many volcano observatories and the USAID-USGS Volcano Disaster Assistance Program (VDAP) have utilized extensive collective experience with geologic, geochemical, geodetic and seismic data over multiple eruption cycles and across volcano types world-wide to successfully forecast eruption size, style and onsets, as well changes in eruptive style and vigor within ongoing eruptions. From observations of seismic signals prior to and during more than 60 eruptions at more than 45 volcanoes, we have developed a 4-stage process-based conceptual model based on Fournier's (2007) geologic model and Hill's (1977) fault-fracture mesh model that, when applied to the seismic data both prior to, and during volcanic eruptions, enables volcano seismologists to forecast eruptive style, size, and timing, especially for stratovolcanoes that have been dormant more than 20 years. We will describe each of these four stages of seismicity (deep, distal, vent-clearing, and repetitive) using examples from 38 eruptions at 25 well-monitored volcanoes. The application of this 4-stage model to the evolving seismicity and eruptions at Sinabung (Indonesia) from 2013 through 2014, demonstrates how forecasts in eruption size and style may be based in part on the changes in seismicity.

S01.10 Poster

Temporal evolution and characterization of the June 2017 eruption of El Reventador volcano

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El Reventador volcano, 100 km East of Quito, Ecuador, experienced a rapid onset VEI 4 eruption in November 2002. The last 15 years of intermittent periods of explosive and effusive activity continues to the present. Since 2012 there has been a different pattern in the type of events registered, specifically with an increase in processes associated with fluid movement. On June 22th 2017, El Reventador started a new eruptive phase, generating pyroclastic density currents (PDC´s) and significant lava flow emissions resulting in the largest deposits since 2008. We propose a correlation between seismic signals and superficial observations to determine a spatiotemporal characterization of the explosive and effusive phases generated during this eruptive episode. We use the number of seismic events per hour, and the strong correlation between the event recurrence and spectral characteristics compared with visual observations for the period June 22th to 27th and finally, with deposit measurements during fieldwork in August 2017. For the explosive phase, we mapped PDC´s deposit area and estimated a volume of 1.6±0.4Mm^3. Through the seismic signals we determine the duration of the main eruptive pulse (10 mins) and used these parameters to model the PDC run out and deposits using VOLCFLOW. Our preliminary results show a good correlation with the actual deposits and lead to a runout distance of ~3.5 km using a 10 m resolution DEM. The model consider similar rheological parameters as those assumed for Tungurahua volcano 2006 PDC´s. For the effusive phase, the emission rate was obtained from lava flow´s area produced during 12 and 24 hours on June 25 and June 26-27 respectively. The range obtained is between 8.1 to 9.8 m^3/s. The knowledge obtained from the different monitoring parameters and their changes dramatically in a very short period of time will help us to improve volcanic hazard assessment.

S01.10 Talk

Ground deformations associated with recent phreatic eruptions in Japan

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Phreatic or phreato-magmatic eruptions recently occurred at several active volcanoes in Japan. These are, for example, phreatic and/or phreato-magmatic eruptions at Shinmoedake, Kuchinoerabujima, Ontake and Kusatsu-Shirane volcanoes. JMA and NIED have deployed seismic and tilt stations around active volcanoes in Japan. Most of these stations are located within a few kilometers distance from the active craters, and ground inflations and deflations are observed before and after eruptions. The present study examines the basic characteristics of these ground deformations to understand the mechanism of phreatic eruptions. The seismic records show that volcanic tremors started a few to tens of minutes before the phreatic eruptions. Almost simultaneously, significant uplift tilts toward the active craters are observed at Ontake, Shinmoedake, and Kusatsu- Shirane volcanoes. The uplifts show accelerated or rapid temporal changes during the tremor activities. Such uplift tilts are not well recognized at JMA station in Kuchinoerabujima, but a Kyoto University's tilt station installed very close to the active cater captured accelerated inflation signal. These results indicate that a few to tens of minutes are necessary for volcanic fluid underground to prepare to generate phreatic eruptions and additional pressure is rapidly built up in shallow volcanic structure. During the eruptions, all the tilt meters captured deflation signals associated with de- pressurizations due to volcanic material withdrawals from underground to atmosphere. The tilt signal amplitudes exponentially decay, which can be explained as a relaxation process of pressurized fluid thorough a conduit. These characteristics are also observed at the magmatic eruptions, suggesting similarity between phreatic and magma eruptions in the viewpoint of mechanics. However, phreatic eruptions must be driven mainly by hot waters underground, hence further analyses and observations are necessary to understand the mechanism of phreatic eruptions and to clarify the difference from magmatic eruptions.

A study on the type of the Qixiangzhan eruption of Changbaishan Tianchi Volcano, China/DPRK

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Changbaishan Tianchi volcano is one of most dangerous active volcanoes in China. Qixiangzhan eruption is one of three eruption events of Tianchi volcano since the Late Pleistocene, and located on the north slop of the Tianchi cone as a snake-like lava flow. It has raised a considerable debate about the type of eruption. Some scholars consider it is the effusive eruption, but others think it is clasticgenic lava flow, but also some scholars suggest it is the small-scale explosive eruption. After the meticulous field geological survey and the geochemical analysis, Qixiangzhan eruption is considered to a set of typical froth (foam) lava, which is a rare and intensively effusive eruption. The main reasons are (1) the magma of Qixiangzhan is characterized by the alkaline rhyolite, which has experienced advanced differentiation and evolution and is with the high potential of foam due to rich in the volatiles. (2) A large number of thin-plate-like layers observed in field are the sedimentation of foam lava after the scatter of volatiles. (3) The structure of rock is loose and the particle support with a large number of irregular pore. It is also show the deposition process like the sand sedimentation in flood. (4) The snake-like morphology demonstrates the strong fluid ability, and only can be explained by the foam flow for rhyolite magma. According to above evidences, we determined the eruption type as foam lava, and reconstruct the eruption process. This provides a reference for understanding and predicting the small-scale eruption of Tianchi volcano, and also compensates the overall eruption history of Tianchi volcano.

S01.10 Poster

Classification of Volcanic Events for Hazard and Risk Assessment

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Volcanic activity brings about magmatic products to surface from the earth mantle and crust. These products interact with earth environmental components; soil, water, air, ecosystems, and sociocultural ones, yielding economic and human live losses. The impact impinged by volcanic events is function of their intensities which in turn are related to spatiotemporal changes in factors such as temperature, velocity, thickness, volume, grain size and so on. To assess the potential impact of volcanic activity it is necessary to get an appropriate characterization of its events and their products expected to show on the earth surface. For risk assessment and mitigation here it is proposed a classification of volcanic events grouping them from their sources; related to magma movement, emerging at an eruptive center, coming from the eruptive column, from the volcanic edifice, happening in volcanic calderas, from a dome, and other volcanic sources.

To accomplish a technical characterization and following the premises stated above we can define, based on their intrinsic characteristics and rheological properties, as volcanic events related to magma movement: tremors, surface deformation, mass movements, gases, water vapor column; from a volcanic center: eruptive column, shockwaves, ballistic pyroclasts, lava flows; from the eruptive column: electric storms, diluted pyroclastic density currents, concentrated pyroclastic density currents, hot air masses, pumice and ash flows, co- ignimbrite breccia, lithic breccia, ash cloud, tephra fall, acid rainfall, hot rainfall; coming from the volcanic edifice: stream flow, hyper-concentrated flows, debris dispersive flows, mud cohesive flows, volcanogenic floods, volcanic landslides, lateral blasts, debris avalanches; from a volcanic calderas: volcanic edifice collapse, boiling over column, ballistic pyroclasts, collapse breccia, Ignimbrites, resurgences, dome settlements: from a volcanic dome: direct blast, base surge, tephra fall, block and ash flows, la breccia, co-ignimbrite ash cloud; and, from other volcanic sources: pillow lavas, tube lavas, smokes, thermal waters, and volcanogenic tsunamis.

S01.10 Poster

The 2017 Fernandina volcano eruption, Galápagos-Ecuador

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A new eruptive period began on September/4/2017 in Fernandina volcano, which is located at the western end of the Galápagos Archipelago. Fernandina is a very active basaltic volcano, with at least 25 reported historical eruptions (1813 – 2009). Between March/2015 and September/2017 in radar satellite interferograms an inflation of ~17 cm was observed in the volcano caldera, possibly associated with the ascent of new magma. The seismic activity of September 4, recorded by the seismic network of the Ecuadorian Geophysical Institute (IGEPN), began around 11:34 UTC, with Hybrid type earthquakes, followed by Long Period earthquakes. The start of the eruption is associated with a volcanic seismic Tremor that started at 18:25 UTC, minutes later a column of gas with a low ash content, ~2.5 km high over the caldera rim, was observed moving in a westerly direction. During an overflight on September 5, personnel of the Galapagos National Park confirmed that the eruption initiated along a circumferential fissure S-SW of the caldera, and from where lava flows were emitted and descended along the S and SW flanks, extending up to 4.3 km, without reaching the seashore. According to the seismic and satellite data, the intensity of the eruption decreased significantly shortly after its beginning on September 4, but until the night of September 5, active lava flows could be observed towards the middle slope of those flanks. The satellite images show that the lava flows covered a total area of 6.44 km^2, so it can be said that this was a short duration eruption with low volume of lava extrusion. A particular feature of this eruption is that the descending lava flows initiated important forest fires, which by the action of the winds were displaced towards the west, and finally covered a total area of 16.2 km^2.

S01.10 Talk

Eruptive activity of Klyuchevskoy volcano (Kamchatka), detected by MIROVA hot- spot detection system. From thermal monitoring to eruptive trend.

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MIROVA (Middle InfraRed Observation of Volcanic Activity) is a volcano hotspot detection system based on the analysis of IR images acquired by the MODIS sensor (Moderate Resolution Imaging Spectroradiometer). The system is able to provide thermal maps (1 km resolution) and Volcanic Radiative Power (VRP, in Watt) time series in near real time (1-4 hours from satellite overpass). In this contribution we present the thermal data acquired over Klyuchevskoy, the highest (4835 m) and one of the most active basaltic-stratovolcanoes of the Kamchatka peninsula. Between 2003 and 2017 more than 4500 thermal alerts were detected by MIROVA and allowed us to study thermal output of Klyuchevskoy during eight different eruptive events. By visually inspecting all the images we were able to discard the data acquired in poorly conditions (i.e. high zenith angle, presence of clouds/volcanic plumes, etc…) and to reconstruct a supervised dataset that accurately reproduce the thermal patterns of each eruption. Hence, the magnitude, intensity and thermal trends are correlated with the reported volcanic activity and with the aviation color code, based on KVERT daily bulletins. The results reveal similarities among the studied eruptions and suggest that the eruptive dynamic of Klyuchevskoy is not consistent with a model of elastic eruptions tapping of a pressurized magma chamber.

Causes of episodic volcanism by magma reservoir dynamics

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We lack a general theory of episodic volcanism. However, recent advances in understanding formation of magma reservoirs and their dynamics provides a basis for a more general theory. The emerging concept of a magma reservoir is one in which regions containing melt extend from the source of magma generation to the surface. The reservoir may contain regions of very low fraction intergranular melt, partially molten rock (mush) and melt lenses (or chambers) containing high melt fractions, as well as exsolved magmatic fluids. The various parts of the system may be separated or connected and continuous. Magma reservoirs and their wall rocks span a vast array of rheological properties, covering 25 orders of magnitude from high viscosity, sub-solidus crustal rocks to magmatic fluids, leading to a very large range of timescales that characterise volcanic systems. Timescales of processes within magma reservoirs range from very slow to very fast. Examples of slow processes include melt and fluid segregation within mush and magma chambers, heat loss to surrounding crust and geothermal systems, and deformation of surrounding host rocks. In contrast fast processes include very rapid development of magma and fluid instabilities, transport and eruption. The fast and slow processes are coupled by highly non-linear dynamics and they provide the basis for a theoretical framework for episodic volcanism due to internal magmatic system dynamics. The emerging concepts for magma chambers suggest some new mechanisms related to magma transport within vertically extensive mush systems. Buoyant instabilities caused by deep magma influx and melt or fluid segregation within a mush can lead to rapid transport, cascading effects as separate melt or fluid rich layers merge and rapid formation of eruptible magma bodies. In contrast to models of recharged magma chambers, pressure changes are only caused by volatile exsolution and expansion due to decompression.

S01.10 Talk

Imaging the 2013 explosive crater excavation and new dome formation at Colima Volcano with TerraSAR-X, time- lapse cameras and modelling

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At dome building volcanoes, eruption patterns change from explosive crater excavation to effusive dome growth. A common problem is the lack of observational data, due to hazardous field access and limited resolution of satellite remote sensing techniques. This paper describes the destructive-constructive crater activity at Colima volcano, Mexico, as occurred from January to March 2013. The crater geometry and early dome formation was observed by combination of high resolution TerraSAR-X spotmode satellite radar images and permanently installed monitoring cameras. This combined time-lapse imagery allowed identifying ring shaped fumaroles prior to explosion occurrence, and distinguishing between sequential explosion and crater excavation stages, followed by dome growth. By means of particle image velocimetry, the digital flow field is computed from consecutive camera images, showing that vertical dome growth dominates at the beginning. We discuss and compare the observations to discrete element models, allowing mimicking vertical and lateral growth history of the dome and to estimate the peak strength of the bulk rock mass. Our results allow moreover discussion of the controls of a critical dome height that may be reached prior to its gravitational spreading. This study, for the first time, allows a detailed view into the explosive crater formation and new dome formation at Colima volcano, with important implications for other dome building volcanoes.

Volcano tectonic seismicity and its value for near-real-time forecasting

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Distal volcano tectonic (dVT) seismicity is usually the earliest reported seismic precursor for eruptions at volcanoes dormant for $\geq$20 years. White and McCausland (JVGR 2016) reported data on 136 dVT earthquakes and swarms that preceded 111 eruptions and accompanied 21 additional intrusions at 83 volcanoes. We showed that the cumulative dVT energy is proportional to the intruded volume. Here we use the same data set to address variations in dVT energy release prior to explosive eruptions, passive eruptions, and intrusions that don’t lead to eruptions. We show that, for very low magma intrusion rates of a few thousand m3/day, similar to the highest deep well H O-injection rates, the dVT seismicity onset may be delayed by months to a few years and may manifest as isolated events or as mainshock- aftershock-type seismicity. However, for high magma intrusion rates (100 thousand to > 10 million m3/day), dVT seismicity ramps up in numbers and average magnitudes,$_2$ usually peaking hours to a few days prior to the initial explosion(s). In general, the larger the cumulative dVT energy release, the more explosive the eventual climactic explosion. For this reason, we believe that dVT seismicity may serve as a near real-time proxy for magma flux when flux is high. Thus it can be extremely useful for forecasting large, explosive eruptions. Finally we show that when significant dVT seismicity recurs during the magmatic eruption, it likely indicates renewed pressurization of the magma storage region and can be used to forecast changes in eruptive size or style.

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S01.11 - Understanding volcanic processes through geophysical and volcanological data investigations

Ground deformation field recorded by the tiltmetric network of Ischia Island before and after the earthquake of August 21th 2017

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The Ischia Island (southern Italy) is an active volcanic area and the dynamics is constantly monitored by the Osservatorio Vesuviano (the Naples branch of the Istituto Nazionale di Geofisica e Vulcanologia, OV-INGV) surveillance system. In particular, ground tilt monitoring is continuously measurement of changes in the slope of the ground surface. It is able to detect slight tilt variations, in both direction and amplitude, of volcano edifice caused by the volcano dynamics. The Ischia Monitoring Tiltmetric Network is operating on the island from the end of April 2015; is composed from 3 tiltmetric stations (ISC, BRN, FOR, called) equipped with digital sensors installed in boreholes at 25 m depths surrounding of Mt. Epomeo.

The objective of the tiltmetric study is the characterization of the kinematics and evolution of crustal deformation associated with volcano activity and noticed temporal correspondences between sharp or slow variations and superficial seismic events.

The Ischia earthquake of August 21th 2017 was recorded by 3 tiltmeters of the network, and it excited the rotation of the tilting directions.

In particular, the ISC tiltmetric station (located about 3 km in the ESE direction respect to the epicentral area) has recorded a coseismic tilt of 6.3 µradians towards NW. The FOR tiltmetric station (located about 4 km in the SW direction respect to the epicentral area) has recorded a coseismic tilt of 5.3 µradians towards W. While the third sensor, BRN tilt station (located about 3 km in the SE direction respect to the epicentral area), recorded a simultaneous anomaly of the geomagnetic declination.

The coseismic tilt detect the arrival of the surface wave-trains generated by the earthquake and this spatial offset is interpreted as a permanent coseismic deformation.

Geometric evolution of volcanic conduits during explosive eruptions: application to the 79 A.D. Vesuvius eruption

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The study of pyroclastic deposits mainly relies on the analysis of dispersal area and thickness distribution, and on the study of their grain size and componentry. Although lithic component represents a significant fraction of pyroclastic deposits, the state of art for interpreting pyroclastic products is quite limited when we study the nature of lithic fragments. Since conduit erosion is mainly controlled by magma properties and pressure profile, the analysis of lithic fragments can be employed for understanding conduit dynamics of a given volcanic eruption. Here we use the well-documented 79 AD Vesuvius eruption for illustrating the use of lithic component information in order to address conduit geometry evolution during explosive eruptions and constrain some key eruptive parameters. The eruption is characterized by the presence of a largely variable lithic component, associated to different lithologies present in the volcano subsurface. We modeled the eruption evolution by considering three main periods during the Plinian phase of the studied event (associated to Eruptive Units EU2a, EU3a and EU3b). Simulation results are consistent with the expected eruption rates and the estimations of the eroded volumes of lavas and carbonatic fragments, which require the use of conduit geometries with depth-dependent dimensions. They also indicate that the onset of the Plinian phase (EU2a) was characterized by intense craterization processes. The water content decrease from the white (phonolitic) pumices to the gray (tephra-phonolitic) pumices produced slightly shallower fragmentation levels during EU3a, whereas the increase in mass discharge rate (MDR) could be associated with a particularly efficient increase of the minimum conduit radius. After the peak of MDR (EU3b), a significant deepening of the fragmentation level can explain the higher fraction of carbonatic fragments observed in the deposits. Exit pressure and velocity would have experimented a monotonic decreasing tendency during all the Plinian phase.

S01.11 Poster

The use of the AMS for the determination of probable eruptive center locations of some ignimbrites and lava from the island of Pantelleria (Sicily Channel)

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The anisotropy of the magnetic susceptibility (AMS) can be used as a proxy for crystal orientation and therefore as flow-direction indicator. In this way, it is possible to retrieve reliable vent locations, assuming the AMS ellipsoid is coaxial to the petrofabric. This study presents the results of AMS analysis from three silica-rich peralkaline ignimbrites, the 187-188 ka Pozzolana, 187 ka Polacca, 179 ka Arco Formation (Jordan et al., 2018) sampled with two sites each and one pantelleritic Lava Bellizzi (~20 ka, Mahood and Hildreth 1986) from the volcanic island of Pantelleria (Italy). The units were sampled at four different localities in the southwest (Scauri, Nicà-Cala Delle Capre), south (Salto La Vecchia) and north (P.Pozzolana) of the island. The AMS tensors are characterised by a generally prolate ($-0.069<T<-0.167$) to strongly oblate ($0.238<T<0.712$) ellipsoid, and by mean values of $P_j \approx 1.014$. Results from the Arco and Polacca Formations (sites Cos35-Cos37-Cos42, at SSW) show a K_1-K_2 foliation plane plunging toward NE and a K_3 suggesting a flow direction toward the WSW; these results suggest a vent situated at ENE, in agreement with the results of Jordan et al. (2018) regarding the Arco Formation, based on field data. Lava Bellizzi results (Cos41, between Nicà and Cala Delle Capre) suggest a NNE orientation of the source vent, which is in agreement with the position to the NE of the "Cuddie Bellizzi" scoria cones. On the contrary, the magnetic fabrics of Arco (Cos39, at Scauri) and Pozzolana (Cos36-Cos40, at P.Pozzolana) show a sub-horizontal magnetic foliation and a flattened oblate tensor probably determined respectively by a paleo-topographic control and a compaction process. This study shows a successful example of the importance of integrating the field and petrographical observations with the AMS to infer the position of the paleo-vents and therefore to unravel the past history of ancient volcanoes.

S01.11 Poster

Spectral analysis of ground thermal image temperatures at Solfatara crater

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The Solfatara volcano, part of Campi Flegrei caldera (Italy), is monitored by INGV ground networks, including thermal infrared cameras (TIRNet network). This last network is composed by 5 permanent stations. They acquire portions of the Solfatara area characterized by significant thermal anomalies.

In this work the dataset is composed by 1347 daily samples from 2014 April 25th to 2017 December 31th, recorded by three TIR stations (Solf1, Solf2 and Ps1), and by environmental pressure and temperature variables.

A pre-processing on the data was carried out in order to remove the components associated to the seasonality and the influence of the tides on all the variables. We chose the STL algorithm (Seasonal Decomposition of Time Series by Loess; Cleveland et al. 1990), since it allows to decompose a time series into three components: seasonal, trend and remainder.

Then, we performed a harmonic analysis on the deseasonalized signals by using the T_Tide software (Pawlowicz et al., 2002) in order to identify and remove the main tidal constituents (diurnal, semidiurnal and long period).

The analysis of the residual time series allows to highlight possible temporal temperature variations both due to endogenous dynamics, or affected by other factors.

Possible correlation between thermal anomalies and the environmental parameters can be, then, underlined through spectral analysis (FFT). For the entire dataset, we calculated the periodograms in the band [10-120] day. This analysis permitted to evidence which are the components common with meto-environmental variables and which are features of a specific TIR-site. In particular, we found two spectral peaks, at about 30 and 50 days, common to all the considered variables. Moreover, Solf1 station shows a marked link to the external pressure for periods larger than 45 days, while Solf2 and Ps1 exhibit a behavior similar to external temperature starting from a period of 80 days.

Characterization of the 2010-2018 eruptive activity of Nevado del Ruiz Volcano from seismological, geochemical and geodetic data

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The Nevado del Ruiz Volcano has been in a state of instability since September 2010, which so far has included two minor eruptive episodes and the rise of two lava domes on the surface of the Arenas crater, as well as a significant number of small emissions of ash.

The first eruptive period was defined by the low-energy explosions of May 29 and June 30, 2012, frequent small ash emissions and continuous volcanic tremor. This period was preceded by an increase in background and hybrid-type seismic activity, high SO_2 emission rates of up to 35,000 t / d, and vertical changes in deformation of up to 7 cm / y of inflation.

Between October 2012 and November 2014, volcano-tectonic earthquakes dominated seismicity, with high rates in the number of earthquakes (up to 4900 events / day) and magnitudes up to 4.6 ML. This seismicity was located in the volcanic edifice and along the main fault systems existing in the area. During this time gas emissions fluctuated and, while new sources of deformation were located in distal areas of the volcano.

The other eruptive period (November 2014 - present) is related to the rise and growth of lava domes accompanied by small ash emissions and ongoing degassing. Seismically, this process has been characterized by episodic pulses of volcanic tremor of variable energy, drumbeat seismicity and increases of volcano-tectonic earthquakes.

In general, the main changes of the volcanic system are reflected in a consistent way in the seismic activity in context of changes in deformation and SO_2 emission rates. Thus, from the variations in the baseline of the seismicity and other monitoring techniques, we propose four periods of volcanic activity between 2010 and 2018.

Characterization of the seismic dynamical state of Ischia Volcanic Island (Italy) through the ICA and the polarization analysis applied to background seismic noise

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We have investigated the seismic dynamical state of Ischia volcanic Island before and after the August 21, 2017 earthquake, by applying classical and innovative techniques to the background seismic noise. First, we searched for the presence of independent signal sources by performing the Independent Component Analysis (ICA). Over 60 days of recordings, from 26 August to 25 October 2017, the application of ICA algorithm successful separated two stable components: IC1, the most energetic and persistent, picked at ~1 Hz; and IC2, concentrated in 3-4 Hz band. The root mean square (RMS) of continuous recordings during three months of the years 2016 and 2017, was estimated in order to investigate coherence properties of the background seismic signal before and after the August 2017 earthquake, for both raw and filtered data in the frequency ranges corresponding to the two ICs. The results show no variations in the patterns. The polarization properties of the same dataset were obtained by applying the covariance matrix method. The polarization parameters were estimated by filtering the signals in the 1-2 and 3-4 Hz frequency bands. The time evolution of the mean values of the polarization pattern does not show any variation during the analysed time intervals. The statistical properties of the polarization pattern were further investigated by analysing the rose plots of the azimuth of the polarization vector.

All the obtained results were interpreted taking into account the existing literature on volcanological, morphological, structural and geochemical studies. IC1 seems conditioned by tectonic and volcanic structures and by the Island morphology. It could be associated with the persistent activity of the hydrothermal system. The signal amplitude of IC2 clearly shows 24h periodicities, likely related to anthropogenic activities.

S01.11 Talk

Surface loading as top-down controls on magma reservoir formation

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Loading due to the growth of volcanic edifices generates stresses in the crust comparable to the order of magnitude of tectonic stresses. Crustal stresses control the pathways and velocity of magma-filled dikes and thus may affect the geometry and location of magma storage zones. We investigate how the loading stress provided by a growing volcanic edifice sets a top-down control on the shape of a magma reservoir. We compiled a dataset with the shape and depth of magma storage of deforming volcanoes from available databases (COMET, Smithsonian). In addition, 2D numerical simulations of ascent pathways of magma through the crust are carried out for different shapes of surface loads. We derive a model of reservoir formation by simulating multiple, successive ascending dikes and probing the relative role of the shape of a volcanic edifice. Based on the selected cases, our numerical simulations and crustal deformation studies reveal that the distribution of surface load is correlated to the shape and depth of the magma storage system. Calderas are associated to sills or top-flatted reservoirs, while stratovolcanoes are related to vertically developed reservoirs such as vertical prolate ellipsoids. Our results suggest that the shape of the volcanic edifice may control, beside being controlled by, that of magma reservoirs.

S01.11 Poster

Seismic polarization of LP and VT earthquakes at Campi Flegrei by ICAP

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We show how to obtain a clear separation of seismic phases in volcanic environments. Specifically we investigated the Long-Period (LP) and Volcano Tectonic (VT) seismic signals recorded at Campi Flegrei Caldera (Italy). We adopt an innovative Independent Component Analysis (ICA) algorithm for mixed seismic series adapted and improved to give automatic procedures for detecting seismic events often buried in the high-level ambient noise. We reconstruct the radiation patterns of the extracted LP events in order to link the individuated signals directly to the sources. We take advantage from ICA that provides basic signals along the three directions of motion so that a direct polarization analysis can be performed with no other filtering procedures. We show that the extracted signals are mainly composed of P waves with radial polarization pointing to the seismic source of the main LP swarm, i.e. a small area in the Solfatara, also in the case of the small-events, that both precede and follow the main activity. From a dynamical point of view, they can be described by two degrees of freedom, indicating a low-level of complexity associated with the vibrations from a superficial hydrothermal system.

Additionally, we also focus on VTs, obtaining a clear separation of P and S phases: the technique not only allows the identification of the interval time P-S giving the timing of both phases but also provides the independent waveforms of the P and S.

The proposed approach (ICAP) can represent an useful tool to obtain the polarization properties on seismic signals both originated from the interaction fluid-solid or by the rock fracturing.

Assessment of eruption source parameters using infrasound waveform inversion at Mt. Etna, (Italy) and Santiaguito Volcano (Guatemala)

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Eruption source parameters such as the volume of erupted material and the rate at which it is ejected during eruptions are parameters of great importance to monitor and quantify intensity of volcanic eruptions and to produce early warnings for aviation authorities. Acoustic infrasound analysis stands as a fast and robust method for assessing these parameters, especially for local infrasound networks (<6 km from the source), where the most dominant factor affecting the propagation of the acoustic wavefield is topography, while wave propagation processes such as geometrical spreading, molecular absorption, and wind can be neglected.

In this study, we gathered infrasound data from explosions recorded during seismic- infrasound experiments at Mt. Etna (Italy) and Santiaguito (Guatemala) volcanoes, to assess directionality of wavefield propagation, erupted volumes and rates. We explore the importance of dipole components compared to simple monopole source functions in both volcanoes. For this purpose, wavefield acoustic simulations were performed taking into account both monopole and dipole components. By using a Finite Difference Time Domain modelling scheme, we investigate the effects of local topography and atmospheric winds on the wavefield propagation. Finally, acoustic waveform inversion is carried out using 3D acoustic wave-field simulations to estimate the source functions from the analysed explosion as well as the rates and volumes of erupted material.

S01.11 Poster

Long-period ground oscillations at Campi Flegrei caldera from borehole tiltmeteric data

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We show an analysis of tiltmetric time series from borehole instruments at Campi Flegrei caldera. We evaluate the crustal response in terms of ground tilting of the entire caldera to external excitations such as long/medium period tidal constituents, by adopting Independent Component Analysis, a nonlinear technique. The main aim to understand an eventual relation between long-period tides and fluid circulating in the hydrothermal shallow system.

Indeed, diurnal (solar) and long-period (fortnightly and monthly) components are recognized in the tilting. These tidal constituents cause an oscillatory deformation pattern, superimposed to the normal deformation trend of the area. Moreover, we show that the tilting plane orientations are controlled by the local stress field and the structural features and that the amplitude of the tilt reflects the rheology of the site.

These observations indicate the occurrence of structural and thermoelastic site effects. Their knowledge is useful not only for removing the external tidal contribution in the tiltmetric series, but also in delineating the local geology and focusing on the internal sources related to the volcano dynamics. A variation in the fluid circulation may induce a change in the revealed pattern, which can be promptly detected.

The promising results we obtain lead us to believe that the same approach can be extended to other tiltmetric networks in volcanic areas, for thorough and detailed analyses of the tiltmetric time series and more accurate studies of the endogenous sources.

S01.11 Talk

Spectral ratio analyses of explosion earthquakes at Sakurajima volcano, Japan

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It's quite important to clarify what physical parameters control the magnitude of volcanic explosion in order to understand magma processes in the conduit. Analyses of explosion earthquakes, which are associated with Vulcanian eruption, enable us to understand dynamic process of the explosive eruptions. We analyze hundreds of explosion earthquakes recorded at Sakurajima volcano during 2012-2013 using the spectral ratio method that can retrieve the source spectral information without being disturbed by heterogeneous structure, to understand scaling relations in Vulcanian eruptions. We use three-component seismograms recorded at three stations operated by Japan Meteorological Agency, and classify the explosion earthquakes observed into four classes according to their maximum amplitudes. Because Vulcanian eruptions continue to effuse volcanic ashes for several to tens of minutes, spectral amplitude ratios of classes II, III and IV to the smallest class I are calculated by shifting a time window of 10 s from the onset to coda wave. The results show that the spectral amplitude ratios are characterized by the low and high corner frequencies: 2 Hz and 4 Hz. Although the corner frequencies do not significantly change with lapse time, amplitude ratios at low and high frequency ranges, which are 1-2 Hz and 4.5-10 Hz, respectively, decrease with lapse time. The lapse time dependence of spectral ratios are completely different from those of tectonic earthquakes. Also, seismic wave simulations show that the spectral ratio changes are not simply caused by source depth change of explosion earthquakes. Since the explosion earthquakes at Sakurajima volcano occur at a same crater without changing vent radius significantly, the observed spectral amplitude ratio changes can be attributed to temporal changes of pressure in the conduit. We infer that these changes are attributed to the eruption style changes from the initial rapid pressure release in the conduit to continuous ash emission.

A reassessment of the Jubangcheon peperite in the Cheongsong UNESCO World Geopark, South Korea: pesudo- peperite produced by hydorfracture

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The Jubangcheon peperite, one of the geosites of the Cheongsong UNESCO World Geopark in South Korea, has been interpreted as the mixtures of basaltic lava flow and wet sediments, and is used for geoeducation site as unique example of syn-sedimentary volcanism. As a result of the field survey, the basalt cutting the underlying sedimentary and volcanic rocks is interpreted as intrusive rock, and the peperite textures within the rock do not match the typical peperite features found at the boundaries between volcanic and sedimentary rocks. The sediments within the intrusive rock envisaged the veins produced by the secondary fluid. It is typical features of the peperite that glassy rim is formed along the margin of clasts of magma origin and the internal sedimentary structures are destroyed by fluidization of the host sediment. We, however, could not find glassy rim along the margin of the basalt fragments and disturbed texture in the vein consisting of quartz and clay minerals during SEM-EDS analysis. On the other hand, the characteristics of the basalt fragments with uneven margins and basalt fragments in the vein body are interpreted that the fluid injected inside crushed the basalt in place and grown and filled the gap with quartz that was carrying it. These results represent that the Jubangcheon peperite is pesudo-peperite produced by secondary hydrofracture rather than the synsedimentary volcanism.

Unbedded lower diatreme deposit at Maegok, Miocene Eoil Basin, SE Korea

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The Eoil Basin is one of the Early Miocene sedimentary basins in SE Korea, which contains abundant volcanic and volcaniclastic deposits with epiclastic sedimentary deposits. Origin of a mafic volcaniclastic deposit at Maegok in the southeastern margin of the basin has remained enigmatic although it was interpreted as peperite by some previous studies. A number of features of the Maegok deposit can be explained as the processes which operate within and adjacent to the conduit of a phreatomagmatic volcano. These features include 1) the occurrence as an isolated vertical cylinder, 2) an abundance of hydroclastically fragmented sideromelane shards in the matrix, 3) tilting, faulting, and ductile deformation of surrounding sedimentary deposits indicating synvolcanic collapse or subsidence toward the vent, 4) dike-like structures composed of fine-grained tephra intruded into the surrounding sedimentary deposits, and 5) some clasts having a jigsaw feature indicating *in situ* fragmentation by shock waves. Plastically deformed mafic clasts, formerly regarded as evidence for peperite, show neither features of simultaneous intrusion and mingling of magma with wet sediments nor features of in situ fragmentation. Other deposit features negate the possibility of peperite processes in forming the volcaniclastic deposit at Maegok. The Maegok deposit is interpreted to be a 'tuff pipe' or the diatreme of a mafic phreatomagmatic volcano. An abundance of sideromelane ash in the matrix and the lack of lapilli-size juvenile grains suggest that the phreatomagmatic explosion was caused mostly by contact-surface stream explosivity, leading to Taalian-style eruption and the construction of a tuff ring. Deposit features of the Maegok exposure belongs to the deeper part of the diatreme in spite of its occurrence at a relatively shallow level, about 100 m below the pre- eruption surface. The conduit of the volcano is inferred to have been relatively shallow and probably had a flared-up geometry.

S01.11 Poster

Lateral texture variation and forming processes of peperite along felsic lava flow and wet sediment in the Cretaceous Buan Volcanics, southwest Korea

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Along undulating boundaries between rhyolite (lava flow) and deformed host sediment expressed as a series of load and flame structures, exposures commonly contain distinct type of peperites. The peperites laterally extend into the interior of featureless rhyolite as layers that decrease in thickness with increasing distance away from the flame zone. These layers exhibit horizontal textural variations, ranging from poorly sorted mixtures of ash- to block-sized angular juvenile clasts in the proximal zone, to closely packed polyhedral and tabular juvenile clasts with jigsaw-crack textures in the middle and distal zones. These peperites are inferred to have formed due to internal steam explosions that resulted from an expansion of heated pore water (leading to an increase in pore fluid pressure) that had been vertically injected into the interior of the rhyolite from the flame zone. The proximal zone, composed mainly of poorly sorted mixtures of juvenile clasts, represents the explosion sites. Juvenile clasts in the middle and distal zones are interpreted to have formed due to three separate processes: the development of fractures in the rhyolite during the internal steam explosions, injection of the host sediment through the fractures, and *in situ* quenching fragmentation. Deformation of the host sediment exerted an important control on peperite- forming processes, with the internal steam explosions suggested to have formed the closely packed, juvenile clasts with a jigsaw-crack texture rather than the clasts that are widely dispersed.

S01.11 Poster

Remarkable VLP earthquakes under the Ticsani volcano, Perù

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The Ticsani volcano (Perù) in the Central Volcanic Zone of the Andes considered a “high risk” volcano (Macedo et al., 2016), has had two last eruptions one before and another after 1600 AD. Geothermal springs located less than 6 kilometers away, as well as small fumaroles at their summit, are evidence of an active magmatic system in the Ticsani.

The zone on and next to the volcano has frequent tectonic earthquake activity, being the earthquake of 5.3 ML of 2005 the last one more important. Since its installation in May 2014 and until March 2018, the network of four seismic stations of the Geophysical Institute of Peru has registered up to 76 swarms of VT earthquakes with magnitudes between 1.2 and 3.4 ML. Since 2015 notable low frequency earthquakes have been recorded dominated by a signal of 0.3 Hz with overtones at higher frequencies, which occur under the volcano at depths close to 12 km, and which can be observed up to 150 km away. The first low frequency earthquakes (which we can consider of the VLP band) recorded on October 01, 2015 occurred after several days of an unusual increase in swarms of proximal VT earthquakes, preferably located along a N350º fault (Lavallèe et al., 2009) that crosses the crater. Other swarms may occur before or after VLP earthquakes. Since then, up to 129 VLP events have been counted; maximum local magnitudes were estimated to be of the order of ML = 3.5. We interpret the swarms followed by low frequency earthquakes as an initial seismicity of fracture that is favored by fluid pressure coming from the magmatic chamber to pre-existing faults, and which are followed by the flow of magma between two reservoirs with characteristic resonance frequencies of 0.3, 4.6, 9.0 Hz.

Time-space variations of low temperature fumaroles as a tool for detecting changes in volcanic activity state

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Fumarolic fields, especially those with near-surface soil temperature <100°C, are very common features of active or quiescent volcanoes, with both open or closed conduits. Their spatial extent, as well as the time variability of their temperature, are conditioned by three main factors: 1) Local hydro-meteorological conditions; 2) Vapour flow from the underlying volcanic-hydrothermal system; 3) Permeability variation induced by stress field changes and/or deposition-dissolution cycles of hydrothermal alteration minerals. Once depurated from the exogenous noise, time variations of the thermal signal, in term of both short lasting transients and medium/long term trends, reflect changes in the activity state of the related volcanic system. The intuitive association of positive temperature anomalies with increments in the activity of the monitored volcanic system is often contradicted by field observations: in open conduit volcanoes, decreasing temperatures of a peripheral fumarolic field could remark phases of intense volcanic activity, during which the most of the volatiles are vented by the main conduits. On the contrary, temperature increases during the wet season could be observed in close conduit volcanoes, due to a different partition of vapour venting from the soil between voids linked to porosity or fracturing. About spatial variations, increments in thermally anomalous soil surfaces reflect both increments in vapour flow and drying of the soil, highlighting that soil temperature surveys must be carried out in short times and under similar meteorological conditions, for not retrieving pseudo-features created by different boundary conditions of the studied system.

Analysis of volcanic tremor wavefield at Etna volcano through array techniques

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This work is based on the characterization of kinematic properties of volcanic tremor recorded at Etna during the 2011 summer time. In this period, Strombolian activity and lava fountains occurred from a new vent opened at the base of the South East Crater (SEC). For this purpose, a small-aperture seismic array at distances of about 1 km SW from the South East Crater (SEC) was deployed. Starting from the spectral and coherence analyses on the tremor acquired from the array, significant wavefield coherence was observed throughout a frequency band spanning the 0.5-1.5 Hz range. For this frequency band, the propagation azimuth and apparent velocity of incoming wavefronts were calculated by inverting the inter-stations delay times for the two components of the vector slowness. More, polarization and particle motion analysis were performed, founding a significant changing of the parameters retrieves before and during the lava fountaining episodes. During a non-eruptive period, our results shown a back-azimuth pointing to the SEC and a wavefield characterized by P-SV waves. However, before the increase of the volcanic tremor amplitude, the tremor source moved toward the NSEC, and the particle motion showed a radiated R-waves. The most values of ray parameter were consistent with a wavefield composed both surface and body-waves.
The comparison between the different properties highlighted the migration of the seismic source from the deepest portion of the SEC, during a quiescent period, to the shallowest portion of the NSEC at the beginning of the volcano activity, showing a linking between the two craters.
These results denoted the ability of the array techniques to track the location of active magmatic fluids and will provide a method for constraining parameters that are relevant to monitor volcanoes and forecast their activity.

Local seismic study of the Ceboruco Volcano using a dense seismic temporal network

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In the western part of the Tepic-Zacoalco rift zone is located the Ceboruco volcano. This volcano had effusive-explosive episodes with eight eruptions during the last 1000 years, providing an average of one eruption each 125 years. The last eruption occurred in 1870, 148 years ago, so the likelihood of a new eruption is extremely high and risky due to nearby population centers, important roads and lifelines that traverse the volcano's slopes. This hazard indicates the importance of studying and monitoring the seismicity associated with this volcano whose ongoing activity is evidenced by fumaroles and earthquakes.

As part of CeMIEgeo project, a temporal seismic network with 25 stations with 3D sensors was deployed in an area of 16 km x 16 km, with one station every 2.5-3 km, recording from November 2016 to July 2017. The objective of this project is to study the local seismicity and the volcanic edifice structure. We present the analysis of the volcano-seismicity data generated by this seismic network for this period. All data were integrated in a database using Antelope software, where we obtained the P and S arrival times and preliminary locations using IASP91 velocity model. After that, the events were relocated with HYPO71 using an appropriated velocity model. We observed the seismicity is concentrated below the crater showing two alignments with hypocenter depths between 4 and 8 km. Moreover, it is possible to identify seismic trace families.

Seismicity Study in the Ceboruco Volcano in the Period 2012 to 2014

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The Ceboruco is a stratovolcano located at Nayarit state, Mexico (104° 30'31.25"W, 21°7'28.35"N, 2280 msnm). This is an active volcano that is part of the Trans-Mexican Volcanic Belt. Nelson (1986) reports that it has had activity during the last 1000 years with averaged eruptions every 125 years, having last erupted in 1870. Currently has fumarolic activity. In the past 20 years there has been an increase in the population and socio- economic activities around the volcano (Suárez Plascencia, 2013); for this reason the Ceboruco study has become a necessity in several ways. Previous investigations of seismicity (Rodríguez Uribe et al., 2013) classified the earthquakes in four families considering the waveform and spectral features. We present analysis of seismicity from March 2012 to July 2014 with four portable seismic stations. In this period, we located 32 events with arrivals of P and S waves clear registered in at least three. The P and S phases time were obtained using particle motion. We located with HYPO71 and an appropriated velocity model for the region. The epicentral distribution is dispersed around the volcanic edifice, as Rodriguez et al (2013) suggested; however, some alignments in NE-SW direction could be inferred from the data, being perpendicular to Tepic-Zacoalco graben trend. The hipocentral depths are located in the first 10 km. The events were classified according Rodriguez et al., (2013).

Energy partition ratios (PEhr) of diffuse coda wavefield to study the velocity structures of the volcanic area of Campi Flegri (italy)

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In this work we used the Energy Partition ratios (PEhr) applied to the diffuse coda wavefield to analyse the differences of the velocity structures in the Campi Flegrei area. The data set consists of 24 earthquakes recorded from 2014 to 2017 by the broadband three component seismic stations of the Mobile Seismic Network of the INGV – Osservatorio Vesuviano, placed inside and around the area of maximum uplift. The magnitude of the earthquakes is between 3.2 and 6, and the epicentral distances vary from 65 km to 630 km. In order to have the diffusive wavefield conditions, after a selection of local and regional earthquakes with the best signal-to-noise ratio, we selected the coda starting from twice S-wave travel time to 3 times the signal-to-noise ratio. For each of the selected earthquakes the PEhr were evaluated in the frequency domain by dividing the power spectra of the two horizontal components by the three power spectra components of the seismic signals. Starting from the simple depth-independent crustal models, derived by tomographic imaging of the interested area, we have improved our velocity models by performing a Monte Carlo inversion of the PEhr curves in stratified models. The input model for each station used in this study is a 1D layered earth model composed by six parallel layers overlaying the half space. In the depth range 0–2 km and 2-4 km, the model is composed of four 0.5 km thick layers, and two 1 km thick layers, respectively. Significant deviations of the PEhr energy ratio from the canonical 0.67 value have been observed suggesting the presence of stratification in the upper crust and anomalies linked to the volcanic activities and fluid circulation, motivating a more specific modelling of the PEhr energy ratio.

S01.11 Poster

Array tecniques and spectral ratios applied to seismic noise to investigate subsoil structures in Campi Flegrei (italy)

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The purpose of this work is to study the subsoil structure (from shallow to deep layers) of the Campi Flegrei area using both spectral ratios and array techniques applied to seismic noise. The dataset consists of seismic noise recorded in the underground by the seismic Array "ARF" and the broadband stations of the mobile network. We estimated the dispersion curves of Rayleigh waves propagating through the array by applying the Frequency–Wavenumber (f-k) technique and the MSPAC method. The phase velocity dispersion curve of the fundamental mode of Rayleigh waves was obtained by plotting the inverse of slowness, as a function of frequency, and selecting the part of the curve bounded by the resolution limits defined through kmin and kmax. For the MSPAC method we divided the array in semi-circular sub arrays called Rings, which radius are defined by the sensor's spacing, and we calculated the spatial autocorrelation coefficients for all the possible pairs of sensors. Further constrains on the dispersion curves are obtained from the estimate of the phase velocity of transient coherent signals recorded by the array. We used the DINVER computer code to perform a joint inversion of the autocorrelation coefficients, the dispersion curves, the single coherent noise values and the mean HVSR of the mobile network station to obtain a shallow shear wave velocity model for the first 200 m, which is in a good agreement with the stratigraphic information of the wells available in the area. The study of the velocity models is crucial to recognize anomalies due to the presence of fluids connected to the volcanic activity and a high quality characterization of the medium allows us to correctly identify, in the geophysical observables, the contribution of the volcanic source.

S01.11 Poster

Recent explosive eruptions of Shinmoe- dake, Kirishima, Kyusyu, Japan, revealed by the near-source broadband seismic network

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Shinmoe-dake is one of 20 eruptive centers of Kirishima volcano group in southern Kyushu, Japan. In January 2011, Shinmoe-dake began its first magmatic eruption in 300 years. Following sub-Plinian eruptions, extruded lava filled the summit crater. In October, 2017, a seismic activity was reactivated and was followed by small phreatic-eruptions. In March 2018, magmatic extrusion restarted. The newly erupted lava covered the 2011 lava, filled the summit crater, and finally overflowed from the crater edge. The magma extrusion stage was accompanied by intense explosive eruptions.

We have been operating a broadband seismic network composed of 14 broadband sensors around Kirishima volcano. The closest station is only 400m from the edge of the summit crater. We have analyzed not only translational signals but also tilt signals extracted from the horizontal components of broadband sensors.

Two days before the October 2017 eruption, one-hour long volcanic tremor occurred, which was accompanied by tilt signal corresponding to a small inflation 1km beneath the summit of Shinmoe-dake. Tilt analyses of the 2018 data show that many of the vulcanian eruptions were accompanied by pressurization a few to tens of minutes before each eruption. The existence of the pressurization phase just before the eruption suggests that vulcanian eruptions are initiated not by a sudden break of a sealing plug at the top of the conduit due to a steady pressure increase but by a plug break due to a sudden pressure surge. Possible cause of the pressure surge would be an additional magma injection into the conduit. Alternatively, the pressurization may correspond to a sealing plug formation at the top of the conduit. In this case, the time scale of the pressurization phase gives constraints on the time scale of the plug formation.

Tidal synchronization of Long Period (LP) events and hydrothermal tremor at Campi Flegrei (Italy)

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The generation of seismic signals within volcanoes is a complex phenomenon that involves the coupling between a fluid phase (magmatic and/or hydrothermal) and the vibrations of the solid rock. This mechanism caused the most relevant swarm of Long-Period (LP) events at Campi Flegrei in October 2006, during the 2004-2006 ground uplift episode. We investigated the source properties of the LPs by analyzing the temporal release of seismic energy, amplitude distribution and inter-event occurrence time. Moreover, we applied the Independent Component Analysis to identify the simpler waveforms representative of the source mechanism. On the basis of the results, we propose a conceptual model for the LP generation: the source process is triggered by a mechanism of fluid charge/discharge in the branches of a dentritic network of the hydrothermal system. Partial shunting of the fluid flow toward different conduits is likely activated by tidal stress variation, thus modulating the time pattern and the energy release of the LPs.

We also recognized the influence of earth tides in the background seismic noise by analysing continuous data recorded at five broadband stations during 2006. We estimated the time evolution of amplitude and polarization of the signal in the frequency band common to the LPs. The series resulted modulated on tidal time scales: the RMS amplitude is basically dominated by solar contribution, while the azimuth of the polarization vector shows lunar diurnal and semidiurnal constituents. Moreover, in the frequency band common to the LPs the azimuths are polarized toward a specific area, suggesting that these persistent oscillations can be induced by the activity of the shallow geothermal reservoir.

All these observations indicate that the interaction between fluid and solid modulated by tidal strain represents a key point for interpreting the seismic activity observed in 2006 and for better understanding the caldera dynamics.

S01.11 Poster

Volcano monitoring using tiltmeters: relationships observed with other geophysical signals

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The tiltmetric study concerns the analysis and interpretation of a particular class of geophysical ground deformation signals. Its primary objective is the characterization of the kinematics and evolution of crustal deformation associated with volcano activity, projected in the final analysis to an identification of eruption precursors.

To date, the Osservatorio Vesuviano (the Naples branch of the Istituto Nazionale di Geofisica e Vulcanologia, OV-INGV) has a lot of tiltmetric, thermal and magnetic time-series, recorded at Phlegraean Fields, Vesuvius, and Ischia.

In particular, the Phlegraean Fields and the Vesuvius have been monitored for over 20 years.

The most important results obtained so far concern the observation of causal and non-causal relationships between seismic activity and ground tilt anomalies. From the study of the tilt patterns observed, in fact, we often noticed temporal correspondences between sharp or slow variations and superficial seismic events. For example, at the Phlegraean Fields, before and after the earthquake swarm of October 2006, a great tiltmetric anomaly was observed, characterized by a change in the pattern and intensity of the tilt.

Moreover, in relation to the earthquake swarm of October 7th 2015, always occurred in this area, just before it was found an anomaly on a tilt signal acquired in depth, in the form of 4 distinct offsets in the range 0.5÷2.8 μradians 9 minutes before 4 of the 6 most energetic events recorded.

At Vesuvius was seen a strong reversal of tilt direction between the end of 2000 and the first months of 2001, occurred at the beginning of a period of a consistent reduction of the energy released by local earthquakes.
All these evidents causal relationship tilt/earthquakes are the starting point for a phenomenological approach that explains why they occur, focused at a correct volcanological interpretation.

Precursory and syn-eruptive changes in 3D attenuation and seismic velocity structure during the 2018 Kilauea eruption

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We present the status of analysis regarding the three-dimensional evolution of seismic attenuation and velocity structure at Kilauea volcano during the recent eruptive activity in 2018. Our analysis looks at temporal evolution of both seismic wavespeed and seismic attenuation beginning in January 2018. Using continuous waveform data from the Hawaiian Volcano Observatory network, we will focus on changes to the shear-wave structure and its evolution through the latest developments in eruption activities, using correlation of high- frequency Rg phases. At the same time we will examine the 3D attenuation structure using relative seismic amplitudes of discrete microearthquakes, both from the catalog and supplementary events identified through correlation and subspace detection. We will compare observed trends and anomalies in both analyses, with a focus on their relationship to located hypocenters and eruptive events of note.

S01.11 Poster

Magma chamber and volcanic conduit interaction: A tale from long-period tremor activities in Aso volcano, Japan

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Long period volcanic tremors (LPTs), typically termed as VLP in the volcanology community, have been widely observed in many volcanic systems around the world. While the excitation mechanism of LPTs is often related to the resonance of volcanic conduit due to fluid-rock interaction, the triggering mechanism of LPTs remains enigmatic. Is there any detectable deformation associated with the magma chamber that may be indicative of a source of triggering? How does the deep hydrothermal system developed in a vast caldera ultimately dictate the pressure in the shallow conduit and upcoming eruption?

In this talk, we will discuss our effort in constructing LPT catalog between 2011 and 2016, which includes the period prior to and during the 2014 strombolian eruption, as well as two phreatomagmatic eruptions in late 2015 and late 2016. With simple waveform stacking of broadband displacement and horizontal tilt recorded at Vnet, we highlight new observations of diverse LPTs with opposite waveform polarities and resonance period, permitting us to infer temporal changes in conduit geometry and fluid properties over the 6 years period.

But most interestingly, the waveform stacking technique allows us to discover weak inflation/deflation events that always occur in concert with the LPTs, representing a repetitive and non-destructive source located away from the LPT source. Joint inversion of tilt and displacement data put the source inflation/deflation events close to the roof of the inferred magma chamber, a few kilometers southwest of the first crater and LPT source, whereas the volume change associated with each event is on the order of 1000 m^3. We will discuss how these inflation/deflation events may shed a new light on the rheology near the deep conduit or/and chamber roof as well as the openness of the entire conduit system.

Moment tensor inversion of volcanic tremor at Mt. Etna (the 2011 lava fountains)

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Twenty-five episodes of lava fountaining characterized Mt. Etna volcano during 2011-2012; a pit-crater formed between 2007-2009 on the Eastern flank of the South-East Crater (SEC) fed intense eruptive activity, which gradually constituted a new cone named New South- East Crater (NSEC). In order to understand the volcano dynamics over the 2011 time period, and to shed a light into the volcanic tremor source mechanism, we made use of data recorded by the broadband seismic network and performed Moment Tensor Inversions on volcanic tremor recorded during 2011's summer.

This study was performed to (i) retrieve the seismic source mechanisms generating this type of signal and (ii) gain a better understanding of Etna's shallower plumbing system. We proceed to the tremor source mechanism via full-waveform inversion of the seismic Moment Tensor. Although this study has not yet reached a definitive conclusion regarding source geometry, our preliminary results indicate that a crack-shaped body is the most likely candidate for describing the source.

Although further tests are needed to better elucidate stability and robustness of our inversions, this study represents the first attempt of Moment Tensor analysis of volcanic tremor source at Etna, and opens the way to the improvement of our knowledge of the physical processes into the shallow plumbing system.

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Analysis of seismo-acoustic signals associated to volcanic eruptions at Stromboli volcano

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Eruption earthquakes and infrasound are usually observed with Strombolian or Vulcanian eruptions or gas bursts. Understanding the origin of these signals is important to disclose conduit dynamics during the explosive processes.
We present preliminary results of a temporary seismo-acoustic observation conducted at Stromboli volcano, Italy, on September 2016 with 9 broad-band stations and 14 infrasonic sensors. The network had been deployed in order to have the better azimuthal coverage of the active craters and as close as possible to the active vents with five stations at only 100-300 m away the craters.
We apply a first-arrival automatic picking based on Akaike information criterion whose signal-to-noise ratio of infrasound is more than 5 at the station nearest to the craters and we found that acoustic signals filtered in the 0.1-20 Hz frequency band are always preceded by the very-long-period (VLP) seismic signals in the 0.05-0.2 Hz frequency band by ~3 seconds. We apply the semblance method to locate VLP source. The peak semblance values are as high as 0.81-0.87, representing high coherency and a strong rectilinearity of the waveforms, which is consistent with an isotropic source. The best position is stable at 200 m west of NE crater and at an elevation of 590 m a.s.l, which correspond to a depth of ~170 m below the craters. Considering this position of the explosive source and the time difference between the VLP and the infrasound we estimate an apparent velocity in the conduit of 43-74 m/s, which seems too fast to support an explosive model based of a gas slug and suggests a quite efficient explosive dynamic processes.

Seismic behavior, degassing and SO_2 concentration related to medium-high magnitude earthquakes from 2014 to the present, Tupungatito volcano in central Chile

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The Chilean margin is characterized by subduction of the Nazca plate under the South- American plate, generating big earthquakes throughout Chile. At the northern extreme of the South Volcanic Zone, it's found Tupungatito volcano at 75 km east of the city of Santiago. This one, is composed of eight active craters and permanent fumarolic activity.

The aim of this study is based on the possible relationship between seismic events of medium-high magnitude, and the probability of disturbance the stability of the magmatic chamber of the volcano, disturbing the gases that are there; which could be associated to the increase of pressure, degassing and increment of seismic events in the volcanic building.
A correlation is established between earthquakes greater than or equal to 6.0 Mw, in a radio of 750 km from the Tupungatito volcano, with the increase in degassing, SO_2 concentration, as well as volcano-tectonic activity and of long period in the eruptive center.
The analysis shows that there is indeed an increase in activity in the massif, evidenced after the analysis of 30 earthquakes. Where it's noted volcanotectonic (VT) seismic increases from 0 to 1746, and from 0 to 770 of long period seismic (LP), the previous related with the fluid dynamics inside the volcanic building; thus also shows an increase in degassing from 200 to 1100 meters above the crater, and an increase in SO_2 concentration, according to the results of spectral bands, from 0.0 to 2.0 [DU]. The above taken from January 2014 to the present.

S01.11 Poster

Fault systems at Mt Vesuvius identified by seismological analyses and structural data

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Peculiar seismological analyses jointly with structural data for volcanic areas characterized by low magnitude seismicity can increase the knowledge about faults geometrical features. It's the case of the Mt. Vesuvius where the seismicity rate has been characterized in the last fifteen years by one hundred of earthquakes per year with duration magnitude $M_D < 3$. Highest seismicity rates occurred during years between 1996 and 2000 when the largest local earthquake was recorded (M_D 3.6 of 9th October 1999). The analyses performed in this work focused on this period when more than three thousands seismic events were recorded. The purpose of the work consists on detection and selection of clusters of similar earthquakes, their relative localization and shear wave anisotropy analysis. The starting data set contains more than 3000 seismic events ($0.5 <= M_D <= 3.6$). By choosing the digital mobile station BKEM as reference, we evaluated the similarity between earthquakes by cross-correlation analysis applied to signals filtered in 2-10 Hz frequency band. Thirty clusters characterized by an average number of ten earthquakes were observed. Cross- correlation analysis was further validated by unsupervised neural analysis on the same dataset. All earthquakes of each cluster were localized by a relative localization technique. The relative localization results identify alignments of hypocenters with direction mainly oriented along NW-SE direction and in a few cases along NE-SW directions accordingly with structural data. Shear wave splitting analysis evaluated on best located clusters, confirms the main stress directions observed in previous studies and the stress direction aligned with main faults directions. The obtained results can be considered of interest in a contest of fault hazard analysis in order to identify the main directions in case of reactivation of the main fault systems.

Tracking the Precursory Activity that Led to the March 3rd Paroxysm at Volcán Villarrica using Seismic, Infrasound, and Web Camera Datasets

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On March 3, 2015 Volcàn Villarrica erupted suddenly, for the first time in 30 years, with a 60-minute-long, 1.5 km-high lava fountaining event. In the weeks prior to the eruption, the Chilean monitoring organization OVDAS-SERNAGEOMIN noted increases in seismic tremor and strombolian activity and on March 2, elevated alert levels to indicate an imminent eruption. This study incorporates continuous seismic, acoustic, and time-lapse web camera data in order to track the progression from a steady state degassing system to the paroxysmal eruption.

We separate the eruption sequence into 4 phases using a multiparametric approach. Phase 1 includes typical background activity in December though a steady rise in both seismic and acoustic amplitudes in January correspond to slight increases in degassing and observed lava lake activity. Phase 2 started on February 4, when seismic and acoustic amplitudes generally increased but fluctuated according to various volcanic activity including vent sealing, ash venting, gas puffing, and increases in Strombolian activity. A sharp increase in seismic energy on February 26 marks the beginning of phase 3 during which emergent and long duration (10 min) eruptions were identified on all 3 datasets and are speculated to be the initial transition from discrete bubble bursting events to more continuous lava fountaining activity. Phase 4 started with an apparent drop in both seismic and acoustic energy on March 2nd but, one day later, the paroxysmal eruption sequence initiated with relatively powerful Strombolian explosions that transitioned into more continuous Hawaiian style fountaining. Immediately following the eruption, infrasound radiation from the vent ceased but seismic activity was ongoing. Moving forward, it will be important to not only monitor and recognize precursory activity before major eruptions using a multiparametric approach, but also better understand the source mechanisms that drive these transitions at Villarrica and other similar volcanic systems.

Clusters of small monogenetic volcanoes in a certain area

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Monogenetic volcanoes are not particular phenomena of volcanisms on the Earth. They are one of the two possible cases, monogenetic or polygenetic volcanisms. When a volcanic vent opens on or around a polygenetic volcano, it would usually continue activities as a parasitic vent. If a vent opens at a distance from a polygenetic volcano and continue activities, it would be a monogenetic vent. Usually its volume is small comparing with polygenetic volcanoes. Parasitic volcanoes are sometimes monogenetic but not always. Origins of monogenetic phenomena were discussed by De la Cruz-Reyna and Yokoyama (2011).
Among various examples of monogenetic volcanolets, we find clusters of small monogenetic cones in a certain area. Here the author discusses the three examples in the Far East. Their volumes of ejecta and lavas are shown here with those of Paricutin and Monte Nuovo:

Jeju (Korea): Average vol. of single cone = 5 km^3 / 218 = 0.02 km^3 “Cluster”
The East-Izu (Japan): 2.5 km^3 / 75 = 0.03 km^3
Wudalianchi (the NE China): 0.46 km^3 / 14 = 0.03 km^3

Paricutin (Mexico) normal group = 3.6 km^3 “Normal”
Monte Nuovo (Italy) single = 0.08 km^3

It is noticeable that volume of a single cone contained in “Cluster” is very smaller than “Normal”, roughly 1/100. In order to explain such a large difference, we need a unique mechanism of magma supply systems for “Cluster”. “Umschlagen von Quantitä zu Qualität”. We need a special system to feed magmas to many vents distributed densely: The author adopts shear fracture model for the magma feeding system (Yokoyama, 2015).

S01.11 Poster

Double-Difference relocalization and focal mechanism of tectono-volcanic events at Colima volcano, Colima, Mexico

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Colima volcano (19.51 N, 103.62 W, 3860 m.a.s.l.) is the most active volcano in Mexico. With Nevado de Colima and Cántaro volcanoes to the north, it forms a volcanic complex rising in the middle of the Colima graben. The activity of Colima volcano, currently the only one considered active, is always accompanied by intense seismicity, composed mostly of volcano-tectonic events with foci within and below the volcanic complex. The seismicity is likely related to the stresses induced by the intrusion of magma, although gravitational stresses in the volcanic edifices of the Colima volcano complex could also be a contributing cause. The locations of the hypocenters found with standard methods show a dispersed view of the source regions. We used the catalog of events obtained from the standard analysis to relocate the hypocenters using the method of double differences. A set of 1486 events were relocated, providing an outlook with more resolution of the active area. The results show hypocenters clustered mostly under the edifice of Colima volcano and a few others around this zone. There is a weak correlation with some of the tectonic features, mapped in other studies, to the west of Colima volcano. Composite focal mechanism of the relocated events shows a variety of common fault plane orientations for 815 events, which show little strike component, and 497 and 318 showing thrust and normal faulting respectively.
The deepest earthquakes, with thrust fault solutions and foci between 10 and 15 km, seem to reflect the state of stress in the region.

S01.11 Poster

Insights into the oblique dome extrusion of Volcan de Colima 2013-2015; loading and unloading stress feedback on magma and fluid ascent and vent positioning

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During eruptive activity, the summit of a volcano tends to rapidly change morphology through excavation during explosions and refilling through the extrusion of magma. Due to the difficult and hazardous access, data revealing these morphometric changes are limited and new developments at the summit crater are often unclear. Here we use high resolution TerraSAR-X satellite radar observations, thermal data and airborne photogrammetry to identify structural features and to reconstruct local morphology associated with crater formation and dome extrusion at Volcan de Colima, Mexico.

During the observation period from Jan-2013 to Jul-2015, we could identify the rapid morphometric changes during extrusion and explosion stages and characterise lava dome growth, subsidence or collapse, crater excavation and lava flow production. We observe W- directed oblique dome growth until Jan-2015. Then in Feb-2015, following the removal of the active summit dome, the surface crater widens and elongates along the NE-SW axis. Later in May-2015, a new oblique dome grows towards the SW of the crater while a separate vent develops in the NE of the crater. We further explain the interplay between the crater/dome morphology, the oblique extrusion directivity and vent formation by applying finite element modeling to explore the type and quantity of stress changes resulting from loading (dome growth) and unloading (crater forming excavation). These stress change calculations allow insight into oblique dome growth and the migration of fluid/magma pathways in response to changing volcano summit morphology. These results highlight the use of detailed volcano summit surveillance as any obliquity of dome extrusion in this region is having major implications regarding the directions of volcanic hazards, such as pyroclastic flows generated by dome collapse.

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S01.13 - Geodesy A critical component of multidisciplinary volcano monitoring and hazards mitigation efforts

Geyser geodesy: Detection of ground deformation at Strokkur Geyser, Iceland, by ground based InSAR and tilt measurements

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Geodetic measurements allow assessing the state and changes associated with magmatic and hydrothermal processes. Geodetic monitoring at volcanoes has allowed identification of characteristic inflation prior to an eruption, and rapid subsidence during and after eruptions, followed by gradual re-inflation. We explored whether geysers might follow similar characteristics. We used Tiltmeters, GPS, and Ground Based InSAR (GB-InSAR) for measuring the dynamics of ground deformation at the Strokkur Geyser, Iceland, one of the most famous geysers in the world. Instruments were installed in a radial configuration with respect to the geyser, recording eruptions during two weeks field work in total. From the deformation data we clearly see eruption timing, short pulses of expansion, and a strong deflation thereafter, followed by gradual re-inflation. Therefore the characteristics of deformation strongly resembles the one at volcanoes. From this data we pick events and analyse eruption intervals, duration and deviations thereof. Furthermore we show that GB- InSAR data is well confirmed by tilt deformation data, hence introducing a new way of geyser monitoring. Just before each eruption we identify an inflation of around 0.02 mm and after eruption we have seen deflation of around 0.05 mm, which then slowly re-inflates again. We compare the degree of deformation with the height of eruptions as captured by video cameras, and find that eruptions higher than 20 m show stronger deformation as well. Large variations are observed, however, associated with a complexity in the conduit and possible gas reservoir geometry at depth, with important implications also for complex deformation occurrence that is observed at volcanoes.

S01.13 Poster

Post-eruptive thermoelastic deflation Usu volcano, Japan, 1992–2017

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Post-eruptive deformation can constrain volume and thermal properties of magma intruded in a past intrusion. In Usu volcano, Japan, secular ground subsidence has been reported around the vents associated with the 1910, 1943, 1977, and 2000 eruptions. The mechanism responsible for the observed subsidence has not bee well understood due to the poor spatial and temporal coverages of previous observations. This study systematically investigates the post-eruptive deformation at Usu volcano with Interferometric Synthetic Aperture Radar (InSAR) based on 111 JERS, ALOS-1, and ALOS-2 images acquired from five different tracks between 1992 and 2017. We also obtained quasi east-west and vertical ground displacements between 2006 and 2017 with available interferograms from ascending and descending SAR images. Our results show three localized deformation corresponding to the vents associated with the 2000, 1977, and 1943 eruptions, respectively. All the deformation sites show apparent east-west contractions and subsidence. The extent and rate of post- eruptive subsidence declined dramatically at the vent of the 2000 eruption between 2006 and 2017, decreased gradually at the 1977 vent, and show a steady pattern at the 1943 site between 1992 and 2017. We modeled the observed post-eruptive subsidence by thermoelastic contraction of a sphere intruded at the time of the eruptions to constrain locations, depths, volumes of heat sources. The thermoelastic modeling reveals three shallow heat sources embedded at depths of 0.232, 0.351, and 0.054 kilometers below sea level with volumes of about 0.005, 0.132, and 0.037 kilometers at the 2000, 1977 and 1943 eruption sites, respectively. The observed and calculated temporal evolution of ground displacements shows a good agreement, justifying the inferred heat sources. The modeling also highlights the importance of underground water in controlling thermal diffusion process to further affect the post-eruptive deformation.

S01.13 Talk

dMODELS: A software package for modeling volcanic deformation

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dMODELS is a software package that includes the most common source models used to interpret deformation measurements near active volcanic centers. The emphasis is on estimating the parameters of analytical models of deformation by inverting data from the Global Positioning System (GPS), Interferometric Synthetic Aperture Radar (InSAR), tiltmeters and strainmeters. Source models include: (a) pressurized spherical, ellipsoidal and sill-like magma chambers in an elastic, homogeneous, flat half-space; (b) pressurized spherical magma chambers with topography corrections; and (c) the solutions for a dislocation (fracture) in an elastic, homogeneous, flat half-space. All of the equations have been extended to include deformation and strain within the Earth's crust (as opposed to only at the Earth's surface) and verified against finite element models. Although actual volcanic sources are not embedded cavities of simple shape, we assume that these models may reproduce the stress field created by the actual magma intrusion or hydrothermal fluid injection. The dMODELS software employs a nonlinear inversion algorithm to determine the best-fit parameters for the deformation source by searching for the minimum of the cost function (chi square per degrees of freedom). The non-linear inversion algorithm is a combination of local optimization (interior-point method) and random search. This approach is more efficient for hyper-parameter optimization than trials on a grid. The software has been developed using MATLAB, but compiled versions that can be run using the free MATLAB Compiler Runtime (MCR) module are available for Windows 64-bit operating systems. The MATLAB scripts and compiled files are open source and intended for teaching and research. The software package includes both functions for forward modeling and scripts for data inversion. A software demonstration will be available during IAVCEI. You are welcome to contact the author at mbattaglia@usgs.gov for additional information, and the software can be downloaded from the USGS website at pubs.usgs.gov/tm/13/b1/

Temporal evolution of the two longest post-eruptive intrusions in 2012-2013 at El Hierro, Canary Islands

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The 2011-2014 volcanic activity at El Hierro (Canary Islands) revealed the intrusion of several batches of magma beneath this oceanic intraplate island. Only the first magmatic intrusion was able to reach the surface in a submarine eruption that lasted for 4 months. Six other deep magmatic intrusions were detected below the island in the following two years. These episodes were characterized by tens of earthquakes a day and centimeters of surface deformation, which contributed to the growth (> 20 cm) of the central and western parts of the island. Here, we studied the longest post-eruptive intrusions that occurred on June/July 2012 and March/April 2013. During these two ~20-day-long events, seismicity migrated away from the center of the island for >15 km. We used a geodetic dataset comprising 10 continuous GPS stations installed around the island and 44 COSMO-SkyMed and RADARSAT-2 satellite images to characterize the temporal and spatial evolution of ground deformation for these events. We initially inverted the daily geodetic data using analytical models to infer the volcanic source (location, geometry, and volume change) for each day. We then used a boundary element method to better characterize these magmatic intrusions. Most of the ground deformation and magma volume intruded occur during the first week for both events. Geodetic models show volcanic sources located at depths between 13-15 km, corresponding to the mantle/lower crust discontinuity, increasing its opening with time at volume magma rates of >0.03 km^3/day. These magmatic events suggest the ascent of magma from the mantle and its accumulation at the lower crust-mantle discontinuity, producing the recorded seismicity and surface deformation in only 20 days, a short period of time since the subaerial age of this oceanic island is estimated at 1.12 Ma.

S01.13 Poster

Variations in Hydrothermal Systems due to a Shallow Magmatic Source Detected by Gravity Changes at Cotopaxi volcano, Ecuador

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Cotopaxi, a stratovolcano 50 km south of Quito (Ecuador), reactivated in April 2015 after 135 years of quiescence. Monitoring data collected by the Instituto Geofísico showed an increase in the daily number of seismic events, SO_2 emission and inflation on the flanks of the volcano. The unrest peaked on August 14 with phreatomagmatic explosions characterized by ash plumes reaching 8 km above the summit. Ash emissions lasted until November 2015, affecting the lower flanks of the volcano and causing distress to the local population. Volcanic activity decreased steadily after January 2016, and monitored parameters returned to background levels by April 2016.

Time-lapse gravity measurements at Cotopaxi were undertaken between June 2015 and April 2016, and were repeated bi-monthly at 8 stations located on the flanks of the volcano. All stations were below the known location of the hydrothermal system. Relative gravity changes were observed before and after the August 2015 eruption, with a maximum gravity increase of 30 μGal before the eruption, followed by a decrease of 70 μGal from October 2015 to March 2016. Mass increase in a shallow cylinder-like source, a simple approximation of the complex geometry of the hydrothermal system, can explain the gravity decrease observed from October 2015 to March 2016. A volume of 2 x 109 m^3 of water is needed in order to explain the observed changes, however such a volume cannot be obtained purely from precipitation. Additional recharge of the hydrothermal system (e.g., by migration of fluids) is needed. Petrologic analysis of the ash showed direct interaction of a magmatic source with the hydrothermal system. Based on the link between the petrology and hydrothermal system, we propose that observed changes in gravity data are due to mass changes and upward fluid migration of an expanding hydrothermal system at Cotopaxi.

S01.13 Talk

Preemptive geodetic response at volcanoes in a state of quietness: the cases of the Quill and Mt. Scenery in the Carribean Netherlands

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The Lesser volcanic arc in the Caribbean is the surface expression of the subduction of the South-American Plate under the Caribbean Plate. The arc is home to some of the deadliest volcanic eruptions in historic times. The 1902 eruption of Mount Pelée on Martinique destroyed the city of St. Pierre killing around 29.000 people. All seventeen volcanoes of the arc are potentially capable of similar explosive eruptions. Some of these volcanoes exhibit clear signs of unrest and are therefore thoroughly observed, others are more quiet and sparsely monitored. We argue that a preemptive geodetic response at volcanoes in a state of quietness is an essential part of volcano monitoring which will contribute to a timely warning in case of a crisis.

The volcanoes of the Quill on St. Eustatius and Mt. Scenery on Saba are part of the Lesser volcanic arc. Even though the last eruption likely occurred several hundred years ago, these volcanoes need to be monitored to be able to observe the onset of renewed activity. However, "tuning" a network is difficult without prior knowledge of past eruptions. Monitoring efforts started in 2006 with the installation of two broadband seismometers and currently the seismic network comprises three broadband seismometers on each island. In 2018 the monitoring network was expanded with one continuous Global Navigation Satellite System (GNSS) station on each island. Before installation much time and effort went into verifying the optimal location with respect to the volcano, the condition of the site itself, the infrastructure for real-time data transmission, the monument design and the logistic feasibility. Overall, to sustain the monitoring network, in tropical island conditions, remains a challenge well worth the effort to help ensure the safety of the local population.

S01.13 Poster

Global satellite observations of magmatic and volcanic deformation: implications for volcano monitoring, volcanic landscapes and the lateral extent of magmatic domains

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Global Synthetic Aperture Radar (SAR) measurements made over the past decades have captured a broad range of volcanic processes and provide baseline information about volcanic deformation critical for monitoring. There remain challenges to using SAR measurements routinely, which we quantify from two global datasets of volcano deformation: the Smithsonian Institution Volcanoes of the World database and the Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics volcano deformation catalogue. We find that a higher proportion of satellite observations capture non-magmatic processes than those from ground-based instrument networks, and that both transient (< month) and long-duration (> 5 years) deformation episodes are under- represented. Improved spatial resolution and coverage have also resulted in the detection of previously unrecognised deformation at both ends of the spatial scale (~ 10 to > 1000 km2). ‘Baseline’ records of past satellite radar measurements, including ‘null’ results, are fundamental for any future interpretation of interferograms in terms of hazard, both by providing information about past deformation at an individual volcano, and for assessing the characteristics of deformation that are likely to be detectable (and undetectable) using InSAR.

Global datasets also provide insights into the characteristics of volcanic landform development and of magma storage zones. The areas spanned by magmatic uplift signals overlap in range with mature landforms caused by intrusive and extrusive processes, but are unique in capturing a geologically brief stage in their development. The relationship between deformation signal location and associated volcanic edifice also provides information about the extent of active magmatic domains. 24% of all potentially magmatic events are located ≥5 km away from the nearest active volcanic vent. This suggests that laterally extensive active magmatic domains are not exceptional, but can comprise the shallowest part of trans-crustal magmatic systems in a range of volcanic settings.

Volcano deformation monitoring via DInSAR processing in Argentina

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Copahue Volcano is located in the Province of Neuquén on the international border with Chile at 37.5°S, 71.1°W. More than 12 historical eruptions were recorded in the last 250 years, being the most recent ones on 1992, 1995, 2000, 2012 and 2015 until the present. The near villages of Caviahue and Copahue within 10km from the crater, increase risk level of this volcano. The active crater host an acidic hot lake with temperatures up to 60°.

Tupungatito volcano is located at the Argentina-Chile border at 33.425°S, 69.797°W. Its last eruptions were in 1980, 1986 and 1987 with VEI2. San José volcano is a 5856-m-high stratovolcano of Pleistocene-Holocene age located at 33.789°S and 69.895°W. Both volcanoes are near to large cities such as Santiago de Chile, with over 7 million and Mendoza, in Argentina, with roughly a million inhabitants.

Maipo volcano is located at 34.164°S and 69.832°W. It rises about 1900 m above the caldera floor and was constructed by strombolian-vulcanian explosions. Last eruptions took place in 1826 and 1912 with VEI2. It is located near the cities of Rancagua in Chile and Pareditas in Argentina (240.000 inhabitants).

Copahue, Tupungatito, San José and Maipo are among the riskier volcanoes in Argentina, according to the Argentine Observatory of Volcanic Surveillance (OAVV). OAVV is deploying new monitoring networks around this volcanoes including IP, seismometers, accelerometers, GNNS, tiltmeters and gas remote sensing equipment. Furthermore, we are carrying out DInSAR based processing aimed to detect surface deformation.

In this work, we present the SBAS-DInSAR results over the four cited volcanoes covering the timespan between 2015 and 2018. ALOS2 ScanSAR and Sentinel-1A/B scenes were processed showing no significant deformation in the northern volcanoes. Copahue is in a period of relative quiescence after being inflating at a mean rate of 12-16 cm/year between 2011 and 2016.

S01.13 Poster

CGPS Network to detect ground deformations in the Albani Hills Volcanic complex

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The Colli Albani volcanic complex is located in Central Italy, about 15 km SE of Rome, in an area belonging to the potassic and ultrapotassic Roman Magmatic Province. The volcanic activity started about 561 ka and ending with the most recent and voluminous activity of the Albano maar (<70 ka). Recurrent seismic activity (Amato e Chiarabba, 1995, Feuillet et al., 2004), temperature and water composition variations (Carapezza et al., 2008) gas emissions, significant ground deformations detected by vertical displacements from high precision leveling, InSAR and GPS time series (Salvi et al., 2004; Riguzzi et al., 2012; Marra et al., 2016; Trasatti et al., 2018) indicate that the volcano cannot considered as completely extinguished.

Although, the area was surveyed by a discrete GPS network since early 1990, the behavior of the Volcano and the intense human and industrial activity present in the area, suggested an intense geodetic monitoring upgrading, since 2007, a first set of 3 GPS vertices belonging to discrete GPS network onto 2 continuous GPS stations (CGPS).

Actually the network consists of seven CGPS stations located on the volcano upgrading 2 discrete GPS vertices (MARN, ROPR) and installing 2 more new CGPS stations (ALPA, LARN) connected by LAN or UMTS router to the RING server (http://ring.gm.ingv.it).

The development and densification of CGPS permanent stations in the Colli Albani, in particular the extension of the RING network to this area, offers the opportunity to refer the local motion of the volcano in a regional tectonic context.

The horizontal and vertical GPS velocities are compared with recent InSAR results consisting in ground mean velocity maps and the relative displacement time series retrieved considering different sensors for different acquisition intervals. In this way, we could better constrain ~15 years of Colli Albani displacement history.

Near real time spatial and temporal filter in order to improve GNSS time series for volcano monitoring: application to Canary Islands (Spain)

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The GNSS is more and more used every day in order to control surface deformation in volcanic areas. The number of permanent GNSS station for this end has increase in recent years and now there is coordinates time series long enough to apply different analysis and filters that allow us to improve the GNSS coordinates results.

With this aim we have processed data from GNSS permanent stations used by the Spanish Instituto Geográfico Nacional (IGN) for volcano monitoring in Canary Islands to obtained time series by double difference processing method with Bernese. We have identified the characteristics of these time series in order to used two kinds of filters to improve them. The first, a spatial filter, has been computed using the series of residuals of all stations in the Canary Islands without an anomalous behaviour after removing a linear trend. The second filter takes account of the temporal correlation in the coordinate time series for each station individually.

This methodology has been proven with the GNSS data network in El Hierro (Canary Island) during the 2011-2012 eruption and the subsequent magmatic intrusions (2012-2014). The results show that in the new series it is easier to detect anomalous behaviours in the coordinates, so they are most useful to detect crustal deformations in volcano monitoring. Therefore, we have applied this methodology to the daily results in near real time when it is possible. The spatial filter can be used in real time to all sets of coordinates of a permanent station since the first day it has been installed. However, the temporal filter needs a long time series and it can be applied when the time series least at least four years.

Anomalous coordinates in GNSS time series: real volcano deformation or meteorological effects?

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Although GNSS is a very useful tool to monitor surface deformations in volcanic areas, their results are affected by meteorological effects that can be misunderstood and can be even confused with real deformation. Furthermore, most volcanoes are made up by large edifices where GNSS data are even more affected by wind, ice and/or snow and the anomalous behaviour in coordinates time series is more frequent and with greater magnitudes. It is also especially important to confirm if a deformation is real or not for real time volcano monitoring applications.

GNSS permanent stations results have been obtained by the Spanish Instituto Geográfico Nacional (IGN) in Canary Islands with different processing methodologies and software in order to identify the meteorological effects in GNSS coordinates time series and try to evaluate these phenomena. We have focus on Teide volcano (Tenerife Island) where some stations have shown these anomalous jumps in coordinate time series, that in near-real-time looks like real surface deformation but it can be proved later it was a spurious deformation. Methods of discrimination between real deformation or strange behaviours in coordinates have been studied for real time results.

Volcano-tectonic deformation in the Kivu Region, Central Africa, observed by continuous GNSS observations of the Kivu Geodetic Network (KivuGNet) and InSAR time series analysis

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The Kivu Region in Central Africa is a part of the western branch of the East African Rift, where the Nubia plate and Victoria plates are diverging by approximately 2-3 mm/yr. Located at the plate boundary are two neighbouring and frequently active volcanoes: Nyamulagira, an actively forming shield volcano, and Nyiragongo, known for its persistent large lava lake. Nyiragongo borders the city of Goma (> 1 million inhabitants including surrounding settlements), which has been overrun by lava flows and undercut by dike injections, last in 2002.

Since 2009 the KivuGNet (Kivu Geodetic Network), comprised of now 16 continuously operating GNSS stations, has been monitoring crustal deformation in the area. Plate motion is superimposed by deformation from the 2010 and 2011-2012 eruptions of Nyamulagira, and a Mw5.8 earthquake weste of Lake Kivu in August 2015. Importantly, KivuGNet also shows an ongoing deformation signal, which is most readily explained by long-term magma accumulation under the volcanic region. We use the GNSS and InSAR time series analysis (MSBAS) of the deformation signals to constrain and compare source parameters of simplistic elastic models for the different time periods. Although not well constrained, the data indicate the presence a ~10 km deep magmatic source centered approximately under Nyamulagira or to the southeast of Nyamulagira, that inflates between eruptions and deflates during the recent eruptions of Nyamulagira. Both the 2011-12 co-eruptive and inter-eruptive deformation fields show a horizontal asymmetry which may be modelled as an ellipsoidal-shaped source striking roughly along the Nyamulagira-Nyiragongo "transform" zone. The total volume changes of these deeper parts of the magmatic system are uncertain and highly dependent on the depth of the source, however, given that the inflation and deflation sources are the same, the source has (in 2017) recaptured less than half of the deflation that occurred during the 2011-2012 eruption.

Investigating asymmetric surface deformation at Tungurahua volcano, Ecuador

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Tungurahua volcano, a steep stratovolcano in the Eastern Cordillera of the Ecuadorian Andes, has been persistently active since 1999 and has previously experienced catastrophic flank failures. The most recent collapse occurred ~3000 years ago and resulted in loss of the western flank. This flank has since built up to its current extent with steep slopes of 30 – 35°. During the ongoing post-1999 eruptive activity, the volcano has undergone significant surface deformation, with the highest rates contained within the amphitheatre-shaped scar from the 3000-year-old failure of the western flank. A dipping magmatic source has been inferred as the likely cause from analytical half-space models that assume a homogenous subsurface. Here we present a range of models using the Finite Element Method to examine a dipping deformation source and other possible causes of the asymmetric deformation, including asymmetric subsurface material properties, surface topography effects, and shear stress along a fracture. Our models are informed by InSAR measurements of the deformation episode in October/November 2015, which show a maximum displacement of ~3.5 cm over a period of ~4 weeks. Vertical uplift and negligible westward motion indicate a shear-stress/fault-slip mechanism is unlikely, while asymmetric flank material properties and topographical effects cannot explain the full magnitude and spatial footprint of the observed west flank deformation. Consequently, asymmetric deformation is likely to be caused by an asymmetric or inclined deformation source. Analysis of the models and the different physical mechanisms that drive asymmetric or inclined deformation sources will have different implications for future potential flank collapse hazard and magma ascent mechanics. Data was sourced from the CEOS Volcano Pilot and GEO Supersites projects.

S01.13 Poster

Monitoring seafloor deformation at Campi Flegrei

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About half of the Campi Flegrei caldera is submerged by the sea forming the Gulf of Pozzuoli. Over the last 15ka, the caldera produced tens of eruptions from monogenic vents located on land, but there is no evidence of recent eruptive vents located under the sea. The caldera is subject to ground uplift generally associated with earthquakes and swarms and of seismically quiet subsidence. Between 1970 and 1984, the Campi Flegrei area showed a cumulative uplift of more than 3m in the center of the caldera, near the city of Pozzuoli. Although instrumental measurements have been performed since the beginning of the last century, no measurements were available until 2008 for the submarine part of the caldera. In 2008, a first step was taken to extend the monitoring network in the submarine sector of the Campi Flegrei with the CUMAS marine platform (Cabled Underwater Multidisciplinary Acquisition System) deployed at a depth of about 100m in the Gulf of Pozzuoli. Since 2016 the monitoring infrastructure, named MEDUSA, consists of four fixed buoys with GPS receivers; each buoy is connected by cable to a seafloor multisensor module, equipped with autonomous power supply and real-time wireless data transmission. Here, we present an assessment of vertical seafloor deformation obtained from GPS and bottom pressure recorder (BPR) data, acquired over the period April 2016 to July 2017 by the new marine infrastructure. The measured maximum vertical uplift of the seafloor is about 4.2cm. The MEDUSA data were then compared to the expected vertical displacement in the marine sector according to a Mogi model point source computed using only GPS land measurements. The results show that, for this period, a single point source model of deformation is able to explain both the GPS land and seafloor data.

S01.13 Poster

Local ground deformation observed with the 2018 eruption at Kusats-Shirane volcano

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Kusatsu-Shirane volcano is a stratovolcano consisting of pyroclastic cones such as Shirane, Ainomine, and Motoshirane. The volcanic activities of Kusatsu-Shirane volcano occurred concentrating around the Yugama on the Shirane in the historical era. On January 23, 2018, a phreatic eruption occurred near the Kagamiike crater on Motoshirane. According to this eruption ground deformation was observed at the GNSS station which installed by Japan Meteorological Agency (JMA). In this study, we examine the characteristics of this ground deformation data and estimate the dynamics of this eruption.

The eruption occurred around 10:02 on January 23 (JST). New craters were formed on the north side of Motoshirane. The Ainomine South-East GNSS observation station was installed about 400 m north from the new craters. We examine the ground deformation data of this GNSS station of 30 s sampling by the kinematic analysis using the RTKLIB (Takasu, 2014). As a result, it was revealed that the displacements were about 15 cm in the north direction and about 7 cm in the upward direction before the onset of the eruption, respectively. These displacements exponentially mitigated in the opposite direction after the eruption. On the other hand, the obvious displacements were not observed on GNSS data at Aobayama West station which located about 2 km east from the new craters. These data indicate that the depth of deformation source was very shallow.

We examined the source depth of ground deformation by using the forward modeling assuming a vertical dyke just below the new craters. As a result, it was revealed that the dyke was located 1700 m above sea level to explain the ratio of upward and horizontal displacements before the eruption. The volume change of about 3 x 105 m^3 was necessary to explain the amount of the horizontal displacement at Ainomine South-East station.

Characterization of Strombolian explosions using continuous gravity measurements

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A continuous gravity experiment was conducted for a week in May 2018, with the goal of characterizing the source of inflation-deflation-inflation cycles observed on tilt time series for stations located within 1km of the summit vents of Stromboli volcano. A Scintrex CG-6 gravimeter was installed at three different locations around the summit crater of Stromboli and recorded gravity continuously at a sampling rate of 10 Hz. Each gravity site is collocated with a broadband seismometer allowing us to estimate the inertial acceleration component of the gravity signal due to ground motion. In addition, ambient temperature, barometric pressure, and wind speed are recorded locally to identify a possible correlation with the gravity changes. After correcting for the long term drift and Earth tides, the residual gravity variations are analyzed in the frequency domain using the Fourier and Continuous Wavelet Transforms. We interpret the residual gravity variations in terms of volumetric changes associated with mass transport in the upper conduit. A seismo-acoustic network consisting of 12 seismometers and 7 microphones was deployed simultaneously providing us with the timing and duration of each of the explosive events. By isolating the gravity signature of the Strombolian explosions we are able to study mass transport in the upper volcanic conduit on the timescale of ~500 seconds. Finally the estimated volumes of gas input to the system can be compared to the volatile budget estimated from gas measurements. This gravity experiment provides important results towards the identification of precursory gravity changes prior to volcanic explosive events and to test the future use of continuous gravity to monitor volcanoes in real time.

S01.13 Poster

The Kīlauea 2018 eruption: Insight from surface deformation and topographic change

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The 2018 eruption of Kīlauea Volcano represents one of its most significant sequence of events in several decades. At the time of this writing, the eruption is ongoing with summit explosive eruptions and fissure eruptions in the lower East Rift Zone (LERZ). We present preliminary analysis of surface deformation and surface topography change data from a number of instruments. Interferometric synthetic aperture radar (InSAR) surface deformation data are from: the Canadian Space Agency’s RADARSAT-2, the European Space Agency’s Sentinel-1A/B, the Italian Space Agency’s COSMO-SkyMed, and the Japanese Aerospace Exploration Agency’s ALOS-2 satellites. We also include GPS and tilt data analysis from the local network. Surface topography changes are being acquired from a NASA G-III jet with the GLISTIN-A instrument: a single-pass interferometric, Ka-band, SAR. Geodetic data constrain the temporal and spatial evolution of the eruption from the initial deflation in the middle ERZ recorded by *in-situ* tilt and GPS instruments starting April 30 and InSAR-observed deflation and dike propagation east of Puʻu ʻŌʻō on May 1-2 into the LERZ toward the initial May 3 fissure eruption. The M6.9 earthquake on May 4 beneath the south flank further enriches the sequence of events while also complicating the InSAR deformation interpretation and modeling. Preliminary data reveal that the ALOS-2 InSAR are especially important in the LERZ where the fissure eruptions have occurred, while Radarsat-2 has provided important constraints on the initial pre-eruption magma movement in the middle ERZ. As the eruption has endured, Kīlauea summit deflation and eruptions have become an increasingly important part of the story. We will present preliminary source models constrained by the InSAR and GPS geodetic data to infer changes in the magma plumbing system. We will compare these source model volume change estimates with the airborne InSAR topographic change measurements of the lava flow volumes.

S01.13 Talk

Vertical ground deformation of Ioyama, Kirishima volcanoes measured by precise leveling survey (during June 2015 - May 2018)

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Ioyama of Kirishima Volcanoes is located in Ebino Kogen volcanic area, southern Kyushu, Japan. In Ioyama, volcanic earthquakes and tremor have occurred since December 2013. Since December 2015, the fumarolic gas and the expansion of the thermal anomaly area are seen around the Ioyama area. In April 2018, Ioyama erupted for the first time in 250 years.

We conducted the precise leveling survey in the Ebino Kogen volcanic area for 11 times from June 2015 to May 2018 in order to accurately measure the vertical deformation. We estimated pressure source models assuming the presence of an inflation spherical source as Mogi's model. We obtained the optimum value of the expansion amount, the horizontal position and the depth of the pressure source by the grid search method.

As a result, inflation of spherical source has been inferred 150 m east of Ioyama's fumarolic gas area, the depth about 700 m from the surface. The lower limit of low resistivity layer assumed to be the clay layer is estimated in this depth (Aizawa *et al.*, 2013). Accordingly, the estimated inflation source is located just under the impermeable clay layer, through the small crack of this clay layer, fumaroles and hot springs are jetting out to the ground. The increase of pressure source volume since June 2015 is up to $4.8 \times 10^4 m^3$ in November 2016.

In the leveling surveys between October 2017 and March 2018, a sudden uplift phenomenon up to 15.5 mm was observed. From April 2018, the fumarolic activity became very active and eruption on April 19th occurred. In this study, we found that the volume change of pressure source was fluctuating 2 or 3 month prior to the surface activity of Ioyama, and the leveling survey helps predict volcanic activities.

Deformation of the 2018 Kilauea Volcano eruption

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After weeks of slow inflation at Pu`u `Ō`ō (the site of persistent eruption in the Middle East Rift Zone (MERZ) since 1983), observers at Kīlauea Volcano, Hawaii, USA, noted a sudden increase in tilt rate at the crater. This was followed by collapse of Pu`u `Ō`ō crater. Soon afterward, tiltmeters and real-time GPS across the volcano began to show contraction of a large area of the MERZ both uprift and down-rift of Pu`u `Ō`ō. Over the next 8 hours, seismicity and geodetic data from instruments down-rift of Pu`u `Ō`ō indicated a dike propagating into the Lower East Rift Zone (LERZ). Initial events had a very subtle effect at the summit of Kīlauea, which has had an active lava lake present since 2008. By May 2, the dike had extended tens of kilometers down-rift of Pu`u `Ō`ō and an eruption began in a residential subdivision on the LERZ. Preliminary models indicate that by May 12, the dike had intruded a volume of approximately 32 million cubic meters, and continued to expand and propagate further down-rift. A M6.9 decollement earthquake occurred on May 4th with slip concentrated beneath the area south of the intrusion. There was very little immediate deflation at the summit reservoir, but this accelerated following the M6.9 earthquake. The summit area has since been subsiding consistently, and rapidly, at about 10 cm/day, with substantial earthquake activity within the caldera, and dropping of the summit lava lake more than 600 meters, to below the estimated level of the water table, and beyond visibility. Small explosions thought to result from conduit wall rock collapses generated ash plumes increasing in intensity and frequency. The largest plume to-date on May 17 exceeded 7 km (20,000 ft). Eruptive events both at the LERZ and the summit are still evolving as of this writing.

S01.13 Poster

2010 - 2017 Geodetic Monitoring of Nevado del Ruiz, Colombia

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In this work, we present the results from 8 years of geodetic monitoring of Nevado del Ruiz using continuous GPS (CGPS). Ruiz volcano is part of a 600-km-chain of volcanoes aligned N-S along the Colombian Central Cordillera. The volcano is monitored by seismological, geochemical and geodetic networks run by the Colombian Geological Survey. There is a clear need to use this information to serve the communities living around the volcano: forecasting future activity to prevent disasters like the destruction in November 1985 of the nearby city of Armero by lahars.

After nearly two decades of background activity between 1994 and 2010, in early 2012 significant inflation occurred with an increase in seismicity, release of SO2, and ash emissions. The initial phase of unrest culminated with two small explosive eruptions in May and June 2012. Deformation of Nevado del Ruiz has been monitored since 1985 and the geodetic network now includes tiltmeters (since 2007) and CGPS stations (since 2011). Our interpretation of models of tilt recorded between 2007 and of 2011 suggested that a small volume of magma (~0.005 km3) migrated to shallower depth (~1.5 km beneath the crater). The 2010-17-time series of GPS components indicate that inflation started in 2012 and stopped in early 2017 when the volcano returned to a phase of low level activity. We invert the GPS deformation velocities from 2012 to 2017 to estimate the parameters of the deformation source: a spheroid at a depth of 19 km beneath the crater (~14 km b.s.l.), with geodetic volume ~0.3 km3, and located ~7 km SW from the crater of Ruiz, between Nevado del Ruiz and Nevado de Santa Isabel volcanoes. Our results are confirmed by quantitative comparison with InSAR data (Lundgren et al., 2015).

S01.13 Talk

The re-awakening of Öræfajökull volcano, Iceland - determining the cause of unrest at a previously quiescent, under- monitored volcano

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In June 2017, Öræfajökull volcano entered a phase of increased activity. This was characterized by elevated seismicity, followed by heightened geothermal activity, gas emissions, and small-scale inflation. In November 2017, the aviation colour code at this volcano was raised to yellow, indicating an increased risk to aviation in the event of an eruption at this previously quiescent volcano.

Öræfajökull is potentially one of the most hazardous volcanoes in Iceland, capable of producing large ash-rich eruptions. These may trigger devastating pyroclastic flows and jökulhlaups. There have been two reported eruptions at this ice-covered stratovolcano in the last 1000 years. The 1362 eruption was a major Plinian event, inundating nearby areas with pyroclastic flows, tephra fallout, ballistic ejecta and jökulhlaups. The 1727 eruption was a smaller flank eruption with a VEI of 3-4, but nonetheless produced damaging earthquakes, tephra fallout and jökulhlaups.

Since the late 1990s the volcano has been rather quiet. Consequently, Öræfajökull was not the focus of an extensive monitoring network. Prior to the onset of unrest in 2017, a limited number of SAR images were available for analysis and only three campaign GPS surveys had been undertaken in this region (in 1996, 2003 and 2005). The closest cGPS stations were over 11 km from the caldera and there was a gap in the seismic network. With the recent unrest, the monitoring network in this area has been significantly improved, including the addition of cGPS and seismic stations, gas and hydrological sensors and the re-tasking of COSMO-SkyMED satellites providing frequent SAR acquisitions over the volcano.

This presentation will provide an update on the current status at Öræfajökull, based on joint interpretation of ground deformation observations, seismicity, gas and hydrological observations. It will also address the problems associated with decision-making and determining the cause of unrest at a newly reawakened volcano.

S01.13 Talk

The anatomy, structural dynamics, and related volcanic hazards of Piton de la Fournaise volcano, La Réunion: Lessons learned from ground- and space-based geodetic measurements

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Like many active basaltic ocean island volcanoes, Piton de la Fournaise (La Réunion, France) can be roughly described as a large and heavy pile of poorly consolidated materials that is still growing endogenously from intrusions and/or exogenously through the emplacement of eruption deposits. The edifice's growth is accompanied by processes of internal structural adjustments that result in measurable surface deformation and/or (sometimes catastrophic) topographic changes. The volcano observatory's geodetic network is employed to collect precise, as well as spatially and temporally dense information on the changing shapes of the volcano in order to facilitate the reconstruction of the volcano's edifice anatomy and inner structural dynamics, as well as to enable eruption forecasting and the assessment of volcanic hazards.

We review what complementary geodetic measurements taught us about the anatomy and structural dynamics of Piton de la Fournaise. We highlight the advantages of integrating multiple data and techniques, including the continuous and real-time deformation data collected by the network of 24 permanent GNSS stations, and spatially dense SAR satellite data, which are routinely acquired since 2003 in the framework of the OI2/SNOV/INSU Observation Service. We focus on the volcano's edifice stability and the use of InSAR time series techniques to investigate the sliding eastern flank of the volcano, which poses a potential hazard to the coastal areas around the Indian Ocean should it (again) catastrophically collapse. While emphasizing the contribution of geodesy to our picture of the Piton de la Fournaise architecture, we also collect some of the most fundamental remaining questions and summarize the limitations and challenges that preclude current geodetic techniques from providing answers.

S01.13 Talk

Resolving the complex co-eruptive 3-D displacement field at Ambrym Volcano using SAR data

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Ambrym is located in the SW Pacific archipelago of Vanuatu, and currently hosts two active lava lakes, Benbow and Marum. On February 21, 2015, an effusive eruption began at Ambrym, the first effusive event since 1989. It lasted 44 hours, erupting a total volume of ~4.8 Mm3.

We processed synthetic aperture radar (SAR) images, acquired on ascending and descending passes, from the Japanese Space Agency's ALOS-2 satellite, to measure co- eruptive ground displacement. Using InSAR, SAR correlation, and Multiple Aperture Inteferometry (MAI), we compute the full 3-D displacement field associated with the eruption. The co-eruptive displacement field is asymmetric, oriented around a dike that extends radially from between the two lava lakes. There is more than a meter of uplift in the south-western portion of the caldera, and significantly less (~0.5 m) subsidence in the caldera center. Horizontal displacements are also substantially asymmetric.
Using a generalized least-square's inversion to solve for distributed opening and slip, we found that the co-eruptive displacement field is dominated by a dipping dike which feeds the lava flow, as well as a normal fault along the NW caldera rim. The WNW-ESE trending dike begins as a horizontal sill at ~4 km depth, and the dip progressively increases until intersecting the surface with a ~65° inclination.

In addition to co-eruptive displacement, using the C-band SAR satellites Envisat and Sentinel-1, we have also identified two separate time periods during which Ambrym's caldera notably subsided (2004-2009 and 2015-2018, ~9 cm per year). We explore different pressure source geometries and sizes to find the best-fitting model, and discuss the possible physical processes driving this subsidence. Finally, using these models, together with the results derived from the co-eruptive displacement field, we outline a conceptual model of the magmatic system feeding effusive eruptions and the volcano’s semi-permanent lava lakes.

Basaltic Magma Propagation: Insight from Inversion of InSAR and GNSS data of the May 2016 Piton de la Fournaise eruption

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Magma stored beneath basaltic volcanoes is often transported by propagation of planar intrusions, which lead to fissural eruptions when they intersect the Earth's surface. This propagation is an unsteady process controlled by the magma-crust interaction, which generates seismicity and surface deformation before the eruption onset. To gain information into the dynamics of magma propagation we invert complementary ground deformation datasets recorded during the 8 hours preceding the May 2016 eruption onset at Piton de la Fournaise volcano (La Réunion, France). We combine SAR interferograms ensuring good spatial resolution and continuous GNSS data providing high temporal resolution. We use 3- D boundary element models combined with a Monte Carlo inversion method. We first retrieve the final geometry of the intrusion based on four interferograms, both ascending and descending paths, spanning the whole propagation phase. The imaged intrusion consists in a 2700 m long sill located at an elevation of 800 m, connected to the eruptive fissure by a 880m sub-vertical dike. We invert the continuous GNSS data performing a succession of independent inversions with a 5min time step in order to localize the pressurized area of the geometry previously retrieved from InSAR data. We take advantage of one Sentinel--1 image acquired during the propagation phase to compare inversion results from GNSS and InSAR data. We show that the a priori knowledge brought by the InSAR data helps to estimate the intrusion depth otherwise poorly constrained. Our temporal inversion provides insights into the dynamics of the propagation. We evidence that the horizontal part of the intrusion opens a few tens of minutes after the beginning of the crisis. The intrusion is then stalled for 4h, while the pressure increases, until the last part of the intrusion propagates vertically to feed the eruption. These observations might indicate the presence of barriers to propagation.

The magma discharge process of a magma chamber associated with the eruptions of Shinmoe-dake volcano, Japan, in 2011 and 2018 estimated from tiltmeters

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Shinmoe-dake is a volcano in the Kirishima-yama volcanic group located in the southern part of Kyushu Island, Japan. A magmatic eruption occurred there in 2011, followed by another one in March 2018. NIED's borehole-type tiltmeters revealed a magma discharge process of the magma chamber associated with the eruptions with high temporal resolution. The temporal change of the contraction rate of the magma chamber had a high correlation with the intensities of the eruptions. In the 2011 eruption, lava flowed out to the crater after intermittent occurrences of three sub-plinian eruptions at about 12-hour intervals. The tiltmeters observed three sharp rises in the contraction rate and gentle contraction of the magma chamber. During the 2018 eruption, no sub-plinian eruption occurred, and the lava flowed out to the crater over about three days. The time when the contraction rate reached its maximum coincided with the time when the intensity of the eruption was maximized. Although the eruptions of 2011 and 2018 were of different types, the total contraction volume within 40 hours was the same after the magmatic eruptions began. This indicates that the magma flowed in the conduit from overpressure of the magma chamber, the former intermittently and the latter continuously. It is suggested that the difference in the frictional properties between magma and the wall of the conduit changed the magma flow and produced the difference in type and intensity of the eruptions. The magma discharge process estimated with high temporal resolution is very important in understanding the process controlling the transition of eruption activity.

Satellite Geodesy Captures Offset Magma Supply Associated with Lava Lake Appearance at Masaya Volcano, Nicaragua

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Ascending and descending Interferometric Synthetic Aperture Radar (InSAR) datasets from various satellites (COSMO-SkyMed, RADARSAT-2, ALOS-2, and Sentinel-1) show a maximum of ~8 cm ground inflation in Masaya caldera over a 15-month period (6 November 2015 to 1 September 2016). The center of inflation is located in the NW part of the caldera, north of the active Santiago vent which has hosted a new lava lake since 11 December 2015. Simultaneous inversions of those InSAR geodetic datasets using a neighbourhood algorithm demonstrate that a spherical magma reservoir explains the geodetic data, with a horizontal location ~3 km north of the active Santiago vent and a depth-to-center of ~3 km. The associated modeled volume increase (~0.0042 km3) is lower than the "excess" magma volume inferred from gas measurements from November 2015 to February 2016. The magma reservoir offset from the current center of eruptive activity may be the result of pre- existing caldera structures.

S01.13 Poster

Low-cost GNSS as a tool for near real- time monitoring of volcanic surface deformation using bespoke geodetic networks

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The proliferation of low-cost Global Navigation Satellite System (GNSS) receivers with sub- decimetre precision has occurred as a critical component of autonomous vehicle development and preparedness for mass-market. This hardware revolution provides geodesists with the opportunity to deploy GNSS receivers at low-cost, as bespoke, semi- permanent, long-duration networks to discern surface deformation at high temporal resolution in support of specific science cases. In parallel, the revolution of the Internet-of- Things and continued reduction in data transfer costs through GSM networks makes it possible to stream GNSS data from deployment locations in near real-time at low cost. The upshot is a feasible replication of much of the functionality of top of the range GNSS receivers used as Continuously Operating Reference Stations (CORS) at relatively low-cost, with some reduction in accuracy and precision. We see the use of low-cost GNSS as a complimentary geodetic approach to the use of CORS networks and campaign surveys. Low- cost hardware is advantageous as it can be deployed to operate continually in locations where it would be impractical to use expensive ‘off the shelf’ solutions, such as where equipment is likely to be destroyed, or where it may perilous to manually retrieve hardware and recorded data. The cost reduction of low-cost GNSS hardware means denser networks of receivers can be deployed at specific budgets, maximising spatial coverage and resolution to help better characterise underlying processes. We present examples of the use of low- cost GNSS to measure deformation during the 2016 Central Italy seismic sequence and following the 2016 Kaikoura earthquake. We will discuss specific relevance to volcanic deformation using developments of a volcano-specific deployment.

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S01.14 - Volcano geology and field observations aimed at validation of numerical models

Historical activity at Volcán de Colima, Mexico: stratigraphic observations of pulsating eruptions

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Volcán de Colima is located in the western Trans-Mexican Volcanic Belt. The highly active stratovolcano has fluctuated between the effusive activity, involving cycles of lava dome growth and destruction by moderate vulcanian explosions, towards more hazardous sub- plinian to plinian eruptions. The last of these occurred in 1818 and 1913. The magmatic conditions which drive these eruptive cycles are not well understood and, given the threat the volcano poses to the surrounding population, research aims to address this incomplete understanding. This study focuses on the petrology, Holocene stratigraphy and magma genesis at Volcán de Colima.

During a field season to the west of Mexico in early 2018, lava and tephra samples from Volcán de Colima were collected, related to various stages of the volcano's eruptive cycles. The trip also provided an opportunity to confirm existing studies on the Holocene stratigraphic tephra record, which is well preserved to the north/northeast of the active vent on the slopes of the extinct Nevado de Colima edifice (Luhr *et al.,* 2010: *JVGR*; Crummy *et al.,* 2014: *J. Pet.*). At one locality, two red pumice units were observed to be almost identical in appearance separated by an ash layer. These inferred cyclical fall deposits contain moderately vesiculated pumice with a large proportion of lithic fragments. This has been interpreted to represent particularly explosive pulses of an eruption, with the lithic component attributed to opening and excavation of Volcán de Colima's vent.

These samples are being prepared for chemical and mineralogical analysis at the NHM to identify pre- and syn-eruptive magmatic processes occurring in the magma chamber. The timescales in which these magmatic processes occur will be constrained via element diffusion modelling of plagioclase and pyroxene phenocrysts from the samples. Data collected will help to reconstruct models of the plumbing system of Volcán de Colima with time.

S01.14 Poster

Lesson from pyroclastic density currents at Mt Etna volcano, Italy: the 11 February 2014 event

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On 11 February 2014, the seismic and infrasonic stations of the INGV surveillance network recorded the collapse of the lower portion of the New Southeast Crater (NSEC), at Mt Etna, producing a pyroclastic density current (PDC). Until then, only small–volume PDCs had been observed over the past 30 years, and not always properly documented. The 11 February PDC was, however, the most impressive since it travelled about 2.3 km on the eastern flank at an average speed of more than 40 m/s. During its emplacement, it formed a hot (up to 750 °C) dense flow accompanied by a relatively hot cloud of fine ash that dispersed over a wider area. The cone collapse and consequent PDC event have drawn the attention of the scientific community and national civil protection authorities toward this type of phenomenon, ultimately promoting the detailed study of deposits to gain insights into possible triggers and flow dynamics.

A field survey allowed mapping the PDC deposits, describing four stratigraphic units, and collecting samples for textural, component and petrographic analyses. The results in terms of grain-size of the different units, component and morphological analyses of lapilli- to bomb-sized fragments, shape parameters and textures at the micron-scale of ash particles, are pieces of a unique mosaic which constrain, describe and explain well the eruptive processes acting during the NSEC collapse and producing the studied deposits. These processes consisted mainly of thermal and mechanical weakening of the cone, gravitational instability, turbulent and fluidized flow mechanisms, abrasion and comminution of particles. Our data may set the basis for modelling crater collapse and be used to simulate the relative PDC events, including their propagation around the summit and even as far as the inhabited centers of the volcano, thereby contributing to assessing the potential hazard from PDCs at Etna.

Monitoring the December 16th 2013 Etna eruption by an Elastic/Raman lidar system

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We present Lidar measurements carried out in Catania on 16 December 2013 when Mt. Etna, Italy, showed an intense Strombolian activity from the New South East Crater (NSEC). Lidar measurements were performed pointing at a thin volcanic plume that was dispersed from the summit craters toward the South East direction. We measured the aerosol backscattering (βA) and the extinction coefficient (αA) profiles at 355 nm, and their ratio (the Lidar Ratio - LR) using an Elastic/Raman lidar system. Moreover, calibrated particle linear depolarization values (δA) were obtained from the lidar profiles measured in the parallel and perpendicular polarized channels at 355nm. The βA, LR and δA values were used to estimate the ash concentration in the volcanic plume at altitudes between 3 and 4 km. Real-time Lidar observations allowed to capture the complex dynamics of the volcanic plume as well as to track the decrease of the explosive activity with time and the opening of the fracture developed late in the morning and located at the North East side of the NSEC. The capability of Lidar measurements to estimate important features of volcanic plumes (e.g. volcanic ash concentration) and improve and validate results from volcanic ash dispersal models is also shown.

S01.14 Poster

An investigation of the internal structure of cones from the Michoacán-Guanajuato Volcanic Field, México

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The understanding of magma transport at shallow levels in monogenetic volcanic fields is key to identify the factors that controlled the actual location of volcanic edifices as means to get insight into the formation and localization of future eruptive vents. The latter remains as one of the most important challenges in volcanology considering that thousands of urban and rural communities worldwide are settled in monogenetic volcanic fields. Such is the case of the Michoacán-Guanajuato Volcanic Field (MGVF) with more than 1200 eruptive vents originated in the last 5 Ma covering an area where 69% corresponds to urban territory and 31% to active rural lands. The internal structure of volcanic edifices in monogenetic fields are constituted by feeder dikes, sills and arrested dikes that form complex geometrical configurations influenced by the structure and mechanical properties of the host rock. Unfortunately, it is rarely possible to observe any detail of the internal structure of cones overall in relatively young volcanic fields where the erosive processes have not yet removed enough materials. However, due to the extensive activities of extraction of materials from quarries in the MGVF this exceptional opportunity to study internal structure is possible in this case. Using a combination of field and satellite-based observations, we have identified from around 147 open pits of volcanic edifices the best exposures to study their plumbing system constituted by dikes. We present the preliminary results of cross sections from dissected volcanic edifices and their related products focusing in the structure, morphology and lithology of each exposition and its relation with the fault system in the area.

S01.14 Poster

How to correctly evaluate and enhance the performance of volcanic mass flow models used for hazard assessment?

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Numerical models of volcanic mass flows (VMFs) are widely used for fundamental research, but their use for hazard assessment is having a growing importance. Because of the high impact that modeling and simulations can have, their performance needs to be properly assessed. Our procedure for testing performance of three VMF models (Titan2D, VolcFlow and FLO-2D) with geological data follows a three-step approach: (1) collect an extensive and quantitative dataset of geological observations and measurements; (2) use these data to calibrate numerical model input; and (3) use validation metrics to quantitatively compare key model output parameters (flow runout and area) against observed and mapped flow features. The ultimate goal of this three-step approach is to provide a probability of safety based on model results for hazard assessment purposes. Here, we compare areas inundated by the 2005 lahars from Panabaj (Guatemala), the 2006 and 2010 concentrated PDCs from Merapi volcano (Indonesia) and the July 2015 block-and-ash flows from Volcán de Colima (Mexico), using the Jaccard fit, model sensitivity, and model precision metrics, all related to Bayes' theorem. These metrics show that false negatives (areas inundated by the observed VMF where not simulated) and false positives (areas not inundated by the observed VMF where inundation was simulated) are reduced using a model calibrated by geological data. Specifically, detailed field measurements of flow inundation area, flow thickness, flow direction, and velocity estimates, collected after flow emplacement, were used to calibrate the input parameters for the models. Importantly, results indicate that the performance of depth-averaged mass flow models are improved through the acquisition of basic field observations and use of a number of validation metrics. The metrics offer a procedure for tuning model performance that will enhance model accuracy and make numerical models a more robust tool for natural hazard reduction.

Field-based inputs for simulating ash fallout and gravity-driven flows for the new hazard map of Guagua Pichincha Volcano, Ecuador

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Guagua Pichincha Volcano (GGP) is the active eruptive center closest to Quito and is located only 12 km SW of the city center. In 1999-2001 it had moderate eruptive activity (VEI 2) with the formation of eight domes that exploded, collapsed and formed ash columns that were directed to the W-NW and eastward, depositing two cm of ash over Quito.

Due to the horseshoe shape of the GGP crater, open to the forested western flanks of the Cordillera Occidental, the trajectory of the incandescent flows has been directed mainly towards an uninhabited zone, totally opposite of urbane Quito. In the 1999-2001 eruptions pf´s traveled 11 km down valley of the crater, channelized by the Cristal and Cinto rivers. Quito citizens were mostly unaware of these events due to poor access and communications.

The young Cristal Dome has generated all GGP eruptions in the past 4000 years, and eruptions of 3700 and 1000 yBP (VEI 5) were the most notable. The 1660 AD (VEI 4) historical eruption was well-recorded in the small town of Quito, but did not have the impact of the earlier fore-mentioned events.

We are working in the western drainages to obtain ground control for modeling volcanic hazards, especially since it is still possible to observe traces of the 1999 pf's, lahars, and products of the 1660 and the 1000 yBP episode. We have found and dated well-exposed 20m high pf terraces of the 1000 yBP eruption some 22 km downstream of the current dome.

Combining field data and historical records has been essential in simulating GGP´s volcanic phenomena--pf's, secondary lahars and ash fallout corresponding to these eruptions. We are employing VolcFlow, LaharFlow, LaharZ, and Ash3D models in order to obtain a better approximation of the limits of coverage and to delimit the potentially affected areas by eruptive phenomena.

S01.14 Poster

Dynamic analysis of ash aggregates revealed through HS-HR imaging at Sakurajima volcano (Japan)

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Ash aggregation processes during explosive eruptions can effectively influence volcanic plume dispersal and ash sedimentation. Recently, dedicated experiments have been carried out and numerical models have been developed in order to produce reliable forecasting of the ash dispersals. However, including ash aggregation processes in numerical simulations is to date a problematic task for volcanologists, because of the lack of solid field-based datasets required to scale, validate and calibrate models. A field-based dynamical investigation of ash aggregates collected at Sakurajima (Japan) with a High-Speed, High- Resolution camera is here presented. Three main types of ash aggregates are recognized to occur into all the examined samples (Single Particles, Coated Particles, Cored Clusters). Using image analysis techniques, clusters were characterized in terms of average dimension, grain size and shape features of the aggregating ash, pointing out important differences between the different cluster types. Dynamical analysis of falling aggregates allowed a significant set of measurements of terminal velocity, bulk density, and size of a large number of observed falling aggregates to be collected. The resulting data reveal the strong influence of aggregation processes in controlling ash deposition processes at Sakurajima.

S01.14 Poster

What Lies Beneath: Using Shallow (<500m) Drilling Information to Increase Our Understanding of Volcanic Hazards in Auckland

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The New Zealand Geotechnical Database (NZGD) is an online database designed to capture drill core information from across New Zealand. Although the database was originally created to facilitate data sharing between geotechnical consultancies, access to the dataset has allowed scientists to make unique discoveries, particularly in relation to the Auckland Volcanic Field (AVF), a monogenetic volcanic field located beneath the city of Auckland (pop. 1.5 million), New Zealand. The AVF has 52 volcanoes, but most are completely covered by the local urban environment making access to samples, determination of the distribution and volumes of tephra and lava, and the reconstruction of eruption progression extremely difficult. With new access to shallow (<500 m) drill core information obtained for geotechnical purposes, scientists have located four previously unknown volcanoes, gained useable samples from unstudied volcanoes, and are now working to create 3D models of several volcanic edifices to better constrain size and volume estimates made from LiDAR mapping. Captured drilling information has also been used to track lava flow run out and constrain geophysical models. As the database continues to grow, we anticipate that more scientific applications will become possible. For volcanic fields covered by the built environment, data from geotechnical drilling is a valuable resource that can provide much needed information in areas where surface mapping and sampling are not a possibility.

Investigating Canada's deadliest volcanic eruption: from field observations to lava flow modeling

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Tseax volcano is a monogenetic cinder cone associated with a basanite/hawaiite lava flow in Nothwest British Columbia, Canada. Tseax is the site of one of the youngest and potentially deadliest volcanic eruption in Canada; an eruption in the mid-1700s killed up to 2000 people of the Nisga'a Nation living in two villages near the volcano. A rich oral history has preserved detailed observational accounts of the eruption, however, the exact cause of the fatalities remains unclear. We aim to establish the sequence and duration of this little known yet important volcanic event.

Detailled field mapping and sampling in 2016 and 2017 in conjunction with aerial photogrammetry survey enabled the development of a high-resolution map and 3D model of the volcano and lava flow. The Tseax lava flow is 32 km-long, topographically constrained, with a volume of ~0.5 km^3 covering a surface of 40 km^2. A range of textures (e.g., blocky, rubbly, hummocky, slabby and sheet pahoehoe) typical of flood basalt surface morphologies are observed and suggest a very low viscosity and rapid expansion of the flow. Field observations correlated with petrophysical data indicate flow discharge rates in the order of 2-3 × 10^3 m/s. This suggests that the entire flow field was emplaced over 2-3 days. Preliminary numerical models using the VolcFlow code show that a large volume of low viscosity lava emitted during a short period of time could effectively reach the location of the two former Nisga'a villages at velocities reaching 10 m/s and thus be directly responsible for fatalities.

S01.14 Talk

Field observations as constraints for numerical models of lava lakes and flows

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We are living in a time of data explosion, and volcanology is no exception. The last decade have seen rapid increase in the number and kinds of instruments that monitor active and non-active volcanoes and provide observations of old and new systems. This wealth of data provides a rich set of constraints to numerical models of volcanic processes. We focus on lava flows and lava lakes, marking the effusive end of the volcanic spectrum.

Lava lakes provide a unique window into the shallow magmatic system. Theoretical models and experimental work suggested that patterns of flow observed at the surface of lakes reflect the dynamics in the conduit and constrain gas flux and magma viscosity ratios. We analyze thermal and visible imagery and produced an extensive set of measurements of lava lake circulation patterns around the world. These observations point to a relation between gas flux and lake geometry, which is not usually considered in models. We will show examples of new lake circulation models that demonstrate the importance of near-surface convection in generating surface variability, even in the absence of conduit-sourced fluctuations. These results highlight the role of numerical models in connecting surface observables to unobserved processes at depth.

Various numerical models of lava flows exist, ranging in techniques and assumptions. Field observations of pre-existing terrain, inundation area evolution, flow thickness, width and advance velocity, provide boundary conditions and tests for models. Finer-scale observations such as flow morphology, folds, roughness and inflation provide constraints on strain rates, cooling, and rheology. The importance of high-resolution topography data is thus clear. Thankfully, the popularization of new technologies, and in particular drone-based photogrammetry, makes such data accessible. We will show examples of high-resolution topography data provided constraints for lava flow models that either exist or that should be developed.

S01.14 Talk

Testing plume and ash dispersal models for highly explosive basaltic eruptions

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Basaltic volcanism is the most common form of volcanism on Earth. These eruptions can impact global and regional climate, and threaten nearby populations with ash, gas, and lava emissions. Generally, basaltic eruptions are less explosive than their silicic counterparts, however, they can produce eruptions with a wide range of styles and scales, including highly explosive eruptions with tall plumes. This was the case for the 1085 AD eruption of Sunset Crater, which produced more than 8 explosive phases with plumes up to 28 km high. Here, we model the eruption columns and ash dispersal to reproduce the well-documented deposit. We aim to test a number of plume and dispersal models against the Sunset deposits first by comparing a series of forward models against the deposit, focusing on mass loading and grain-size distribution. At this time we present a combination of PlumeMoM (plume model) and the most recent version of HYSPLIT (dispersal model). As expected, results are dependent upon the wind field, although wind fields from the region are always from the W or NW resulting in deposits roughly consistent with field observations in terms of mass loading. PlumeMOM releases particles from different heights within the plume depending on settling velocity, which, when combined with variable wind directions with height above the volcano, results in a complex deposit such that some particle sizes are preferentially distributed in directions off the main dispersal axes. We are currently processing field data in order to test the validity of these complex patterns. Future work involves using Tephra2 (dispersal/inversion model) and the combination of PlumeMoM and HYSPLIT to invert the deposit seen at Sunset Crater to better constrain the eruption parameters of the 1085 AD eruption.

S01.14 Poster

Comparing different numerical models for granular flows in volcanic areas

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The research on behaviour of volcanic granular flows is one of the main topics in present day geophysics and volcanology. The vast interest is justified by the complex nature of these currents and by their very dangerous nature that threaten communities around active volcanoes and exposed to slope instabilities. Granular flows can be defined as gravity-driven currents of solid particles in which the particle-particle interaction dominates the motion. In this category are included volcanoclastic debris flows triggered by prolonged rainfall. The aim of this work is to simulate these geophysical flows through numerical codes that numerically resolve the governing equations of the flow of granular material. For this study, we considered the following numerical codes: Titan 2D, VolcFlow and Flo2D. The numerical codes were applied to both natural and laboratory granular flows, in particular the block and ash flow of the 9th of June 2005 at Colima Volcano (Mexico), the volcaniclastic debris flows of the 5-6th May 1998 of Sarno (Italy) and some experimentally-generated granular flows with natural volcanic material carried out at University of San Luis Potosì (Mexico). The application of different numerical codes to each considered case allowed us assessing strengths and weaknesses of the different codes. For each code, we also varied the rheological descriptions available, as to evaluate the rheological model that best fits experimental measurements and field data. Finally, sensitivity analyses were carried out using the flow runout and thickness of the deposits as benchmarks.

S01.14 Poster

Reconstructing fallout dispersal and total grain-size distribution of Cretaio Tephra (150 AD) (Ischia Island, Italy) through field data analysis and numerical modelling

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The Cretaio Tephra is the highest magnitude and intensity event in the last 10 kyrs in Ischia which covered almost all the eastern sector of the island. This eruption started with a phreatomagmatic phase that produced base surges, and was followed by the formation of a pulsating violent strombolian to sub-plinian eruption column.
The aim of this work is to establish the dispersal of the fallout related to the climax phase of the eruption and characterize their physical parameters, such as magnitude and intensity.
Samples were collected in the proximal area of the buried vent, and in the island along and across the apparent dispersal axis. Grain size distributions show a bimodal trend probably due to aggregation processes of the finest particles by moisture in the plume and to the balistic component, especially in the most proximal sampling sites.
The total grain-size distribution has been estimated, after the calculation and the removal of the ballistic component, using the Voronoi tessellation method. The latter needs the definition of the zero-mass contour and the reconstruction of the prevailing wind during the eruption.
The main results, such as the estimation of the magnitude, the height of the eruptive column, and the total grain-size distribution are crucial for the volcanic hazard assessment on the Ischia island and surrounding areas.

S01.14 Poster

Vents and eruptive fractures positioning in the last 4000 years of Vesuvius activity

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Eccentric and on-fissure eruptive vents of the last 4000 years of activity of Vesuvius in the past literature was underestimated in number and frequently imprecisely positioned and aged. We produced a revision and integration of data regarding this matter, adopting a multidisciplinary approach that comprises detailed field work, the use of a GIS instrument in comparing historical maps with present morphology, the study of the historical accounts of the past eruptions and toponymical changes of these locality during times, archaeomagnetic dating of the scoria cones and lavas they emitted and the petrochemical characterisation and comparison of the deposits attributed to some historical eruptions. By means of this accurate geological and multidisciplinary work, we reconstructed the distribution of the eccentric vents positioned at the foots of the main volcanic cone (Vesuvius Gran Cono), in proximity of the Vesuvius shoreline and generating a number of lavas that resulted to be emitted during Middle age. In addition, the eruptive fractures and vents that opened during the post-1631 Vesuvius activity inside and outside the Monte Somma caldera, has been accurately repositioned on the present-day Vesuvius morphology. They cluster onto well- defined structural elements. The resulting picture is not a radial centripetal distribution, as proposed into previous literature models of Vesuvius recent activity, but confirms the strict influence of the tectonic trends, resulted to be active inside Vesuvian area, on the positioning and directions of these fractures. These new data are destined to change the uncertainty and the content of the next vent opening probability density maps and models, and have important implications on the mechanisms of the Vesuvius alimentation models.

S01.14 Poster

Insight into the CE 1600 Huaynaputina Plinian tephra, combining the re-analysis of observational datasets with recent methods for tephra dispersal modelling

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In the Central Andes, large Plinian eruptions (VEI ≥ 6) occur at a relatively high frequency: one every 2000 to 4000 years over the past 50,000 years in southern Peru. This recurring, explosive activity poses a challenge to a region hosting c. three million people. Our objective is to use the 1600 CE Huaynaputina eruption as a reference to better assess the impacts of large events in the region. With VEI 6, this is considered the largest historical eruption in South America. In the framework of the Huayruro project, we have re-examined the Plinian stage of the eruption using recent models to estimate the volume and dispersal of the tephra-fall deposit.

We reconsidered the case study in 2015–2017, revising the dataset and applying recent models to unravel to which extent these developments improved tephra studies. These studies have considerably evolved over the past decade. Sampling strategy is now standardized. New tools allow to propagate measurement errors into uncertainty of eruption source parameters. Volume estimation methods have been developed allowing thickness extrapolation to be made beyond the most distal isopach contour, thus better accounting for fine ash dispersed far away from the source. More recent methods consider thickness measurements instead of isopach data, removing the subjectivity inherently associated with hand-drawn contours. Previous studies of the Huaynaputina eruption were done in 1999-2002.

The bulk volume of pumice fallout from the Plinian stage is approximately 14–15 km^3, almost twice as the previous estimate (7–8 km^3 within the 1 cm isopach). The revised plume height estimate, 32.2 ± 2.5 km, is consistent with past studies. As a result, the Huaynaputina 1600 CE Plinian eruption lies in the upper part of the Plinian field close to the ultra-Plinian transition, making this eruption one of the largest in the past millennium.

A new strategy for the estimation of plume height from clast dispersal

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Plume height represents a critical parameter required to characterize explosive volcanic eruptions and assess the associated hazards and risks. However, a direct observation of the eruptive column is not always possible, as, for example, for ancient eruptions. In the last decades various strategies have been proposed in order to constrain this critical parameter based on field data. One of the most widely used approaches is the Carey and Sparks method, which relates fallout clast distribution to plume height and wind speed through the so called nomograms. Here we present a revised strategy for the determination of plume height from field data that accounts for key aspects of plume dynamics and particle sedimentation. Implementations include the effect of wind advection on the clast support envelope of weak and transitional plumes, a modified equation of the gravitational spreading in the umbrella cloud for distances within the plume radius (where the clast support envelope is usually defined), the effect of particle shape on particle sedimentation, the effect of different atmospheric structure at different latitudes, and three-dimensional meteorological fields from the Era-interim database as well as the real topography. This strategy has been validated with small, intermediate and high intensity eruptions (i.e. Shinmoedake 2011, Japan; Mount St Helens 1980, USA; Pinatubo 1991, Philippines). Intensity scenarios had to be introduced as the wind advection of volcanic plumes results in non-univocal relation between plume height and particle sedimentation. The new proposed model can be used not only for the determination of plume height but also for the compilation of isopleth contours and probabilistic maps describing the hazard associated with the proximal sedimentation of large clasts.

S01.14 Talk

Resistivity tomography technique for investigating Volcanic Debris Avalanche Deposits: preliminary results from northern Ecuador

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Volcanic Debris Avalanche Deposits (VDAD) are common products of catastrophic volcanic edifice collapses, which are extensive (few to tens of Km^3 and tens to hundreds of Km^2), chaotic, heterolithologic bodies characterized by mounds (hummocks) and depressions. These deposits display variable thicknesses and complex shapes that drastically change the topography of the area where they are emplaced. In many cases the analyses of VDADs are restricted to few outcrops along ravines and/or in quarries excavated in lava-dominated hummocks and rarely investigate the entire thickness of the body. Often the investigations concentrate on the superficial morphology further complicated by anthropic infrastructures, younger deposits and/or soil and vegetation cover. Recently, a VDAD underlying the city of Ibarra located within the Inter-Andean valley in northern Ecuador, was investigated with a multidisciplinary approach through detailed fieldwork along the Tahuando ravine and in some quarries and road-cuts. However, the complete geometry of the VDAD is still unknown. We set out to investigate the VDAD by in-situ geophysical techniques even in sectors where the outcrops are absent. Here we present new preliminary Electrical Resistivity Tomography (ERT) results that provide 2D images of the VDAD distribution in the subsoil. This in-situ geophysical technique is able to measure physical parameters directly or indirectly linked with the lithological, hydrological and geotechnical characteristics of the terrains related to the deposit and provides information integrated on a greater volume of the soil. To our knowledge, this is the first case where the ERT is applied for the analyses of VDAD.

S01.14 Poster

Pre-caldera lateral activity at Somma- Vesuvius

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Five pre-caldera, scoria- and spatter-cones at Somma-Vesuvius were produced by alternative pulses of Strombolian and Hawaiian activity that emplaced scoria and welded spatter fall deposits, several meters thick. These vents cover a wide azimuth around the volcano. A persistent feature throughout the exposed stratigraphy of the studied parasitic cones is the abundance of coarse, juvenile material (97–100 wt%), a feature suggesting an overall magmatic style during these eruptive episodes. Most of the observed eruptive units show an alternation of unwelded scoria and welded spatter suggesting a repeated variation of the eruptive style. A dominant Strombolian style of fragmentation, with bubble coalescent and rhythmic outbursts, emplaced thick scoriaceous succession; episodically, lava fountaining activity ejected coarse clots of magma which fell near the vent producing spatter horizons. The fragmentary nature (spatter-fed) of lava-like facies strictly associated (transitional) to less welded to agglutinated facies, as well as the plastic deformation (flattening) of spatter fragments indicate the continuous fall deposition from Hawaiian fire-fountain episodes alternated with Strombolian phases emplacing loose scoria deposits. The remnants of two cones show a continuous sequence (no breaks) of pyroclastic beds emplaced as a result of a single cone-forming eruptions. This allows us to define them “monogenetic”. Conversely, the presence of thick paleosols, reworked material, exotic tephras and deep erosional surfaces in the pyroclastic succession of the other three cones has to be regarded as clear, well developed and laterally traceable breaks in the pyroclastic sequence of these small parasitic volcanoes. In light of this, we define such edifices as the result of a polygenetic (multi-phase) evolution. These evidences indicate resumption of activity after a quite long, non-quantifiable period of quiescence. This behaviour should suggest more caution when considering the parasitic volcanoes that erupted in historical time, completely extinct.

S01.14 Poster

Validating the combined PLUME-MoM and HYSPLIT numerical models using field data from Ecuadorian volcanoes

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Volcanic fallout represents a major threat to human activities, and in order to address this source of risk, different numerical models have been developed over the past years. One of the most important goals is to obtain new tools for implementing probabilistic hazard maps useful for civil protection authorities. Ideally, such tools should represent the best compromise between an accurate modelling of the physical process and the computational speed, which requires that the process is simplified to an acceptable degree. A relevant method for evaluating the appropriateness of the approximation is to perform quantitative validation of the numerical model by comparing its results with those of recent eruption.

In this work we perform the validation of a recently developed plume model (PLUME-MoM) which has been coupled with the well-known HYSPLIT lagrangian dispersal model. Particularly, PLUME-MoM is an eulerian integral model which describes the steady-state dynamics of a plume in a 3-D coordinate system. The model is based on the method of moments, and allow to decrease computational costs by describing the pyroclastic mixture not as a discrete number of phases but as a continuous distribution of particles.

We tested the PLUME-MoM/HYSPLIT model using field data from eruptions of different scales of some Ecuadorian volcanoes, ranging from the ash emission during the long-lasting 2015 eruption of Cotopaxi to the short-lived Plinian 2002 eruption of Reventador. Validation was done a) by quantifying the degree of overlapping between areas enclosed by the same isomass line (from the actual deposit and from the model) and b) by comparing the grain sizes and mass loading measured in the field with those obtained with the model at selected locations. Results allow to discuss the most sensitive parameters of the model and its suitability for the development of probabilistic hazard maps.

Possible Subterranean Effects of Lava Flows: the Application & Verification of a Lava Flow-Subsurface Heat Transfer Model

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One primary cause of impacts from lava flows is their intrinsically high temperatures. While a lava flow is active, sustained elevated temperatures frequently cause damage to assets, including buried infrastructure. As the lava flow cools, it releases heat into the surrounding media. While several studies have focused on how the air around a lava flow dissipates heat, few studies have addressed how lava heats the ground below. A lava flow can transfer heat into the media below during two phases: a flowing phase while the lava is moving, and a cooling phase during which the lava flow is stationary. Here, we present results from laboratory experiments from the Syracuse University Lava Project and fieldwork to determine how lava flows heat the media beneath them. The laboratory experiments simulate a stationary, thin lava lobe cooling. This data serves to constrain the existing simulation model (ANSYS) of a lava flow during its cooling phase (step one). The simulation model is then scaled to thicker flows, with a second time step added to calculate the heat transfer during the flowing phase of the lava flow. These two time steps are combined to represent the duration of a lava flow and predict the thermal profile in media under the flow. The model is further constrained by the paleotemperature record extracted from soil profiles beneath Hawaiian lava flows. Charcoal reflectance and rock thermomagnetic data reveal the maximum temperature to which soil samples at different depths were heated by the overlying lava flow. This paleotemperature data indicate that the duration of the flowing phase exerts the strongest control on the maximum temperature reached. Our lava flow- subsurface heat transfer model can be used to predict subterranean impacts caused by pāhoehoe lava flows in a substrate with known parameters (e.g. unit depths, moisture content).

Characterization of lava flows from an andesitic volcano as input data for numerical flow simulations, case El Reventador volcano (Ecuador)

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Detailed studies on dynamics of andesitic lava flows are very scarce. The lack of information for this kind of flows inhibits the possibility to generate accurate numerical model. Since 2002, El Reventador volcano is the most active volcano in Ecuador and has generated more than 60 lava flows. Between 2002-2009, it generated 17 lava flows with an accumulated volume of 87.7 x $10^6 m^3$. After a pause in effusive activity between 2009 and 2012, activity started again and produced 20 shorter and less voluminous flows than those from 2002-2009. The total volume emitted during this period reached $95x10^6 m^3$. Here we present a detailed analysis of the morphology of 37 well-exposed flows from 2002-2014, including accurate dimensions, volumes, thicknesses, velocities and emplacement durations. The data collected were then used as inputs parameters to simulate new lava flows using a modified version of VolcFlow, that takes in to account the cooling of the flow and the rheological variation during the emplacement. Owing to this method, we are able to simulate different scenario for future flows. For example, in June 2017, we could well reproduce the generated lava flows by using the input parameters extracted from our detailed description of the previous eruptions. This result recalls the attention to the importance a having accurate analyses of old flows to be used as input parameters for possible future lava flows generation.

Tephra layers in the Wilson Creek Formation

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Tephra deposits within the Wilson Creek Formation were formed during the late Pleistocene, and are interbedded with lacustrine deposits formed in Lake Russell (the ancestor of present-day Mono Lake). Most of the tephra layers are rhyolitic in composition, and were produced from the Mono Craters. In this work, we present detailed stratigraphy and sedimentology of these tephra layers sampled at ten outcrops near the shoreline of Mono Lake and the Mono Craters, and implement grain size, componentry, and surface morphology analysis to characterize their physical properties. Sub-unit correlation is proposed for certain tephra units. Interpretation on B7 and tephras in Sequence A is given, which includes the number of eruption pulses, dispersal direction, occurrence of pyroclastic flow and surge, and other processes taking place during and after the eruptions. Noticeable features of the tephras, such as the occurrence light rounded or highly vesicular pumice within certain sub-units, are highlighted with interpretation presented. The abundant obsidian, lithics, and ostracods within many sub-units suggest that the associated eruption pulses were involved with water-magma interaction. Tephras in Sequence B may have their vents located in the southern half of the Mono Craters, or are smaller in volume (except for B7), and vents for A4, A3, and A1 are located near the northern end of the Mono Craters. The detailed field data presented along with our careful interpretation give constraints to the processes taking place during and after the eruptions, and hence can be used as examples for testing and validating numerical models of tephra transportation and sedimentation.

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S01.15 - Looking toward the next generation volcanic hazard assessment efforts

Forecasting the rupture of a magma chamber using sequential data assimilation: Application to Grímsvötn volcano, Iceland

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We focus on forecasting the tensile failure of the magma chamber at basaltic volcanoes that exhibit inflation-deflation behaviour. In this study, we propose a new method to have an updated information on the overpressures by sequentially assimilating geodetic data using Ensemble Kalman Filter (EnKF) into a two-magma chamber model. Data assimilation has the advantage of: 1) incorporating data in real-time, 2) accounting for model errors and 3) estimating evolving model parameters.

The strategy that we developed can provide information about: 1) the timing of the eruption given some assumptions on the threshold failure overpressure, 2) the information on the volcanic system (e.g. state of stress, geometry of the reservoir) and 3) the initial magma overpressure necessary to infer whether or not the magma will reach the surface after chamber rupture. We initially explore the 2004-2011 inter-eruptive dataset at Grímsvötn volcano in Iceland. We find that if the probability of the magma chamber to rupture reached 25%, an actual eruption is imminent.

We further test our approach on the 2011 post-eruptive dataset. Results show that just before the 2014 rifting event, Grímsvötn's shallow magma chamber was already at the critical stage of rupturing and could have erupted in 2015. However, no eruption has occurred up to now, suggesting that a transient event may have happened and postponed Grímsvötn's supposed eruption.

Using EnKF, we then show that the basal magma inflow rate at Grímsvötn dropped up to 85% around 10 months before the Bárdarbunga rifting event. We interpret the loss of at least 0.016 km^3 in the magma supply of Grímsvötn as a consequence of magma accumulation beneath Bárdarbunga and subsequent feeding of the Holuhraun eruption. We therefore demonstrate that, in addition to predicting volcanic eruptions, sequential assimilation of geodetic data has a unique potential to give insights into volcanic system roots.

Tracking the emplacement of the long- lived 61G pāhoehoe lava flow of Kīlauea with visible and thermal structure-from- motion

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The emplacement of pāhoehoe lava flows is hard, if not impossible to forecast, resulting in high levels of uncertainties that make current predictions of little use for authorities during crises. This limitation is particularly relevant at Kīlauea volcano, where the three past decades have seen multiple lava flows from the active vent of Pu'u'Ō'ō threatening and destroying surrounding communities located tens of kilometres from the source. Our poor understanding of the relationship between source conditions, topography and advance rates and their impacts on the mass partitioning between crust formation, inflation, breakouts and the formation of a stable tube system limits the ability to describe the physics of these flows. Alternative approaches to document the emplacement of pāhoehoe flows are therefore required to inform processes behind their dynamics and, ultimately, produce better forecasts during crises.

Here, we document 1.5 months of the 61G flow (2016-current) before its ocean entry using helicopter-based structure-from-motion (SfM). Visible and thermal images were collected for seven dates and used to create georeferenced DEMs and thermal maps of the flow. Flow perimeter and textures were mapped in the field. This dataset allows tracking the evolution of thickness, width, total volume and temperature of the flow, which can be used to quantify the number and location of breakouts and the roughness of both the DEM and thermal maps. Results show that the combined use of visible and thermal SfM captures well the gradual insulation of the flow field, from initial frontal hummocky breakouts to lateral- dominated and surface breakouts marking the onset of inflation, up to the development of a tube system in a dominantly-insulated flow. This dataset also shows that the maturity of a pāhoehoe can quantified by describing breakouts in terms of size, elevation roughness and thermal roughness, which could be used to benchmark numerical models.

Improving lava flow simulation robustness by managing topographic data uncertainties: a case study

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The emplacement of lava flows, like all gravity-driven flows, is mainly controlled by the topography, making topographic data an essential input parameter to all numerical simulation models. Errors, uncertainties and low level of detail of the topographic data can affect the accuracy and reliability of simulation, based on how the model sensitivity propagates these uncertainties into the resulting emplacement. A sensitivity analysis of the model to topographic data is therefore of primary importance to constrain the uncertainty in the prospected lava inundation hazard, to identify the main aspects that affect the sensitivity, and to devise appropriate strategies to improve the model robustness by taking the sensitivity into account. We present here a methodology to quantify the sensitivity to topographic data for gravity-driven flow models, and apply it to the MAGFLOW cellular automaton model for lava flow simulations. We analyze the impact of rheology and model resolution on the model sensitivity to both horizontal and vertical errors, uncertainties and level of detail of the source data. We show that the most influential external factors are rheology and vent geolocation, and that increasing the automaton resolution, even for data with low level of detail, improves the accuracy of simulations, while making them more sensitive to the vertical error in the topography. We discuss the implications in terms of data quality requirements for civil protection purposes, highlighting the importance of frequent topography updates, even at moderate or low resolutions, and illustrating how to compensate for the sensitivity to vent geolocation errors by running a larger number of simulations to cover the uncertainty in the horizontal data.

S01.15 Poster

Paroxysmal Explosions, Lava Fountains and Ash Plumes at Etna Volcano: Eruptive Processes and Hazard Implications

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Between 2011 and 2015, 49 paroxysmal explosive episodes occurred at two of Mt Etna's five summit craters: the New South-East Crater (NSEC) and the Voragine (VOR). At the NSEC, each event was usually preceded by Strombolian activity, increasing in intensity with time, and climaxed with powerful lava fountains, often accompanied by lava overflows from the crater rim and by the development of ash plumes that spread several kilometres above and hundreds of kilometres away from the crater. In turn, the ash plume caused fallout and often disruption to airports and traffic on the motorways well beyond the area of the volcano itself, impacting also on the stability of buildings and public health. The four episodes at VOR were more intense and of greater magnitude compared to the NSEC events, resulting in a higher ash plume, and were produced by a deeper source region. In this paper, we examine the features of the 40 episodes occurring at the NSEC during 2011-2013, and of the 4 events at VOR in December 2015. We study these paroxysmal explosions from monitoring data, characterise the episodes, and analyse all available data statistically, with the aim of recognising the eruptive processes and extracting common parameters that may prove useful for hazard assessment and risk mitigation.

Characterizing the 2011-2015 eruptive events of Etna volcano from satellite remote sensing

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Mapping the volcanic deposits and quantifying the emitted lava volumes are crucial to understand the evolution of the volcano, as well as to provide input data for predictive lava flow modeling. To this aim, a great potential is offered by geostationary remote sensing data in the mid- and thermal-infrared acquired at a high temporal frequency. Here remote sensing data from SEVIRI are analyzed by the HOTSAT system in order to characterize the eruptive events occurred at Mt Etna between January 2011 and December 2015, which lead to the emplacement of numerous lava flows and to the formation of a new pyroclastic cone (NSEC) on the eastern flank of the South East Crater. The time-series analysis of SEVIRI data provides an estimation of event magnitude, i.e. mass in kg or volume in m^3, and intensity, i.e. mean output rate in kg/s or m^3/s, of the effusive portion of the material erupted during each event, revealing a decreasing trend in eruption intensity beginning from 2013 and reaching lower values (around 5 m^3/s) in 2014 and 2015. The SEVIRI-derived cumulative volume for the entire period adds up to ~10^6 millions of cubic meters of lava and is constrained using a topographic approach, i.e. by subtracting the last topography of Etna updated to 2005 from a 2015 digital elevation model, produced using tri-stereo Pléiades satellite images acquired on December 18, 2015. The total volume of products erupted from 2005 to 2015, calculated by integration of the thickness distribution over the area covered, is about 287×10^6 m^3, of which ~55×10^6 m^3 is the volume of the NSEC cone.

S01.15 Poster

UAVs for volcano monitoring - A new approach applied on an active lava flow on Mt. Etna during the 27 February-02 March 2017 eruption

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Etna (Italy) is one of the most active volcano in the world, with million people living on his flanks and visited by thousands of tourists every summer. For this reason, the lava flow monitoring for risk mitigation and Civil Protection purposes is one of the fundamental task of the Cartographic Laboratory of the INGV-OE. FlyEye Team, during the 27 February - 02 March 2017 eruption, applied Unmanned Aerial Vehicle to monitor the active lava flow. In particular two high-resolution UAV surveys were performed on the lava flow field on the south flank of Mt. Etna between 3050 and 2600 m a.s.l.. Structure-from-Motion technique was applied to create orthophotos and Digital Terrain Models of the lava flow field and surroundings; the accuracy of the DTMs and orthophoto was improve using several Ground Control Points measured with global navigation satellite system. The elaborated DTMs have a resolution of 14.2, and 20.7 cm/pix. Overall, the 95.8% of the lava flow was mapped using aerial images covering an area of 307404 m^2. The volume was calculated as the DTM difference between the lava flow roof surface and the base (pre-eruption) surface interpolated. The volcanological parameters calculated are comparable to those of the previous activity of Etna (between 2011 and 2016) with a strongly increase in the resolution and in accuracy. This research demonstrates the reliability of the proposed technique that allows a first fast processing realizing a low-resolution orthophoto of the lava field, useful for "decision maker" to plan a timely response to an eruptive crisis. Moreover, a secondary slow processing allows realizing a high-resolution DTM to update the topography, important factor affecting the simulations for the updating of the lava flow hazard maps.

LAV@HAZARD: a Web-GIS Framework for Lava Flow Hazard Monitoring

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Quantifying lava flow hazards by combining satellite data and numerical modeling has immediate applications to the real time monitoring of effusive eruptions. By monitoring, we mean here both following the manifestations of the eruption once it has started, as well as forecasting the areas potentially threatened by lava in an effusive scenario. To deal effectively with these crises, we developed, in collaboration and thanks to the support of the Department of Civil Protecion, a Web–GIS framework, named LAV@HAZARD, which uses satellite-derived discharge rates to drive a lava flow emplacement model to simulate lava flow paths and to quickly update flow simulations. Any significant changes in eruption conditions at the vent are thus included in the forecasts of the flow evolution. As a result, LAV@HAZARD now represents an operational monitoring system that allow to give during an eruption: (i) the current state of the effusive activity; (ii) the probable evolution of the lava flow field; (iii) the potential impact of lava flows. We will describe and demonstrate how Lav@Hazard can be effectively used during eruptive crises at Mount Etna to produce realistic lava flow hazard scenarios and to assist Civil Protection in making decisions during a volcanic eruption.

S01.15 Poster

Modelling ballistic hazard of a partially observed phreatic eruption at a tourism hotspot

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Volcanic ballistics are a major hazard in areas proximal to volcanic eruptions, particularly volcanoes prone to unheralded hydrothermal or phreatic eruptions. The >18,000 annual visitors to Whakaari (White Island), walk within block fields emplaced during recent ballistic-producing phreatic eruptions, necessitating a quantitative ballistic hazard assessment. A small unheralded, phreatic eruption at Whakaari on the night of the 27th of April 2016 produced ballistics and at least two low temperature surges over ~40 minutes. Had the eruption occurred during tour operational hours, casualties would have been likely. We present data defining the high ballistic hazard zone suitable for incorporation into a probabilistic ballistic hazard map at Whakaari, informed by field mapping, geophysics and 3D numerical modelling.

Ballista, a semi-probabilistic 3D volcanic trajectory model by Tsunematsu (2016), is utilised and calibrated through a combination of fieldwork and seismo-acoustic data to determine eruption source parameters and block impact energies. A 5m resolution DEM allowed best fit to be determined through replication of the observed variable spatial densities, including topographic shielding. This is the first known study in which detailed spatial density variation within a ballistic field, as well as the field outline, has been systematically used to constrain eruption parameters.

The deterministic eruption scenario consists of three separate, directed, ballistic pulses ejected at 30° from horizontal which emplaced small blocks up to 360m from the vent. 22.5% of the path used by tourism operators is impacted by blocks with sufficient kinetic energy to maim or kill, with high impact densities of greater than 25 ballistic/m^2 in some ocations. The average time between eruptive bursts of 7 minutes suggests that sheltering in place before immediately evacuating (if possible) may be appropriate life safety advice to give visitors to Whakaari in case of an unexpected eruption.

Effusive crises at Piton de la Fournaise 2014-2018: Source term provision and quantification of uncertainty in lava flow modeling for a real time response

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Here we review how near-real time assessments of lava flow propagation were developed using rapid provision, and update, of key source terms. This was achieved through a dynamic and open integration of near-real time remote sensing, modeling and measurement, and was applied during effusive crises at Piton de la Fournaise (La Réunion, France) between 2014 and 2018. Our lava flow run-out assessment is based on the FLOWGO model (now updated to PyFLOWGO); a model which assesses the cooling-limited potential of flow length at a given Time-Averaged Discharge Rate (TADR). The model was initialized and validated using the physical and dimensional properties of the channel-fed flow system emplaced during the December 2010 of Piton de la Fournaise. Once initialized the three main variables that need to be defined (i.e., source terms that need to be changed from eruption-to-eruption) are: (i) vent location, (ii) line of steepest descent (i.e., flow path and underlying slope profile), and (iii) TADR. The model is launched upon first-reception of a TADR as derived from MODIS thermal infrared imagery by the MIROVA system, and output is delivered to the observatory as a short email report with maps and graphs attached. As part of a debriefing process, model-based appraisals are cross-checked against available ground-observations (actual flow length, path, TADRs, channel dimensions, velocities) and measurements (flow crystallinity, density, temperature). If correctly initialized and validated, we find that the main uncertainty is that associated with the TADR estimation, where a ±30% uncertainty in TADR gives a 2% uncertainty in run out. The main error is from the Digital Elevation Model (DEM), especially as it rapidly becomes out of date at a frequently active effusive center. This latter issue means that both paths and slopes cannot be modeled if new topography (lava flow fields) is not included in the DEM.

Modeling of Lava Flow Emplacement with Smoothed Particle Hydrodynamics Method using High-Performance Computing

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SPH is a lagrangian mesh-free method for Computational Fluid Dynamics (CFD), where the simulated domain is discretized by means of particles that are free to move, each of them carrying information about the physical properties of a small volume of material. Thanks to its properties, SPH copes very well with the issues that generally arise simulating lava flows, like the free surface, the interaction with irregular topographies and the high dynamicity. At the Tecnolab of INGV-Catania we designed GPUSPH, an implementation of weakly-compressible SPH running fully on Graphics Processing Units (GPUs). GPUSPH is able to model both Newtonian and non-Newtonian fluids, solving the three-dimensional Navier–Stokes equations, using either a fully explicit integration scheme, or a semi-implicit scheme in the case of highly viscous fluids. Thanks to the full coupling with the thermal equation, and its support for radiation, convection and phase transition, GPUSPH can be used to simulate many aspects of lava flows. In this work study the influence of the main parameters of the SPH method, such as the spatial resolution and the boundary model, on the simulation of a lava flow, comparing the simulated result to analytical and experimental tests.

S01.15 Poster

Assessing spatial and temporal probabilities in San Miguel Volcano, El Salvador

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San Miguel volcano, one of the most active volcanoes in El Salvador, hosts an important population and infrastructures around it. The last eruption in 2013 affected local and regional economy and prompted the evacuation of part of the surrounding population, which remarked that mitigation measures such as hazard assessment must be undertaken. Thus, we conducted the first systematic and comprehensive, long-term volcanic hazard assessment for San Miguel using available historical records of past eruptive activity, new geological information, and monitoring data gathered over the past sixteen years, aimed at helping to reduce the potential risk it poses. We used probabilistic tools (QVAST and HASSET) specifically designed for volcanic hazard assessment to conduct two hazard analyses: temporal and spatial probability analyses. For the first it was considered a forecasting time window of two years using information on volcanic activity over the past 430 years (historical period), and another with a forecasting window of six months, with information from the past 16 years (monitoring period). In both cases we used the same susceptibility map constructed using the most relevant structural elements, which indicates the spatial probabilities of hosting a new vent on San Miguel volcano. Then, we calculated the most likely eruptive scenarios for each analysis and their corresponding forecasting windows, which revealed that the most hazardous areas correspond to Conacastal canton and hamlets of San Jorge, San Miguel and San Rafael Oriente – all lie within 5km of the central crater on the northern and southern flanks. This methodology is easy to update, and results can be improved by incorporating new information. This long-term hazard assessment is a significant contribution that will enable local authorities to implement more rational territorial planning and to design better emergency plans for coping with future volcanic crises.

Experimental investigation of damage by ballistic impacts: Implications for hazard assessment

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Volcanic eruptions pose numerous threats to surrounding populations at a local to global scale, for example ballistic impacts may severely and irrevocably damage infrastructure. Whilst the resistance of many materials to impacts has been tested to simulate a range of anthropogenic catastrophes, the role and extent of natural impacts relating to volcanic explosions remains poorly investigated. Explosive volcanic eruptions can be highly energetic, e.g. the 1980 eruption of Mount St. Helens was measured at approximately 1600 times more energetic than the atomic bomb in Hiroshima. In extreme cases, explosive eruptions may release up to ~5000 km^3 of fragmental materials at velocities of up to several 100 ms^{-1}, reaching high altitudes and distances of 1-10 km. Ballistics are a primary threat of both explosive magmatic activity1and catastrophic phreatic (gas and fluid) explosions; yet no regulation of buildings in vulnerable areas exist. Recent work that examined damage on buildings from volcanic ballistic impacts and tested the resilience of some structures to ballistics using a rock cannon, urged in-depth quantification of impacts for future hazard assessment2. Here, we present the results of a series of ballistic impact tests in which we used a gas-gun to fire volcanic projectiles (lavas from Pacaya, Guatemala) with a range of porosities at variable velocities at 1-3 mm thick aluminium sheets. To establish the resilience to ballistic impacts we quantify the damage zone created in the metal as a function of changing (a) the velocity of the impact and (b) the density/ porosity/ permeability of the projectile, and we then model the damage zone created in the metal to establish the energy consumed by the impact, for extrapolation towards a probabilistic ballistic impact model.

S01.15 Poster

Accounting for uncertainties of different nature in volcanic hazard and eruption forecasting

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Ubiquitous uncertainties of different nature make the deterministic prediction of most volcanic eruptions impossible. Although the presence of such uncertainties is the main motivation for introducing probabilistic forecasts, the link between uncertainties and probability is far to be obvious, and poorly explored in volcanological literature. We argue that clarifying this relationship is of paramount importance for scientific advancement in eruption forecasting and volcanic hazard sciences. Here, we describe a unified probabilistic framework, already introduced in seismic hazard analysis, which allows: i) an unambiguous distinction between uncertainties of different nature such as aleatory variability, epistemic uncertainty and ontological error; ii) a formal structure for a meaningful validation of forecasting models, which is essential to keep volcanic hazard and eruption forecasting in a scientific domain and build the ground for scientific advancement; iii) a proper handling of all uncertainties through an ensemble modeling; iv) addressing the strongest recent critics to natural hazard analysis as a scientific enterprise. For the sake of example, we apply the framework to the tephra fall hazard for Campi Flegrei.

S01.15 Poster

Ensemble-based model data assimilation for eruption source parameter characterization

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Source term quantification is the main source of model uncertainty in volcanic ash dispersal forecasts routinely used by civil aviation. Ash emission profiles are commonly parametrized depending on the eruption column height, physical properties of particles, and wind forecasts. As these model input parameters are often poorly constrained during a volcanic eruption, estimations of inputs rely on a priori experience or on indirect measurements. This major source of uncertainty can be circumvented using an ensemble-based model data assimilation system that obtains key model input parameters related to ash emissions and introduces an objective correction in the ash cloud concentration. We couple the Ensemble Transform Kalman Filter (ETKF) method with the FALL3D ash dispersion model and perform a sensitivity analysis of the ETKF-FALL3D system using different observing system simulation experiment (OSSE) in which synthetic observations of ash cloud column mass are generated and assimilated every 6 hours. These synthetic observations mimic quantitative total column mass retrievals from satellite data. In this experiment, the ETKF-FALL3D system is used to estimate the 3D distribution of ash together with the eruption column height and the emission profile. Results show that the ETKF-FALL3D system can produce an on-line optimization of uncertain volcanological parameters as well as objectively correct the 3-dimensional distribution of volcanic ash concentrations.

Unravelling the emplacement dynamics of silicic lava flows: the case of the Grande Cascade trachyte flow (Monts Dore, France)

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Silicic lava flows are a rarely observed style of volcanism for which emplacement models remain poorly constrained. Yet they represent a hazard where oversteeping flow fronts can collapse and generate block-and-ash flows as at Santiaguito (Guatemala) in 1929, 1973 and 1986, Unzen (Japan) in 1991, and Sinabung (Indonesia) in 2014. Here we focus on the Grande Cascade trachyte flow (Sancy stratovolcano, Monts Dore, France). This flow was emplaced 0.38 Ma and can be divided vertically into three subunits: a basal breccia; a shear zone; and a massive, thick plug. We conducted a field campaign to map the flow, and to measure structures and collect oriented samples. Chemical, petrological, textural analyses were carried out to characterise the lava, and the breccia grain size distribution and particle morphology was defined. Textural data, such as crystal orientation, along with anisotropy of magnetic susceptibility, also allowed us to define local flow directions. We find that the dynamics of the Grande Cascade lava flow was different from the "classical" stick-slip model of rhyolite flows. Emplacement was driven by deformation. The solid plug, which is typically 40 m thick and represents 90% of the flow thickness, "slid" over an approximately 3-m-thick basal shear zone, with the plug undergoing little-to-no deformation. The shear zone and the basal breccia accommodated most of the stress. As a result, the breccia is composed of finely ground lava and is similar to a fault gouge. This study stresses the need to build new emplacement models for silicic lava flows. Instead of Newtonian or Bingham fluid dynamics applied to basaltic flows, we need to consider the rheological and mechanical properties of solid rocks under high shear stress, with possible analogies with orogenic or even glacial settings. Fitting appropriate models to observed structural clues greatly reduces uncertainty in emplacement scenarios.

Exploring the different characteristics of volcanic plumes generated by basaltic and silicic explosive eruptions

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Modelling of volcanic plumes has traditionally been focussed on large explosive silicic Plinian eruptions. Recent paroxysmal eruptions at Mount Etna, in Italy, have demonstrated the need to investigate volcanic plumes that develop during basaltic explosive eruptions as they show distinct characteristics. Unlike silicic volcanic plumes, the temperatures in basaltic plumes are higher, the gas content is lower, and the initial grain-size distribution is coarser. They can also form above moderate to high lava fountains creating additional complexities in their source conditions. We will explore how such differences at the vent propagate through the eruption column and affect dispersion and sedimentation.

We will use a one-dimensional plume model to assess plume dynamics. We focus specifically on evaluating the impact of an initial coarse grain-size distribution on a plume characterised by a range of temperatures, gas contents and velocities typical of observed basaltic plumes. When the initial grain-size distribution is coarse, such as those of paroxysmal eruptions, the proportion of particle fallout is high and thermal disequilibrium will become important. Subsequently, we will investigate how these processes can change dispersion and sedimentation patterns.

The plume model will be coupled to a dedicated sedimentation model to quantify how this can affect the sedimentation of hazardous large clasts (> 5 cm) in the proximal area around the vent. Furthermore, the effects on tephra dispersion will be studied by coupling the plume model with volcanic ash dispersal models. We will use an analytical Eulerian tephra sedimentation model (e.g. TEPHRA2) to look at the effect on the thickness of the local deposit, and a Lagrangian approach (e.g. NAME, PUFF) to explore the tephra dispersion and concentration at regional scale of basaltic plumes. We will perform sensitivity analyses to reveal some of the main differences between the paroxysms at Mount Etna and silicic Plinian eruptions.

S01.15 Poster

Topographic Constraints on Lava Flow Channel Network Architecture: the December 2010 Eruption of Piton de La Fournaise

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We examine the channel-fed ‘a’a flow system that was emplaced during the very short lived December 2010 eruption of Piton de La Fournaise. The system had four branches that, with one exception, were emplaced over a pahoehoe flow field with a vertical relief of 1–2 m. The exception was a branch that erupted from the same vent as the 1957 eruption and re-used the pre-existing channels of that eruption. Down the three systems that were unconfined we identified channelized flow sections in the proximal-medial sections, characterized by the presence of either a single channel or multiple braided channels that fed a distal zone of dispersed flow. We subsequently investigated the role of pre-existing topography and rheological parameters (as controlled by downflow variations in crystal and bubble content) in triggering the transitions between single and braided channel flow sections. Crystal content varied between 10vol% and 70vol% and vesicle content was 18vol% to 55vol%. Neither parameter appeared to play a role in controlling lava flow structure. Instead, it appears that the channel network architecture could be related to even modest underlying slope variations, where a slope increase resulted in the confluence of all channels, while a slope decrease resulted in bifurcation of the channel. This process was reversible, in that a downflow slope variation could drive the channel network to switch back and forth between a single channel and multiple braided channels several times along its length. Dispersed flow is always present behind the flow front, irrespective of underlying topography. Conversely, three previous studies found that steeper slopes favor braiding, while shallower slopes prompt confluence. We suggest that the underlying substrate morphology may exert a control on this behavior.

Lava flow simulations with VolcFlow using simple and complex rheologies

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Lava flows are the most abundant volcanic products on Earth. Although they are not the most hazardous phenomena, they threat populated areas and cause irreversible damages causing significant economic losses. The development of numerical models has been mainly used to forecast lava flows paths over the topography. Lava advance is highly dependent on the evolution of thermo-rheological properties including viscosity and yield strength increase due to cooling and crystallization. The numerical code VolcFlow (Kelfoun and Druitt, 2005) was modified and improved to simulate lava flows using different rheologies. Three approaches are proposed: 1) we assume a plastic-viscous isothermal model with a Bingham rheology; 2) we consider cooling and evolution of the thermo-rheological properties as proposed by FLOWGO (heat box model and increasing of viscosity due to cooling and crystallization; Harris and Rowland, 2001); 3) we consider cooling as proposed by FLOWGO but implement an increasing viscosity following an empirical sigmoidal law as function of temperature. These three approaches were tested in four lava flows cases: molten lava flow from the Syracuse project, the Dec. 2010 andesitic flow from Tungurahua (Ecuador) and four andesitic flows from El Reventador volcano (Ecuador). Results shows that basaltic flows are better reproduced by models that takes into account the cooling of the flow and variable rheology (first and second approaches). On the other hand, for andesitic flows, best fit is obtained when considering the cooling and evolution of the thermo-rheological properties as proposed by FLOWGO. Results of the simulations shows that these models are capable to almost reproduce completely the flows. The lack of updated topography's and precise input data can produce errors in the simulations. It is necessary to continue to explore these models to perform them with more realistic data.

Volcanic ash dispersion modeling for operational forecasting and hazard assessment

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To accurately forecast the downwind location, concentrations, mass loadings, and fallout deposits of volcanic ash clouds requires a comprehensive understanding on the eruption dynamics to evaluate the range in the dispersion modeling inputs as well as the variability in downwind atmospheric conditions that drive the cloud dispersal. Therefore, the operational hazard analysis of these ash clouds involves integrating eruption plume models with multi- dimension cloud dispersal models along with numerical weather predication data (either coupled or offline) along with probabilistic estimates on the critical parameters needed in the coupled modeling system. I will present on monitoring and forecasting volcanic ash plumes from an operational point of view, as well as discuss the combination (assimilation) of observational data/geophysical monitoring with numerical models for operational purposes. I will present some opportunities on future developments and how volcano observatories could advance their hazard evaluation of volcanic ash plumes and dispersing clouds.

Relationship between infrasound-derived and buoyancy-derived eruption cloud volume estimates

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Infrasound pulse signal accompanying a discrete explosion has been explained by volume change of a monopole source assumed at the vent. Here, the inferred volume V_{inf} is considered to be equivalent to that of mixtures of hot volcanic particles and gases emerging from the vent. However, it is still challenging to understand the nature of V_{inf} quantitatively based on the dynamics of eruption cloud. An eruption cloud accompanying the discrete eruption has been modeled as a thermal. Terada and Ida (2007) proposed a simple method to estimate initial buoyancy F_0 of a spherical thermal with the maximum eruption cloud height and a vertical profile of ambient air density. We focus on that the volume of the thermal V_{b} obtained from F_0. Investigating relationship between V_{inf} and V_{b} can be valuable to understand how V_{inf} can be linked to the dynamics of eruption cloud.

The present study examines the relationship between V_{inf} and V_{b} for 53 eruption events at 5 volcanoes (Aso, Kirishima, Lokon-Empung, Sakurajima, and Kuchinoerabujima). Following the method proposed by Terada and Ida (2007), we estimate F_0 and V_{b}. Our result shows that the ratio of $V_{\mathrm{b}} / V_{\mathrm{inf}} = 1.6\times10^1$ throughout all events. Since examined infrasound waveforms share a prominent pulse at the onset, V_{inf} is likely to link starting process of the eruption cloud where it is driven by gas thrust, i.e., jets. Meanwhile, V_{b} can be regarded that the thermal volume when it has entrained enough amount of the surrounding air to ascend with the buoyancy only. Referring the previous works, difference of the bulk density of both eruption cloud regimes yields the volume change rate of the $1.8–3.2\times10^1$, that explains our result of $V_{\mathrm{b}}/V_{\mathrm{inf}}$ ratio. We believe the result provides an effective index to constrain the eruption cloud volume with infrasound data.

S01.15 Talk

Stability of lava eruption modelling with SPH

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Smoothed Particle Hydrodynamics (SPH) is a Lagrangian mesh-free method for Computational Fluid Dynamics (CFD) that is advancing in the field of lava simulations. Thanks to its properties, SPH copes very well with the issues that generally arise when dealing with lava flows, like the simulation of a free surface, the interaction with irregular topographies and the high dynamicity of the flow. A major aspect of simulating a lava eruption concerns the generation of the flow. Several approaches are possible in SPH, with different levels of implementation complexity, performance and quality of the generated flow, the latter affecting the entire emplacement process. Here we present a comparison of two different inlet designs simulated using GPUSPH, an implementation of weakly- compressible SPH running fully on Graphics Processing Units (GPUs) developed at the Tecnolab of INGV-Catania. A simple inlet, obtained as an injection of fluid by means of a piston, is compared to a more sophisticated model, where new fluid particles are generated during the simulation and open boundary conditions are imposed using Riemann invariants. A description of the two models will give a view of the pro and cons in terms of implementation, while a comparison of the two flows with the analytical results will highlight the effects of the inlet model in the emplacement.

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S01.16 - Magmatic processes, eruptive histories and their timescales implications for volcano hazard assessment and monitoring

Temporal evolution of long-lived magmatic systems: the Chachani volcano complex, south of Perù

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The Chachani Volcanic Complex (CVC) is an extensive (~289±10 km3) assemblage of spatially, temporally and genetically related major and minor eruptive centers. The c. 1.2 Myr-long activity suggests that the CVC is a long-lived volcanic system characterized by semi-persistent activity and short periods of quiescence.

The stratigraphy, Ar/Ar and U/Pb chronology, spatial distribution along lineaments, and the degree of landform preservation help distinguish two groups of edifices in the CVC. The 'old' edifice group is characterized by large stratovolcanoes and small dome coulees. This group has been built between <1200 and 641 ka in the northeastern part of the complex, following a N150°-N160° arcuate spatial trend with eroded ridges oriented to the NNW-SSE and amphitheaters (glacial cirques and collapse scars) open to west and southwest.

The 'young' group has formed a 12.5-km long ridge, trending N80°, located S/SW of the 'old' edifice group. Eruptive activity between 463 and 56 ka has produced cumulo-domes, dome coulees, block lava flow fields, composite cones and stratocones. Voluminous block- and-ash deposits on the southern flank and a lava dome in the central part of the complex are also associated with this group. One substantial chronological gap of ~180 kyrs may have occurred between the 'old' and 'young' edifices.

The 'young' group volcano eruption rates (0.08-0.09 km^3/ka) are two to three times slower than the 'old' group eruption rates (0.15-0.24 km^3/ka). The 'young' group of edifices suggest a change towards an extrusive style of eruptions as domes, domes coulees and extensive lava fields dominate the most recent CVC eruptive history. In contrast, the 'old' edifice group consists of stratovolcanoes with voluminous lava flows and small volumes of pyroclastic deposits that have been subjected to glacial erosion and a wetter climate than today.

S01.16 Poster

Constraints on a large magnitude phreatomagmatic eruption at 29 ka from Campi Flegrei caldera and its widespread ash dispersal (Y-3 tephrostratigraphic marker)

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The spatial distribution of the 29 ka Y-3 distal tephrostratigraphic marker preserved in sedimentary archives across the central Mediterranean region implies that it was associated with a large magnitude eruption. Glass compositions of this tephra reveal that it was sourced from Campi Flegrei caldera (CFc) Italy, however, no prominent proximal eruptive deposit is preserved near the caldera in the appropriate chrono-stratigraphic position. New field, geochemical and chronological investigations reveal the near-source deposits of the eruption which dispersed ash over 400 km from the vent across the central and eastern Mediterranean. These deposits found just beyond the eastern sector of CFc at Ponti Rossi and within a nearby drill core display the diagnostic geochemical variability of the Y-3 distal tephra. $^{40}Ar/^{39}Ar$ dating of the deposits yield a mean weighted age of 29.3 ± 0.7 ka (2σ), which is in strong statistical agreement with the 14C age (28.69-29.42 cal ka BP [95.4 % confidence]) of the distal Y-3 tephra. The near-source deposits are fine-grained and contain large accretionary lapilli, characteristics that are consistent with phreatomagmatic activity. Magma-water interaction is likely to have enhanced fragmentation, facilitating the widespread ash dispersal, and perhaps in part explains the lack of a coarse deposit near the vent. The tephra deposit thicknesses were collated and modelled using the two-dimensional HAZMAP code to provide some constraints on the eruption parameters. Modelled outputs indicate that ~8.5 km^3 (DRE) of magma was erupted and the column height reached ~48 km. This study illustrates that CFc produced a magnitude 6.3 eruption between caldera forming eruptions at 39 ka and 15 ka, and this eruption was an order of magnitude greater than those of the post-15 ka activity.

S01.16 Poster

Coupling geochronological dates and numerical simulations to determine the longevity of magma chambers

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Detailed study of granitoid plutons provides insight into the longevity of silicic magma chambers. High-precision zircon geochronology shows large differences in zircon ages between different parts of a pluton. Assuming zircon ages date the emplacement of magma, results indicate that the construction of plutons is protracted. Numerical simulations and heat transfer computations suggest that many plutons were emplaced over a time scale incompatible with development of vast and long-lived magma chambers. In slowly emplaced plutons, magmas solidify shortly after having stalled and only a small part of the pluton is above solidus at any time during its construction.

Within a single hand sample, granitoid zircon ages often range over several hundred thousands years. If zircons crystallize in-situ, this means that the magma remained above the solidus and zircons saturated during a similar time span. We tested this hypothesis using the Mte Capane granite (Elba Island) as a case study. Results of our numerical simulations suggests that magma reached subsolidus temperatures an order of magnitude sooner than suggested by the spread of zircon ages. In another study, geochronometers with different closing temperatures constrain the cooling time of the Don Manuel Igneous complex (Chile) to several hundreds of thousands years, a timescale that is difficult to reproduce numerically with a typical geotherm. Another relevant observation is the commonly observed difference of orders of magnitude between magma residence timescales inferred from zircons and those inferred from diffusion profiles in crystals. Collectively, these observations challenge our current conceptual models of magma transfer and emplacement. Zircons might crystallise before magmas reach their final emplacement level or we might systematically underestimate geothermal gradients.

Effects of pre-eruptive long-term passive degassing on the dynamics of 2010 - 2013 eruption of Kizimen Volcano in Kamchatka, Russia

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Long-term passive degassing has a fundamental control on the dynamics of viscous magma chambers and can have a significant effect on the style of the forthcoming eruption (Peléan vs. Plinian). We present a case study of the first historical magmatic eruption of Kizimen volcano between 2010 - 2013. The event started with the deposition of block and ash flows subsequently accompanied by slow extrusion of a highly viscous block lava flow. All erupted products are characterized by intricate mingling textures between a dacitic and a silica rich andesitic component. The dacitic magma was formed during a long dormancy after the previous magmatic eruption several hundred years ago whereas the silica rich andesite represents a hybrid magma, which shows signs of recent thermal and compositional disequilibrium. The formation of the hybrid magma probably started in 1963 when a swarm of deep earthquakes indicated an input of mafic magma from depth into the 6 - 11 km-deep silicic magma chamber. It took the following 46 years to activate the large shallow dacitic magma chamber to reach an eruptible state. This long hiatus and the overall poor mingling of the two melts is attributed to its high viscosity which in turn is associated with the pre- eruptive long-term leakage of volatiles from the chamber through a regional tectonic fault. Such prolonged reactivation times should have implications for eruption forecasts which need to include a possibility of long time lag between a swarm of deep earthquakes (indicating the recharge of basic magma from depth) and the following swarm of shallow earthquakes (indicating final ascent of the hybrid magma towards the surface). The forthcoming eruption can be of moderate or low explosivity and include extrusion of viscous lava flows and domes composed of poorly mingled magmas of contrasting compositions

S01.16 Poster

Evolution of the Ecuadorian arc: construction periods, magmatic productivity and erosion rates

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In the northern volcanic zone of the Andes, the Ecuadorian arc presents a large number of Quaternary volcanoes, spread over a rather restricted and populated surface area. The activity of the southern termination of the arc seems partly related to the tectonic activity, while the northern part is located above the inland prolongation of the oceanic Carnegie ridge. In this study, we focus on two E-W transects, in the northern and the southern termination of the arc. The former includes Mojanda, Imbabura and Cusín, and the later Igualata, Huisla and Tungurahua volcanoes. We performed numerical reconstructions of the volcanoes flanks morphology before their erosion by using the available DEM. These reconstructions allow us to estimate the total volume of magma emitted, and the amount of eroded material due to abundant precipitations and glacial-interglacial alternating periods. Together with new groundmass K-Ar ages, these volumes are used to quantify the rates of volcanic emission of these volcanoes, as well as their erosion rates during quiescence periods.

The volcanic emission rates obtained here are rather similar for both segments, ranging between 0.1 and 5.6 $km^3.ka^{-1}$, while the erosion rates vary between 0.01 and 0.14 $km^3.ka^{-1}$. Both rates are not related to the geodynamic or tectonic settings. The highest emission rates are obtained for volcanoes constructed over less than 100 ka, and could represent sporadic eruptive pulses, whereas rates calculated over longer time periods include quiescence phases and do not exceed 1 $km^3.ka^{-1}$. The highest erosion rates are obtained for young volcanic edifices, whose activity ended recently. These results highlight that the volcano morphology is carved by chemical and physical erosion processes that mainly depend on the age and degree of weathering of rocks.

Deep pre-eruptive storage of silicic magmas feeding Plinian and dome- forming eruptions of central and northern Dominica (Lesser Antilles) inferred from volatile contents of melt inclusions

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Volatiles embody the main driving force of magma ascent through the sub-volcanic plumbing system. Here we investigate melt inclusion compositions in terms of major and trace elements, as well as volatiles (H_2O, CO_2, SO_2, F, Cl, Br, S) for Quaternary Plinian and dome-forming dacite and andesite eruptions in the central and the northern part of Dominica (Lesser Antilles arc). Melt inclusions, hosted in orthopyroxene, clinopyroxene and plagioclase are consistently rhyolitic. Post-entrapment crystallisation effects are limited, and negligible in orthopyroxene-hosted inclusions.

Melt inclusions are among the most water-rich yet recorded (≤8 wt% H_2O). CO_2 contents are generally low, although in general the highest pressure melt inclusion contain the highest CO_2. Some low-pressure (<3 kbars) inclusions have elevated CO_2, suggestive of fluxing of shallow magmas with CO_2-rich fluids. CO_2-trace element systematics indicate that melts were volatile-saturated at the time of entrapment and can be used for volatile-saturation barometry. The calculated pressure range (0.8 to 7.5 kbars) indicates that magmas originate from a vertically-extensive (3-27 km depth) storage zone within the crust that may extend to the sub-Dominica Moho (28 km). The vertically-extensive crustal system is consistent with mush models for sub-volcanic arc crust wherein mantle-derived mafic magmas undergo differentiation over a range of crustal depths. All MIs, regardless of provenance, describe the same Cl/F correlation, indicating that the magma source at depth is similar. The high H_2O content of Dominica magmas has implications for hazard assessment.

Zircon from the Öræfi Volcanic Belt: Identifying and Evaluating Hazardous Icelandic Subglacial Volcanoes

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The Vatnajökull ice cap - which currently covers ~10% of Iceland's surface area - obscures from view the majority of the Öræfi Volcanic Belt (ÖVB), a nascent rift. Historically, ÖVB volcanoes have produced jökulhlaups and explosive phreatomagmatic and rhyolitic eruptions. As climate changes and icecaps thin, there is increasing concern about future hazardous activity of these sugblacial volcanoes because glacial unloading may impact the productivity and stability of shallow magma bodies. Despite the associated threats, investigations into the patterns and past behaviors of these volcanoes are hindered by ice and accessibility. We turn to the zircon record to begin reconstructing magmatic histories and processes in this enigmatic region.

We present in situ U-Pb and U-Th ages, trace elements, and morphology and zoning from whole rock-derived and detrital zircons from the northern and southern extremes of the ÖVB. Zircon from lavas and tephras provide magmatic insight for Öræfajökull (south) and Snæfell (north) volcanoes; detrital zircons represent the enigmatic sub-Vatnajökull systems between. Results indicate southward younging (0.25-2.5 Ma in the north, and <0.5 Ma in the south), and the detrital record expands the whole rock age range. Northern zircons have avg. Ti <10 ppm and Hf ~7,000-12,000 ppm; in the south, Ti averages >10 ppm and Hf ranges from ~6,000-11,000 ppm. Compositional trends suggest southern zircon crystallization in hotter, less-evolved magmas than in the north. Some zircon morphology (penetration twins and C-axis-parallel melt inclusions) and zoning patterns (little oscillatory zoning, lack of inheritance) suggest brief magmatic storage time and rapid crystallization.

The zircon record uncovers previously undetected silicic magmatism under NE Vatnajökull; hints at a systematic north-to-south shift in petrogenetic processes over time; and reveals short residence times for zircon-saturated silicic magmas. This study represents important progress in the effort to better understand past behavior of subglacial volcanic systems that pose future threats.

Experimental constraints on pre-eruptive conditions of the poorly evolved magmas at Campi Flegrei

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Experimental petrology can provide useful information on the phase relations of the magma prior to ascent and eruption. Here, we performed phase equilibrium experiments on magmas of three volcanic events at Campi Flegrei caldera (Fiumicello, Minopoli 1 and Fondo Riccio eruptions) characterized by poorly evolved compositions, from trachybasalts to latites. Based on indications from geophysics and previous melt inclusion studies aimed at defining the depth of the magma reservoir, experiments were performed at 1 - 2 kbar, using an internally heated pressure vessel (IHPV) equipped with a fast quench device. Temperature was varied between 850-1030°C at 2 kbar, and 950-1030°C at 1 kbar, with fO_2 between NNO and NNO+1 using Ar-H_2 mixtures. About 100 experimental charges were prepared by loading into gold capsules the powdered dry glass with known amounts of water and CO_2 (added as silver oxalate). Melt water contents ranged from about 1 up to 5-6% by varying fluid composition to determine the effect of H_2O on phase equilibria. Run products consisted of glass and mineral phases including biotite (bt), clinopyroxene (cpx), alkali feldspar (af), olivine (ol) and Fe-Ti spinel (sp). At 2 kbar at 1030°C cpx is the liquidus silicate phase both in Minopoli 1 and Fiumicello, while in Fondo Riccio sp is followed by cotectic crystallization of ol, cpx, plg, af which occurs for H_2O melt contents <3 wt%. At lower pressure the crystallization interval of Fondo Riccio is confined just between 950-1000°C for different H_2O contents, whereas in Fiumicello and Minopoli 1 the crystallization interval appears wider. Additional experiments at higher temperatures are underway to better define the ol stability field. Natural phase assemblages and compositions will be compared with the experimental results to infer the most likely P, T, X (H2O) conditions for the Phlegrean mafic magmas prior to eruption.

Experimental constraints on alkali mobility in the Campi Flegrei magmatic system

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The Na_2O/K_2O ratio of Campi Flegrei (CF) magmas varies from ~2 to ~0.2 with no clear correlation with the MgO content ($2 \leq MgO \leq 6$ wt.%). Such a significant alkali variation cannot be explained by a mere crystal fractionation process in closed system, but it can be more correctly related to an increase of H_2O in the system. This would affect the stability and proportions of the crystallizing minerals and the composition of residual melts. Moreover, the presence of a free fluid phase could have an influence on the liquid line of descent of the system and in particular on alkali mobility. To test the water effect on alkali mobility in the CF magmatic system, we have performed equilibrium experiments on a primitive alkaline (S_{alkali}=4.32 wt.%) basalt at 800 MPa and different initial water contents ($1 \leq H_2O_i \leq 6$ wt.%). The experiments confirm the fundamental role played by water content on the liquidus phases (i.e. clinopyroxene *vs* clinopyroxene+olivine). However, the change of liquidus phases alone does not explain the TAS differentiation trends shown by the experimental melts at different water contents. In particular, the experimental subalkaline glasses produced under hydrous conditions ($4 \leq H_2O_i \leq 6$ wt.%) cannot be explained invoking a closed melt+crystal system. In particular, the low alkali content (S_{alkali}=1.48 and 3.26 wt.% at 1050°C and 1000°C, respectively) characterising these experiments is inconsistent with the type (clinopyroxene+olivine+orthopyroxene±amphibole±spinel) and abundance of crystals in the charges. The occurrence of bubbles in these hydrous charges indicates that melt and crystals were in equilibrium with free aqueous fluid phase and that alkali were distributed in the coexisting phases (fluid+melt+crystal). These experimental results and the Na_2O/K_2O ratio variability could indicate that the CF magmatic system is characterised by a relatively early and deep degassing process able to remove different proportion of Na and K from the melt.

S01.16 Poster

Systematic pre-eruptive dynamic of the magma plumbing system leading to Plinian eruption at Montagne Pelée Martinique (Lesser Antilles)

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Mush dynamic may be at the origin of pressure/temperature variations that may destabilize parts of the transcrustal magmatic system. Crystals can register these modifications of environment and thus offer the unique opportunity to unravel pre-eruptive spatio-temporal dynamic of the mush. Such perturbations may produce at the surface geophysical or/and geochemical signals that could be registered by monitoring network, constituting precursory signals. For volcanoes where the plumbing system is well established in terms of volume and depth for a given cycle, repetitive eruptions of the same order of magnitude and involving similar magma composition may occur. It was the case for Montagne Pelée (Martinique, Lesser Antilles) that produce repetitive Plinian eruptions in the last 15 ky. Are the perturbations in the dynamic of the magma storage identical for all these eruptions and is the timescale between these disrupting events and the eruptions in the same order of magnitude?

We attempt to identify the disrupting event(s) leading to eruptions and the timescale between this event(s) and the eruption. By studying the last five Plinian eruptions of this volcano the question of the systematic occurrence of one process at the same time prior eruption will be discussed. To achieve this goal we performed a detailed petrological description of the eruptive products of the first Plinian phase of these eruptions to build a Crystal System Analyses tree through EPMA and SEM analyses, coupled to Fe-Mg diffusion modelling in orthopyroxenes to retrieve timescale between the disrupting event in the reservoir and the eruption.

We thus highlight that: i) the perturbation event is not systematically the same through all eruptions; ii) the timescale that separate this event from the eruptions is in the order of the year, significantly shorter that what was up to now estimated for large silicic eruptions.

S01.16 Talk

Investigating heterogeneous magma systems by detailed characterisation of the juvenile products: example from the Upper Pumice eruption of Nisyros Volcano (Greece)

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Understanding differentiation processes and transfer of magmas is of crucial importance to improve our knowledge on the behaviour of active volcanoes and thus constraining the processes driving the eruption style as well as the related hazard.

We present a study of a pyroclastic succession generated by the last sub-Plinian explosive eruption of Nisyros Volcano (Greece) known as Upper Pumice (UP) formation. The deposit is constituted by fallout, interlayered with diluted pyroclastic density current (PDC) deposits and is closed by a lag-breccia unit overlaid by a grey ash flow level. The juvenile is mainly constituted by white-yellow, moderately crystalline pumice with rhyo-dacitic composition and homogenous Sr-Nd isotope values (clustered around 0.70456 and 0.51226, respectively). Some amount (<4%) of dense, grey, crystalline juvenile lapilli clasts, with rounded shape and less evolved composition (andesite to dacite) are also present in the basal fallout unit and PDCs. They show a large variability in textures (from peculiar dicktytaxitic to strongly fragmented without a defined structure) as well as in geochemical and isotopic composition (i.e., $^{87}Sr/^{86}Sr$ ranging between 0.70426-0.70489). Contrarily, the juvenile material of the lag-breccia deposit is constituted by dense, gray, crystalline bombs, with crenulate or bread-curst surfaces and microcrystalline, dictytaxitic textures. They show less evolved, basaltic-andesite, compositions with generally low $^{87}Sr/^{86}Sr$ (down to 0.70420).

The presence of different juvenile products, erupted together, but physically separated, together with the observed heterogeneity of the geochemical and isotopic composition, also combined with texture variability of the mafic, crystal-rich clast population, suggests the occurrence of two (or more?) variably evolved magmas, interacting each other in the UP reservoir prior the eruption. This implies the development of complex interaction processes in the plumbing system of Nisyros point to a peculiar pre-eruptive dynamic of the UP eruption as a possible model for similar contexts.

S01.16 Talk

How to make phonolites? An experimental approach

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Phonolites from intraplate volcanoes may occur as both effusive lava domes and pyroclastic sequences emplaced during explosive eruptions. Phonolitic magmas have been proposed to originate by either crustal melting or very low-degrees of melting of mantle peridotites, as well by shallow to deep crustal assimilation/fractional crystallization processes. Uninterrupted eruptive sequences can comprise a spectrum of rock compositions varying from intermediate tephriphonolite/trachyandesite to more differentiated phonolite, hence providing the opportunity to better understand the differentiation mechanisms leading to the internal geochemical variability within one single eruptive unit.

In this study we investigate the Al Shathaa eruption, an explosive event that generated pyroclastic density currents within the central portion of the Harrat Rahat, Kingdom of Saudi Arabia. The eruption begun with a relatively evolved trachytic/phonolitic magma and ended with intermediate tephriphonolitic compositions. We performed phase equilibrium experiments under hydrous and anhydrous conditions to simulate the magmatic evolution that could have potentially produced the observed geochemical variability. The starting trachytic and trachyandesitic compositions were equilibrated at 200-500 MPa, 850-1000 °C, 0-8 wt.% H_2O and the NNO+1.5 buffer. Anhydrous experiments at 200 MPa better reproduce the variation from intermediate to trachytic compositions, whereas hydrous experiments shows Na_2O depletions in the residual melts. Feldspars obtained at 200 MPa also mimic much better the natural feldspar compositions, relative to those derived at 500 MPa. None of the experimental charges reproduced the phonolitic compositions of two samples of the Al Shathaa eruptions. It is suggested that phonolitic magmas may be the result of dynamic processes due to extraction of highly evolved melts from a relatively high permeability crystal mush zone, thus leading to alkali enrichments in some portions of the erupted magma batch. In this view, phonolite generation is a result of crustal plumbing processes.

S01.16 Poster

Characterising olivine diffusion timescales within a monogenetic-style volcanic centre of the Newer Volcanic Province, Australia

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The Newer Volcanic Province across southeast Australia, is composed of many basaltic and andesitic monogenetic volcanic centres formed as recently as 5,000 years ago. This province, consisting of over 400 vents, is considered still active due to CO_2 flux from wells in the region and the detection of a thermal anomaly beneath the Earth's crust. Despite many of the vents being located close to population centres, including Melbourne, little is known about the subsurface activity of these volcanoes should another eruption occur in the future. Furthermore, public education is non-existent, and the transient nature of their activity and poor outcrop makes for challenging study.

Red Rock (~8,000 years old), a complex volcanic centre with over 40 identifiable eruption points located in the Western Plains, is the focus of our study. Past activity has alternated between magmatic and phreatomagmatic episodes where olivine (likely disaggregated from mantle xenoliths) from the rind of a volcanic bomb ejected during a magmatic phase show a range of compositions and textures. They are often euhedral-subhedral, up to several mm in size and normally zoned (Fo_{90-76}) with thick, more-evolved overgrowths, but they also occur with complex or reverse zoning patterns exhibiting various reaction textures. Using Mg-Fe diffusion modelling and evaluation of the olivine textures, we capture the characteristic timescale between disaggregation of the olivine in the subsurface and the eventual eruption and cooling of magma at the surface. Whilst it has been assumed for some time that these magmas ascend to the surface rapidly with little opportunity for ponding or shallow storage due to their high abundance of mantle xenoliths, this is still to be tested. This information provides a better understanding into how these monogenetic volcanoes behave and evolve for those living nearby and may relate to other similar systems worldwide e.g. Auckland Volcanic Field.

S01.16 Talk

Unravelling plumbing system dynamics linked to explosive eruptions through geochemical and in-situ isotopic micro- analyses: the Campanian Ignimbrite (Campi Flegrei, Italy) case study

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Ignimbrite deposits represent an excellent source of information on magma storage conditions and volcanic evolutionary processes as they display great compositional variations and record significant zoning in magma reservoir. Configuration of these magma chambers is still not clear, so their knowledge is an important task to better understand how emptying dynamics work during explosive eruptions. The Campanian Ignimbrite (CI) eruption, from Campi Flegrei volcanic field, produced a voluminous pyroclastic sequence of trachy-phonolitic magma around 39 ka ago. Whole-rock geochemical variations are present, both horizontally and vertically along the sequence.
To provide a complete picture of the compositional variability within the proximal CI deposits, a detailed geochemical and Sr-Nd isotope study of matrix glasses and minerals of all juvenile components have been carried out. We collected samples along seven different proximal CI outcrops, which are representative of all the six stratigraphic units recognised or the proximal CI sequence (PPF-USAF-Piperno-LPFU-BU/SU-UPFU). Our geochemical and isotope data on matrix glasses point out a very slight variability along the sequence while a strong heterogeneity at the micro-scale (i.e. inside single clast: K2O%: 2.71-11.09; Na2O%: 3.43-8.24; $^{87}Sr/^{86}Sr$: 0.706950-0.707487; $^{143}Nd/^{144}Nd$: 0.512452-0.512521), possibly revealing the presence of multiple magma components in the system, interacting in a complex magmatic network. Moreover, crystal geochemical compositions (pyroxenes and feldspar) show a much larger variation than that already displayed in literature (e.g. An-rich plagioclase in PPF).
Recent hypotheses have suggested the presence of a crystal-mush reservoir in the CI magmatic system, which evolved by incremental addition of deeper recharge into its high- cristallinity region. In this light, the present work contributes to better understand crystal mush systems linked to highly explosive eruptions, through a detailed in-situ isotopic micro- analytical study.

S01.16 Talk

Field study of pyroclastic deposits help constraining the emplacement mechanisms from pyroclastic flows

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Pyroclastic flows are a particular type of gravity flow. They move following the acceleration of gravity, under the action not only of a density contrast but also of a velocity gradient with respect to the surrounding atmosphere. Hence, what makes pyroclastic flows unique and dangerous in nature are energy contrast (combined density and velocity) and topographic control. In order to account for both peculiarities, field study (from stratigraphy to petrology) is necessary to better understand the emplacement mechanisms of pyroclastic flow deposits. This is because eruptive conditions play a first order role during pyroclastic flow formation; on the other hand, topography plays a role during pyroclastic flow propagation. For example, longitudinal or transversal thinning of pyroclastic flow units is related first to eruptive mechanisms, then to depositional processes, meaning that the absence or exceptional thinning of the deposits does not necessarily imply erosion. Instead, when an erosion surface is recognized in the field, then the involved deposits can be related to different eruptive events. Another example is the maintenance of pyroclastic flow thickness with runout distance (ignimbritic plateau), which reflects sustained energy during the eruption, but that does not necessarily imply that the single pyroclastic flow units are not rapidly emplaced. Stratigraphic, sedimentological and petrological combined studies can corroborate previous assumptions, then can improve our better understanding the emplacement mechanisms from pyroclastic flows.

S01.16 Poster

A petrological insight on the juvenile products of the last 1000 years of explosive activity at La Soufrière Volcano, St. Vincent (Lesser Antilles)

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Understanding the recent history of active volcanoes is crucial to assessing the volcanic hazard for the surrounding areas. In this perspective, a detailed petrochemical characterization of the emplaced products can give useful insights on the ongoing magma processes driving the volcanic system to its current state. This is particularly true for the La Soufrière Volcano of St. Vincent, the most active subaerial volcano in the Lesser Antilles in historical times, with the last eruption of 1979 reaching a VEI of 3 and leading to the evacuation of ~20000 people. However, most of the current knowledges on magma processes at La Soufrière relies on petrological studies performed on the products of the oldest prehistorical activity, covering the ~600-1.3 ka age interval.

We here present a petrological characterization (whole-rock, mineral and glass phases geochemistry) for the juvenile products of explosive events occurred during the last 1000 years at La Soufrière: the historical eruptions of 1902/03 and 1718/1812 and the prehistorical eruptions of 1580, 1440 and an older undated event. The products of the prehistorical eruptions are represented by basaltic andesite scoria clasts displaying a quite homogeneous composition in terms of both petrography (with labradorite-bytownite plagioclase, Mg- and Al-poor augite clinopyroxene, Mg-poor orthopyroxene and Ti- magnetite) and whole-rock geochemistry (e.g. SiO_2 = 55.1-56.7 wt.%, MgO = 3.13-3.73 wt.%, wt.%, Cr = 20-30 ppm, Zr = 82-96 ppm). Products of the historical eruptions are generally similar but also include less evolved lithotypes, with 1902/03 scoria clasts reaching basaltic compositions with labradorite-anorthite plagioclase, Mg- and Al-rich diopside clinopyroxene and Mg-olivine, SiO_2 = 50.6-51.2 wt.%, MgO = 7.64-7.91 wt.%, wt.%, Cr = 270-300 ppm, Zr = 60-65 ppm. This speaks in favour of a recent magma renewal which possibly triggered a phase of relatively intense volcanic activity (~80-100 year periodicity), culminating with destructive events causing ~1500 deaths.

Volcanic hazards vs. resources: The hidden calderas and recent activity of Bora-Baricha and Tullu Moye, Main Ethiopian Rift

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The Bora-Baricha – Tullu Moye volcanic field (8.2 °N; 39.0 °E) is a poorly known active volcanic area of the Main Ethiopian Rift (MER). Developments in geothermal energy exploration and local and industrial-scale volcanic rock excavations highlight the socio- economic value of the volcanism in this region. Seismicity and deformation, vigorous hydrothermal activity and accounts of historical eruptions around AD1900, suggest that the volcanic field is restless, and future eruptions remain possible. We revisit the volcanic geology of the area, with a focus on the stratigraphy and geochemistry of the products of Late Quaternary volcanism, providing a broader context of the present-day geophysical unrest.

The volcanic geology of Bora-Baricha is dominated by metre-thick stacks of pyroclastic fall and density current deposits alternating with palaeosols. These deposits represent >18 individual eruptions of pantellerite magmas. They overly a sequence of 2 chemically distinct pumice fall and obsidian and pumice lag breccia deposits, both representing major (caldera- forming) eruptions, the youngest of which is dated at 101 ± 17 ka. In contrast, the Tullu Moye area comprises obsidian lava flows/domes, small-volume comendite pumice bomb breccias and fault-controlled basaltic scoria cones.

The presence of basalts and rhyolites erupting from the same locations at Tullu Moye is consistent with volcanic centres further north in the MER; whereas the rhyolite-dominant Bora-Baricha is more similar to silicic systems further south, where “shadow zones” are inferred to deflect mafic magmas to the peripheries of shallow silicic reservoirs. The distinct compositions and fractionation trends of the rhyolites at Bora-Baricha and Tullu Moye also support the presence of separate magmatic plumbing systems. High-resolution DEMs and geophysical data further reveal a structurally complex setting, with transfer faults facilitating a shift in style and volume of volcanism between Bora-Baricha and Tullu Moye. This area is therefore critical in understanding the structural evolution of the MER.

S01.16 Poster

Insights into caldera cycles at Campi Flegrei by combining eruptive history, petrology, and numerical modelling

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Understanding the mechanisms that control the accumulation of large silicic magma bodies in the upper crust is key to determine the potential of volcanoes to produce caldera-forming eruptions. Campi Flegrei is an active and restless volcano, located in one of the most populated regions on Earth, which has produced two cataclysmic caldera-forming eruptions and numerous smaller eruptive events over the last 60’000 years. Here we combine the results of an extensive petrological survey with a thermo-mechanical model to investigate how the magmatic system shifts from frequent, small eruptions to large caldera-forming events. Our data reveal that the most recent eruption of Monte Nuovo is characterized by highly differentiated magmas akin to those that fed the pre-caldera activity and the initial phases of the caldera-forming eruptions. We suggest this eruption is an expression of a state shift in magma storage conditions, whereby significant amounts of volatiles start to exsolve in the shallow reservoir. The presence of an exsolved gas phase has fundamental consequences on the physical properties of the reservoir and might indicate that a large magma body is currently accumulating underneath Campi Flegrei.

The Queréndaro-Indaparapeo cinder cone alignment in the eastern Michoacán-Guanajuato Volcanic Field, México: Geology and volcano-tectonic interactions

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Aligned monogenetic volcanism is very common in the Michoacán-Guanajuato Volcanic Field and in many monogenetic volcanic fields around the world. It is well known that these aligned volcanoes can be related to a pre-existing tectonic fault or fracture, or to a new fracture perpendicular to the minimum horizontal compressive stress along where magmas rise. However, it is not quite understood how do these alignments occur; if they erupted at the same time (within a few dozens of years), if they erupted during a short time interval (hundreds of years) or during a long time interval (thousands of years); and if the eruptive style and magma volumes are controlled by these faults and the regional tectonic stress regime, etc.

In this study, we address the conditions that allowed a 11-scoria cone alignment in close temporal and spatial relation in the Queréndaro-Indaparapeo area, in Michoacán, México. This volcanic alignment is clearly set along a E-W normal fault segment that is part of the active Morelia-Acambay Fault System. A fault source characterization from paleoseismological data indicates that the 20 km-long Queréndaro-Indaparapeo fault is active and capable of producing a M_W 6.6 earthquake.
A new geological map and volcanic stratigraphy assisted by $^{40}Ar/^{39}Ar$ geochronology indicate that this volcanic cluster was emplaced ca. 250 ka ago, likely in a brief time span.

Petrography and chemistry of rocks (SiO_2 55-57 wt.%) suggest that all cones were fed by the same magma batch but vented from independent feeder dikes along the same pre-existing fault. Therefore, the volcanic and tectonic histories of the Queréndaro-Indaparapeo area suggest direct links between volcanism and tectonism in the Michoacán-Guanajuato Volcanic Field.

S01.16 Poster

Long-lived compositional heterogeneities in magma chambers, and their implications for volcanic hazard

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Magmas discharged during individual volcanic eruptions commonly display compositional variations interpreted as new arrivals at shallow depth of more primitive, hotter, volatile- rich magma batches mixing with resident, colder, partially degassed magma. Heterogeneities in eruption products are often interpreted as evidence of short times of order hours from new magma arrival to eruption, raising concerns for exceedingly short time available for emergency planning since the first detection of new magma arrival into a shallow system. Our numerical simulations of the transient, 2D, multi-component dynamics of magma mixing in a shallow chamber reveal that under many conditions, favored by higher magma viscosity, compositional heterogeneities remain in the chamber, up to large regions occupied by nearly pure components. Such heterogeneities are then adsorbed over a time scale dictated by large scale diffusion, that is expected to be of order months to years. Therefore, heterogeneities found in the eruptive products are not necessarily the fingerprint of new magma arrival shortly preceding or triggering the eruption; and short to very short mixing time scales of order hours may in many cases reflect sin-eruptive processes, rather than being associated to new magma arrivals in the shallow magmatic system.

S01.16 Talk

Explosive volcanic activity during the evolution of the Skaros lava shield, Santorini, Greece

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Santorini (Greece) is one of the most explosive arc volcanoes in the world. Major explosive activity of Santorini volcano began ~360 ka ago. Since then, 12 major (Plinian-style) eruptions and many smaller explosive (interplinian) eruptions occurred. Monogenetic and several intracaldera effusive centres, including the Skaros lava shield (~67-54 ka), also formed during this period [1].

This paper focuses on the occurrence of tephra deposits associated with explosive activity of Santorini during the evolution of the Skaros volcano, a mainly basaltic to andesitic lava shield that filled a pre-existing caldera [1, 2]. We recognise a minimum of 8 time intervals with tephra deposits between the ~30 lava flows that constitute the Skaros shield. These tephra deposits consist predominantly of scoriaceous (Strombolian) fallout layers, phreatomagmatic tuffs and, rarely, PDC deposits that range in thickness from a few centimetres to several metres. They were deposited from single, minor and short-lived explosive events or from multiple eruptions closely spaced in time. Bulk-rock compositions of juvenile clasts within the tephra deposits vary between ~51 and 57 wt.% SiO_2, which is broadly in line with the compositional range observed in the Skaros lavas (~50-58 wt.% SiO_2) with the exception of the basal dacitic Skaros domes (~65 wt.% SiO_2).
The occurrence of tephra deposits within the Skaros lava sequence provides evidence of mildly explosive and phreatomagmatic eruptions during constructional intracaldera activity of Santorini. Having originated from the Skaros centre itself or, possibly, from other vents on Santorini, the intra-Skaros tephra layers may provide valuable local stratigraphic markers. Furthermore, some of these previously unidentified tephra layers may well have left a record in the marine realm close to Santorini.

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Evidence of Weichselian volcanic activity in Iceland - records from marine tephra stratigraphy

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Volcanism is a major force in shaping the Earth´s environment. Understanding volcanic processes is therefore an important goal, which can benefit significantly from a thorough knowledge of past behaviour of volcanoes and the course of volcanic events.

For the past approximately 10,000 years the explosive activity in Iceland is relatively well known through studies of numerous soil profiles and lake sediment archives across the country. In this study, the goal is to investigate explosive volcanic activity within the Weichselian glaciation using tephra stratigraphy and tephrochronology in marine sediments from the North Icelandic shelf.

Research questions concern, i) which volcanoes were active, ii) what was the level of their activity and iii) is it possible to detect periodicity in the explosive volcanic activity.

Preliminary results from the marine archives indicate that the most active volcanic systems in Iceland during the last 50,000 years were Kverkfjöll, Bárðarbunga-Veiðivötn, Grímsvötn and Katla. Evidence from Hekla, Krafla volcanic system and the Kolbeinsey ridge are present. There are strong indications that volcanism in Iceland during the Holocene has been periodic at several timescales, with apparent periods of 140, 500, and 4-5000 years. Preliminary results from this study indicate that the 4-5000 year periodicity extends as far back as 50,000 years, with eruption frequency peaks between 1-2000; 5-7000; 9-10,000; 12-14,000; ~16-18,000; ~22-23,000; ~32-33,000; 36-~37,000; ~45-46,000; and ~49-50,000 years BP.

S01.16 Poster

Magma degassing timescales at Soufrière Hills Volcano, Montserrat

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Examining the role which gas plays in volcanic systems is vital for understanding the magmatic system prior to eruption, as well as for natural hazards predictions. Short-lived isotopes of the uranium series decay chain are ideal for tracing degassing histories at recently active volcanoes as the isotope ^{226}Ra decays to ^{210}Pb (half-life = 22 years) via its intermediary daughter ^{222}Rn (half-life = 3.8 days), which partitions into the gas phase of magmas. Consequently, excesses of ^{210}Pb relative to ^{226}Ra can constrain the longevity and extent of gas transfer prior to an eruption, while deficits indicate persistent open system degassing of the magma. By analysing age-constrained eruptive material, timescales can be modelled for the duration of degassing or gas build-up prior to eruption.

The 1995-2010 eruption of Soufriere Hills Volcano (SHV) on the island of Montserrat is separated into five distinct phases of activity. Mafic enclaves are a notable feature within andesitic dome material and provide an excellent opportunity to investigate the deeper parts of the magmatic system feeding the eruption. The andesites are almost entirely in equilibrium or have deficits of ^{210}Pb with the deficits becoming more pronounced over time. This suggests that the andesitic reservoirs involved were subject to continuous closed-system degassing over the course of the eruption. The majority of enclaves, however, have excesses of ^{210}Pb, showing recent gas enrichment. The highest (^{210}Pb/^{226}Ra) ratios are from enclaves in Phase II, and we suggest that the deeper system was closed to fresh gas influx from Phase III onwards, consistent with monitoring and petrological observations.

S01.16 Poster

Elucidating timescales of magma storage and mixing during the 2013-present eruption at Volcán de Colima, Mexico

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Volcán de Colima is one of the most active volcanoes in the Americas. Previous work has identified abrupt transitions between effusive and explosive eruption phases, with five recorded Plinian eruptions in the past 500 years. These events present serious hazards to the 300,000 people living within 40 km of the volcano.

Studies of past eruptive activity have proposed that injections of new magma may control abrupt transitions in eruption style. However, the timescales of pre-eruptive magmatic processes within the volcanic system have not been quantified, and their relation to the seismic and gas monitoring record has not been explored. This poses a major limitation on our understanding of the magmatic system at Colima.

The current (2013-present) phase of activity, characterised by lava dome growth and collapse events, lava flows, and occasional Vulcanian eruptions and associated pyroclastic flows, provides an unique opportunity to understand the eruptive behaviour of Volcán de Colima and to unravel the explosive-effusive transition and eruption trigger factors. The extensive monitoring records at the volcano also allows us to explore the link between timed magmatic processes and monitoring data.

Fieldwork was undertaken in April to June 2018 to collect samples of the eruptive products of the 2013-present phase. We will use petrological and mineral chemistry data and diffusion modelling to constrain timescales of magma recharge events and understand the dynamics of the plumbing system. We will also combine monitoring data with petrological information to construct robust models of the pre-eruptive dynamics of the magmatic system.

The results of the project will investigate underlying causes of the transitions in eruptive styles, a key unresolved question in volcanology and will help inform volcanic hazard assessment at Volcán de Colima.

Mixing, Mingling and Magma Mushes: dynamics and timing of twinned eruptions

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Magma mixing and recharge have long been recognised as eruption triggers. Numerous volcano-tectonic episodes have occurred in Iceland where melt was transported and erupted along a fissure system. In the 2014 Holuhraun episode, a 45-km dyke was quickly emplaced and gradually extended threatening to intersect Askja's plumbing system[1]. Whilst this was not the case, the Torfajökull volcanic system provides evidence of successful injection of more primitive material into a silicic system.

Torfajökull is the largest silicic centre in Iceland. Situated in the south east, it intersects the southern tip of the Veiðivötn fissure swarm. Historically, Torfajökull and Veiðivötn erupted simultaneously in 871AD and 1477 and whole rock chemistry and macrotextures show evidence for mixing between rhyolitic and basaltic material[2]. Macro-scale petrological investigations highlight the presence of mafic blobs and filaments, suggesting failed hybridisation and a large viscosity contrast. Such interactions are observed microscopically in the crystal cargo. Plagioclase populations contain zoned crystals, mushy glomerocrysts and exhibit kinked CSDs indicating the presence of multiple populations. Crystals show large anorthite ranges within single eruptions (30-80 An%) where high anorthite cores and low anorthite rims show evidence for two levels of magma storage, at ~4 and ~2 kbar.

CVD timescales suggest fast mixing to eruption times, consistent with diffusion timescales calculated from SIMS data of ~10 days, with magma ascent rates of ~0.02 km/h.

Seismological techniques haven't been able to identify a large shallow magma chamber[3], and it is thought that rhyolitic melts are present in the crust as small pockets[4]. Nevertheless petrological observations and short timescales provide evidence for recharge and magma mixing to be able to remobilise and erupt magma underneath Torfajökull.

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Evolution of monogetic volcanism in Sierra Chichinatuzin and hazard implications

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Monogenetic volcanism in Sierra Chichinautzin has an important effect in landscape and cultural behaviour of the inhabitants of the south of Mexico City. This volcanism has been recurrent in at least 1 Ma and, based on the results of morphometric study, mapping, relative dating, twenty-four new 40Ar/39Ar dates, and chemical analyses, the monogenetic cones in Sierra Chichinautzin were divided into four groups: (1) Peñón Monogenetic Volcanic Group (PMVG; 1,294 ± 36 to 765 ± 30 ka; (2) Older Chichinautzin Monogenetic Volcanic Group (Older CMVG; 238 ± 51 to 95 ± 12 ka); (3) Younger Chichinautzin Monogenetic Volcanic Group (Younger CMVG; < 35 ± 4 ka) and (4) Sierra Santa Catarina Monogenetic Volcanic Group (SSC; 132 ± 70 to 23 ± 4 ka). Initial monogenetic volcanism started in the northern part of the study area with basaltic-andesite cones that are aligned N60°E. After last eruption, monogenetic volcanism stopped for ~527 ka. The second monogenetic field (Older CMVG) was reactivated at 238 ± 51 ka in the southern part of the area with andesitic to basaltic andesite cones and ended at 95 ± 12 ka, then monogenetic volcanism stopped again for ~60 ka. The third volcanic field (Younger CMVG) started in the eastern part of the area at ~35 ka, close to Popocatépetl volcano, the cones are aligned in an E-W direction and this field is considered still active since the last eruptions took place less than 2 ka, possessing considerable ash and lava flow hazard to Mexico City. The fourth volcanic field (SSC) is located in the northern part of the area, separated for the rest of the volcanoes by lacustrine deposits, and formed basaltic andesites to andesitic cones oriented N70°E. Chemical variations in major and trace elements between each volcanic field suggest different magma source.

S01.16 Poster

Magma output rates of the Late Quaternary Ciomadul (Csomád) lava dome complex using digital elevation model (DEM) volumetry and Cassignol- Gillot K-Ar dating

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Volumetric analysis and Cassignol-Gillot K/Ar dating have been used to infer the rates of magma output for the Late Quaternary Ciomadul (Csomád) dacitic lava dome complex, East Carpathians, Romania. The volcano showed an extended eruptive history from ~850 ka to <30 ka. A dominantly effusive activity took place during the first several hundred thousand years, producing isolated, peripheral domes and, subsequently, a central dome cluster. In contrast, during the youngest phase of evolution (~60 to 30 ka), highly explosive eruptions occurred, resulting in the formation of two central, adjoining craters (Mohos and St. Ana) decapitating the central dome during highly explosive eruptions. The calculated 7.99 km^3 cumulative total volume of the lava domes, which includes the related volcaniclastic as well as erosionally removed material, matches the dimensions of medium-sized dacitic lava domes worldwide. Such a volume was produced in the long term at a rate of 9.7 km^3/My (0.0097 km^3/ky). However, most of the domes (7.52 km^3) formed between 200-30 ka, implying a significantly increased lava extrusion rate of 44.2 km^3/My (0.0442 km^3/ky) in the second stage. Within this, individual lava domes with volumes between 0.02 and 0.4 km^3 could have been emplaced at even higher rates in the order of 1-10 km^3/ky. The most recent eruption of Ciomadul has been dated at 27.7±1.4 ka. Such a young age, which was obtained on brecciated lava dome rock draping the southern slopes of St. Ana explosion crater, shows that in the latest phase both extrusive and explosive activity were going on.

The origin of the K-feldspar megacrysts in trachydacites from Mt. Amiata Volcano (Southern Tuscany, Italy)

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K-feldspar megacrysts are common in plutonic rocks and well known in the literature, but relatively rare in volcanic products. This study documents the complex textural and chemical zoning of the K-feldspar megacrysts (up to 5 cm long) hosted in trachydacitic lava domes and *coulées* of Mt. Amiata volcano (Central Italy). BSE and CL images coupled with core to rim major and trace element patterns evidence a crystallization history mainly driven by disequilibrium/re-equilibration phases due to influx of mafic magmas and/or convection in the magma reservoir. Repetitive events of magma mixing are testified by the field occurrence of abundant microgranular mafic enclaves. The internal portion of the crystals are typified by patchy zoning and major resorption surfaces associated with sharp chemical variations due to influx of mafic magmas. The chemical composition rimward of the resorption surfaces is related to the degree of hybridization of the magma, while disequilibrium crystal growth can result in anomalous increase of Ba contents. The patchy portions of the crystal are intercalated with oscillatory zoned layers showing smaller chemical variations and weak dissolution and are related to crystal growth/dissolution in a convective magma chamber. The same textural feature is observed in the external corona of the megacrysts. The occurrence of portions with different trace element enrichments (e.g. Sr, Rb, Ba and Li) within the megacrysts is seen as evidence of influx in the shallow trachydacitic reservoir of mafic magmas with distinct chemical signature. The megacrysts originates by an interplay of dissolution and crystallization kinetics: (i) a relatively low nucleation rate promotes homogeneous crystallization and (ii) coarsening of crystals brings to the formation of aggregates that act as nuclei for a new megacrysts.

S01.16 Poster

Lithosphere thermal structure and magmatism of the Tyrrhenian margin of Central Italy: implication for long term volcanic hazard assessment

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We present a research project aimed at reconstruct the thermal evolution of the crust and the emplacement level of magma since late Miocene along the Tyrrhenian margin of the Central Italy (Tuscany and Latium) by using intrusive and effusive products as a "gouge" of the thermal state of the crust. Thinned continental crust (about 23 km), high heat fluxes and shallow seismicity characterize the present Tyrrhenian margin of Central Italy and such scenario can be bring back in time to early Pleistocene (2.5 Ma; Chiarabba et al., 2014; Faccenna et al., 2014). Magmatism along the Tyrrhenian margin occurred since late Miocene (8 Ma), intrusive record predominates in the northwest sector whereas volcanism predominates in the southeast one (Peccerillo, 2017). Thermo-barometric estimation will be performed by analyzing composition, mineralogy and texture of selected intrusive and effusive rocks (Anderson et al., 2008). Time scales of magmatic processes will be derived from thermo chronology on zoned crystals (i.e. zircon; Barboni and Schoene, 2014). Expected results will gather information on the magma emplacement depth or its pre- eruptive stall along the Tyrrhenian side of Central Italy. Moreover, they will provide the basis for the long-term volcanic hazard assessment along this sector of the Tyrrhenian margin of Italy.

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Eruption history and event tree of Semeru volcano, Indonesia

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Semeru volcano is one of the most active volcanoes in Indonesia. The major purpose of this study is to make an event tree for Semeru volcano, based on understanding its eruption history. The recent activity is represented by persistent small-scale Vulcanian and gas burst. The activity increases every 5–7 years producing several km-high eruption columns, ballistic bombs, and tephra fall. Dome extrusion in the vent and subsequent collapses produce block and ash flows. The activity is limited in the summit area but flank lava flows occurred on the lower SE and E flanks in 1895 and in 1941–1942. We carried out the field inspection in the SE, SW flank and the N slope to the summit in 2016 and 2017. Based on the geological surveys and ^{14}C age determination, the stratigraphy of tephra and lava flows was constructed. The eruptive history can be divided into major three stages. The younger stage (after 11th Century) is characterized by explosive andesitic eruption. The middle stage (3-10th Century) was dominated by effusive eruption mainly of basalt magma in parasitic cones. Scoria cones on the northern foot of the volcano were activated in this stage. The older stage (before 3th Century) was dominated by explosive andesitic eruption. Volcanic rocks are chemically bimodal (andesite, 56-61 wt.% in SiO_2; basalt, 46-53 wt.% in SiO_2) throughout the eruption history. Furthermore, 3D models of the volcano were made from satellite images of the whole area and drone-images on the summit-crater area. The data is used to estimate the volume of the summit dome and topographical features of the entire volcano, which are essential to calculate discharge rate and to expect the maximum scale of pyroclastic flows and their directions. Based on field inspection, laboratory analyses, and review results, we construct a preliminary event tree.

S01.16 Poster

Timing is everything: Magma injections in the build-up to effusive and explosive eruptions at Popocatépetl volcano, Mexico

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Understanding the transition from effusive to explosive activity is a major challenge in modern volcanology, both from a scientific and hazard mitigation perspective. Popocatépetl is a typical andesitic – dacitic arc volcano exhibiting a variety of eruptive styles, with at least three Plinian eruptions and six voluminous effusive episodes in the last 14.1 ka, as well as mildly explosive present-day activity.

In order to constrain pre-eruptive magmatic dynamics and timescales for both explosive and effusive eruptions at Popocatépetl volcano, we model Fe – Mg diffusion in compositionally zoned orthopyroxenes of the Yellow Pumice Plinian eruption (YP, 2150 ys BP, VEI = 6; Siebe and Macías, 2006), the Pink Pumice Plinian eruption (PP, 1100 ys BP, VEI >4), and the intercalated effusive Nealticán fissure eruption. All three events show evidence for a mafic injection into a shallow evolved reservoir in the weeks to months prior to the eruption, indicating a causal relationship. However, while opx in the Nealticán lavas only record one injection <1 y before the eruption, and two further ones <100 ys, the Plinian events show a significantly higher frequency of magma injections in the decades preceding the eruptions. In case of the YP, a series of mafic injections 2 – 20 ys prior to the event is recorded in opx, and timescales <1 y are rare. In contrast, the PP shows a peak of injections <1 year before the eruption.

These results suggest distinct pre-eruptive dynamics and triggering mechanisms, not only for effusive and explosive activity, but also between the Plinian eruptions. However, a consistent pattern of increased injection rates prior to the YP and PP explosive events compared to the effusive Nealticán eruption indicates that magma injections exert crucial control over eruptive styles at Popocatépetl volcano by replenishing and pressurising the shallow plumbing system with melt and volatiles.

S01.16 Talk

Insights into the origin and correlation of the Brown Tuffs on the Aeolian Islands, Italy

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The Brown Tuffs (BT) are widespread lithologically-homogeneous, reddish-brown to grey, ash-rich pyroclastic deposits in the post-80 ka stratigraphic sequences of most of the Aeolian Islands and on the Capo Milazzo peninsula (Sicily).

Here we present a revised stratigraphy and new grain-specific volcanic glass (electron microprobe) chemistry for the different BT units on the islands of Lipari, Vulcano and Salina, which provide constraints on their large-scale correlation and insights into the eruptive and depositional mechanisms. The three stratigraphic macro-units in which the BT are principally subdivided, Lower (70-56 ka; LBT), Intermediate (56-27 ka; IBT) and Upper (24-8 ka; UBT), can be geochemically distinguished based on the SiO_2, alkali and TiO_2 glass contents. There is a significant increase in the degree of evolution of the magmas through the succession, from basaltic trachy-andesites to trachytes. Compositions are consistent with an origin from the area of La Fossa Caldera on Vulcano. Here, we highlight that the UBT compositions are similar to those of the early pyroclastic products (Punte Nere) erupted at the active La Fossa cone indicating the magmatic system typically erupts homogenous melts.

In different BT depositional units on Lipari we have observed the presence of a minor component of rhyolitic pumice clasts compositionally correlated to the underlying (local) pyroclastic units (P. di Perciato, Falcone, M. Guardia, V. del Gabellotto). The incorporation of these older pumices is evidence of abrasion of the unconsolidated substratum during the emplacement of the PDCs that deposited the BT in proximal to mid-proximal areas.

The interlayered tephra layers which provide stratigraphic boundaries between the BT units have been geochemically related to widespread central Mediterranean isochronous markers, particularly recording a multiple ash fall activity from the Ischia volcano. Importantly, some of these tephra layers have not been previously reported in the volcanic stratigraphies of the Aeolian Islands.

S01.16 Poster

Pairing Vent Distributions and Recurrence Rates to Better Understand Volcanic Hazards at Medicine Lake Volcano, Northern California, USA

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Medicine Lake Volcano (MLV) is the largest Cascade Volcano by volume (~600 km3) and has erupted 9 times during the Holocene. Detailed mapping by the USGS has shown that during the last 500 kyr MLV has erupted >200 lava flows, one ash-flow tuff (VEI 5-6), and built at least 17 scoria cones. Rhyolite, dacite, andesite, basaltic-andesite, and basalt have all erupted throughout the geologic record, but mafic vents make up 78.2% of the total mapped vents. During the Holocene the proportion of felsic vents is significantly higher (54.5%) than mafic vents (39.9%).

Though the possibility of explosive eruptions does exist at MLV, new vent openings and lava flows are the most frequent and expected volcanic hazard. We use 522 vent locations to complete a series of spatial density calculations aimed at exploring the temporal and geochemical distribution of volcanism at MLV. Our analyses show that felsic vents cluster at the center of the volcano (near and within the caldera) regardless of age. In contrast, Pleistocene mafic vents are widely distributed but become more focused during the Holocene. Two linear trends, along which vents of all compositions cluster, develop during the late Pleistocene and Holocene. Using the Volcanic Event Age Model (VEAM), developed at USF, we calculate recurrence rates using 60 radiometric dates and 735 stratigraphic relationships. Results show Pleistocene mean recurrence rates to be relatively constant within a range of 0.5–2.0 events per kyr. A sharp uptick occurs between 12-13 ka reaching a peak rate of 7.8 events per kyr. A hiatus follows before elevated activity resumes at 6 ka and reaches 6.0 events per kyr at 1 ka. By combining high-resolution temporal and geochemical data to better constrain past volcanism at MLV, we aim to better anticipate the nature and hazards of its future eruptions.

S01.16 Talk

Facies architecture of a felsic subaqueous volcano in the Katakai gas field, Niigata, Japan

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Volcanic oil and gas reservoirs are among the most important targets for exploration in Japan. The Katakai gas field in Niigata prefecture, northeast Japan, is an uncommon field producing gas from the "Green Tuff" formation. This reservoir was formed by a subaqueous volcanic eruption in greater than 4000 m of water during back-arc rifting in the middle Miocene.
To describe the petroleum geology of the field, we employed a geological concept model composed of felsic subaqueous lava flows and cryptodomes based on the analysis of cores, well cuttings, and electric well logs. While the model generally predicted the facies architecture, difficulty in classifying facies of felsic volcanoes from microscopic analysis can result in inconsistencies between the concept model and well data.
In order to fine-tune the geological concept model to a natural geological architecture, a concept previously used to classify the facies architecture of the felsic, subaqueous volcano in Kamisannai rhyolite to the Katakai field as an analogue. This methodology combined the microscopic observation of cuttings with well logs correlation and restoration of the volcano.
Consequently, the volcanic facies of Katakai felsic rocks were classified into seven facies of which perlite/pitchstone (P) and in-situ block lava facies (IB) were identified as good reservoirs. The interior of the lava flow consists of coherent rhyolite lava (CL), perlite/pitchstone (P), and flow-banded perlite/pitchstone facies (F). In the exterior, in-situ block lava (IB) and rotated block lava facies (RB) were observed. The outermost facies are proximal resediment (PR) and distal resediment facies (DR). Moreover, we detected several units of felsic subaqueous volcanic lava flows, each 100–300-m-thick, which is consistent with the thickness of lavas in Kamisannai Rhyolite. Further work includes expanding these interpretations for the entire area of the field to better understand the geological system and increasing the gas reserves in Japan.

S01.16 Poster

How complete is the explosive eruption history of Iceland and are the missing chapters important?

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Iceland is one of the most active volcanic regions of Earth. During the last 11 centuries eruption has occurred on average every 3-5 years. Two out of three of these are tephra- producing explosive eruptions and by adding hybrid eruptions, 75% of the eruptions are tephra-producing. Therefore, the tephra record is ideal to obtain information on history of explosive and hybrid eruptions in Iceland. The Grímsvötn and Bárðarbunga volcanic systems, situated at the presumed hot spot centre and partly covered by the Vatnajökull ice- cap, are the most frequently erupting systems. Comparing the number of preserved Grímsvötn and Bárðarbunga tephra layers in Vatnajökull ice-cap and in terrestrial, lacustrine and marine environments for the same time period, it is evident that the preserved tephra record is incomplete. Tephra profile sites closest to the Grímsvötn and Bárðarbunga volcanic systems (i.e. near the glacier margins) reveal that the tephra deposit from one out of four tephra-producing eruption is preserved in the Holocene soil and sediment records and preservation decreases with distance from source. In the third-ranked and ice-capped Katla volcanic system, about half of Holocene eruptions are preserved as tephra layers east of the volcano. This indicates that up to 75% of these explosive eruptions are not recorded in the Holocene soil and sediment achieves, because deposition of significant amount of the erupted material was confined to the area covered by glaciers. Frequency of eruptions that never break through the ice to form detectable tephra deposits is unknown. These unrecorded eruptions can be a hazard for the nearby populated areas, caused by tephra fall, lightning's and jökulhlaups. Populated areas in Iceland that can be affected by small eruptions that would probably not leave a trace in the neighbouring strata are in the vicinity of Katla, Eyjafjallajökull and Snæfellsjökull.

S01.16 Poster

Micron-scale trace element heterogeneity: Understanding syn- eruptive degassing during the 2011-2012 Cordón Caulle eruption

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Hybrid activity, simultaneous explosive and effusive volcanic behaviour from a single vent, was observed during the 2011 – 2012 crystal-poor rhyolite eruption at Cordón Caulle in Chile. It marked the transition from the explosive plinian phase to the effusive, rhyolite flow phase. Preserved groundmass glass variations in major volatile species (e.g. H_2O and CO_2) have contributed to our understanding of degassing processes at many other volcanoes, but Cordón Caulle is uniformly H_2O- and CO_2-poor, thus less is known about how this rhyolite lost its volatiles. However, major volatiles act as carrier gases for volatile trace elements, as evidenced by their enrichment in fumaroles and the surface environment. Here we assess the extent of chemical heterogeneity in bombs from the hybrid activity phase and vent structure. We explore how this heterogeneity can gas pathways and the timescales of degassing events.

Our results indicate minimal major- and trace-element variation across both explosive and effusive products. However, individual samples show large spreads in concentrations that correlate with textural variations. Electron microprobe analyses of groundmass glass indicate intra-sample variations are associated with oxide banding (e.g. TiO_2), fracturing and tuffisite veins (e.g. Cl). Laser ablation ICP-MS analyses indicate depletions of volatile metals (e.g. Cu, Pb) in vesicle-rich zones and tuffisite veins. Furthermore, diffusion profiles of volatile elements (e.g. Li, Cu, Tl) have been observed towards fracture surfaces allowing for quantification of the timescales of melt-fracture induced degassing. Results indicate element mobility is restricted to short distances and is primarily a consequence of local, syn-eruptive loss of metals to the vapour phase and subsequent microlite and oxide crystallisation. Combining a chemical approach with textural studies is helping to constrain the enigmatic degassing processes at Cordón Caulle. We show trace elements can be a viable alternative to assessing degassing in samples with minimal residual water contents.

S01.16 Talk

From rocks to forecasts: Determining physical magmatic history from crystal chemical records. Eyjafjallajökull 2010 and beyond

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Crystal Rain is a novel concept of magma petrogenesis that explains systematic patterns of crystal chemical disequilibria. It combines elements of fractional crystallisation, partitioning and diffusion, and crystal transfer into one self-regulating mechanism that takes place within a sill prior to eruption. By integrating these crystal chemical patterns with element diffusion chronometry, detailed 4-dimensional magmatic plumbing system behaviour can be reconstructed. The concept was conceived from data gathered from the flank eruption of Eyjafjallajökull 2010; magma-mixing failed to explain these data. Since it is possible to determine the origin and history of all the crystals within a single causative framework, the degrees of freedom for physico-chemico-temporal models are greatly reduced. Thus fully determinable pre-eruptive physical histories, and by extension surface expressions of those histories, are a step closer to being reconstructed. Here we focus upon the petrogenesis of the Eyjafjallajökull summit eruption, and also look further afield to gauge how useful Crystal Rain may be in explaining crystal cargo and chemical disequilibrium in some other cases.

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Quantitative measurement of olivine composition in three dimensions using X- ray micro-computed tomography; implications for crystal disequilibria libraries and volcano behaviour typification

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Here we develop a quantitative and reproducible method to measure olivine composition in three dimensions without destructive analysis, meaning full textural context is maintained. The olivine solid solution between forsterite and fayalite was measured using a combination of three-dimensional (3D) X-ray imaging techniques, 2D back scattered electron imaging, and spot-analyses using wavelength dispersive electron probe microanalysis. The linear attenuation coefficient of natural crystals across a range of forsterite content from ~72-92 mol% were confirmed to scale linearly with composition using 53, 60 and 70 kV monochromatic beams at I12-JEEP beamline, Diamond Light Source utilising the helical fly- scan acquisition. A polychromatic X-ray source was used to scan the same crystals, which yielded image contrast equivalent to measuring the mol% of forsterite with an accuracy <1.0 %. Now polychromatic beam characterisation has been applied quantitatively to silicate materials (Pankhurst et al. SoftwareX 2018), X-ray tomography can now provide fully integrated textural and chemical analysis of natural samples containing olivine, which will support 3D and 3D+time petrologic modelling. The method is ultra-fast in comparison to in-situ techniques, offering a technological solution to the vision of a) construction of large crystal chemical databases and b) responsive petrologic study in the event of volcanic crises.

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Global time-size distribution of volcanic eruptions on Earth

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Volcanic eruptions differ enormously in their size and impacts, ranging from quiet lava flow effusions along the volcano flanks to colossal events with the potential to affect our entire civilization. Knowledge of the time and size distribution of volcanic eruptions is of obvious relevance for understanding the dynamics and behavior of the Earth system, as well as for defining global volcanic risk. From the analysis of recent global databases of volcanic eruptions extending back to more than 2 million years, I show that the return times of eruptions with similar magnitude follow an exponential distribution, therefore, that the eruptions are Poisson distributed. That implies that the probability of a next eruption on Earth with given magnitude does not depend on the time since the last eruption of that same magnitude. The relative frequency of eruptions with different magnitude displays a power law, scale-invariant distribution over at least six orders of magnitude. These results suggest that similar mechanisms subtend to explosive eruptions from small to colossal, raising concerns on the theoretical possibility to predict the magnitude and impact of an impending volcanic eruption.

Rapid mixing and short storage timescale in the magma dynamics of a steady-state volcano

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The Present-day activity of Stromboli volcano (Italy) is typical of a steady-state volcano, with a shallow magmatic reservoir (*hp*-magma) continuously refilled by more mafic magma (*lp*- magma) at a constant rate, accompanied by mixing, crystallisation and eruption. We investigated the Post-Pizzo (PP) pyroclastic sequence and one of the Early Paroxysms (EP) of the Present-day activity to clarify timescale and dynamics of the plumbing system at the establishment of the Present-day steady-state activity.

Clinopyroxenes from both PP and EP record a complex history that reflects growth in three different melt domains: a high-Mg# proto-*lp*recharging magma, a low-Mg# proto-*hp*resident magma, and a transient intermediate-Mg# magma. These are the result of complex turbulent flow fields and mixing regimes produced by repeated injections of the proto- *lp*magma in the shallow proto-*hp*magma reservoir. During the PP period the magmatic system was already able to regain the pre-input proto-*hp*composition owing to efficient (days to a few years) stirring and melt homogenisation (homogenisation time < residence time) (Petrone et al., 2018 *EPSL*).

Based upon Fe-Mg diffusion in clinopyroxene the total residence time during PP and EP periods, from the arrival of the mafic magma in the shallow system until the eruption, ranges from 1 to ~50 years. Some clinopyroxenes from the PP recorded the mafic triggering event of the feeding proto-*lp*magma occurring within few months to a few days before eruption. Remarkably, other clinopyroxene portions crystallised and captured the rapid timescales (a few days) of the on-going mixing and homogenisation process between the proto-*lp*and the proto-*hp*magmas leading to the eruption (Petrone et al., 2018 *EPSL*). The lifetime history captured by Fe-Mg zoning of Stromboli clinopyroxenes suggests that the interplay between rapid mixing and short storage timescales can be a key parameter controlling the dynamics of the plumbing system of steady-state volcanoes.

Simulating the emptying of a closed magma chamber by a self-organized fracture mechanism: a conceptual framework for linking different eruptive regimes

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We study the statistical features of eruptive events causing the emptying of a closed magma chamber by using a discrete dynamical system where magma spreads through self- organized fracture networks. Specifically, the complex interactions between magma and rock are modelled by means of three dynamical variables that, respectively, control the occurrence of self-organized crack networks, the magma diffusion and the formation of high-density dikes, which magma uses to eventually reach the surface. In particular, the numerical analysis has been carried out for investigating the main features of erupted volumes and repose times statistical distributions. Interestingly, the model predicts that erupted magma is, generally, a mixture of magma that has continuously stopped during the whole ascent path from the chamber to the surface, except for eruptions above a given size threshold, for which it is possible to distinguish two dominant components deriving from specific depth ranges. Such a finding can provide a theoretical framework for the general feature of many volcanic eruptions whose deposits are characterized by two different magmas. Furthermore, in the distribution of repose times a timescale separation between short and long more probable repose times is found, which increases by deepening of the magma chamber. The identification of two different types of repose times suggests the presence of different patterns, which could help the understanding of the processes responsible for different eruptive regimes.

S01.16 Talk

Magmatic evolution of rhyolitic melts: A melt inclusion study

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Pudahuel ignimbrite is a rhyolitic (~76% SiO_2), quaternary, crystal poor deposit associated to the Maipo volcanic complex in the Southern Volcanic Zone of the Andes. It was emplaced during a massive eruption of ~450 km^3 of pumice and ash. Even though its deposits are near main cities in Chile and Argentina, its genesis is not well understood. This work pretends to elucidate the magma processes that could be involved in the origin of this eruption through the study of composition and volatile content of melt inclusions.

The products of the eruption are present in Chile and Argentina, in three main valleys, and samples were collected from each of them. A general description shows that the main phases are glass, plagioclase, biotite, magnetite, ilmenite, zircon, monazite and apatite. Plagioclase is the most abundant mineral (~1.6%), and display melt inclusions that were selected for analyses. It can be identified two families of plagioclase in the samples: normally zoned (An_{40-17}) and unzoned (An_{17}), with both families contain melt inclusions. Eight samples of Pudahuel deposit were selected for this study: six belonging to the same stratigraphic column, in order to study if variations in magma composition exist during the event, and two corresponding to the upper part of the ignimbrite deposit, sampled in other locations.

At least three melt inclusions assemblages (MIAs) have been identified for the samples: MIA1, trapezoidal inclusions, completely homogenized; MIA2, rounded ellipsoidal inclusions, with a single bubble; and MIA3, rounded ellipsoidal inclusions with more than one bubble. The average size of inclusions is between 30 and 10 um.

This melt inclusions are trapped in both plagioclase families, both in the core and the rim of the crystals. Therefore, their composition will allow to determine the evolution of the melt in the magma chamber, and possibly explain how this catastrophic eruption was originated.

The $^{3}He/^{4}He$ signature of two Chilean volcanoes: Lascar and Lastarria

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Recent studies on arc volcanism argue that subducting sediments can modify the composition and flux of major volatiles degassed at the surface. Instead, less clear is the influence (if present) on the composition of trace volatiles, especially helium. This problematic is even more complex in volcanic arcs developed on continental crust, like the South American segment, because of the occurrence and overlapping of crustal contamination processes due to high crust thickness.

In this study, we investigate the geochemistry of noble gases in fluid inclusions (FI) trapped in olivine and pyroxene crystals separated from rocks erupted from two Chilean volcanoes: Lascar (5,592 m a.s.l.) and Lastarria (5,697 m a.s.l.). These volcanoes are located in the Central Volcanic Zone (16° S - 28° S), at the edge of Nazca plate and above 40–71 km of continental crust. FI data are integrated by the composition of minerals and whole rocks, and finally compared with those from fumaroles.

The $^{3}He/^{4}He$ measured in olivine-hosted FI from Lascar are between 6.9 and 7.3, falling at the lower limit of MORB range (8±1 Ra). These values are comparable to those in fumaroles, indicating that the latter are representative of the magmatic source. Instead, FI in pyroxene show lower ratios (5.2-5.4 Ra) indicating shallower crystallization than olivine, and the entrapment of fluids contaminated by radiogenic ^{4}He.

In Lastarria volcano, olivine FI yield 8.0 Ra, within MORB, while pyroxenes vary between 5.3 and 6.6 Ra, suggesting shallow contamination as observed for Lascar pyroxenes. Fumaroles from Lastarria vary in the same range of pyroxene, indicating that are fed by shallow and contaminated magma bodies.

Assuming $^{3}He/^{4}He$ signature of olivine FI as representative of local mantle, we conclude that ^{4}He-bearing fluids from the slab could contaminate the wedge below Lascar, while this seems not to occur below Lastarria.

The pre-eruptive magmatic processes prior to the large 1886 AD explosive eruption at Tungurahua volcano (Ecuador) revealed by petrology and in situ Sr isotopes

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Understanding the pre-eruptive dynamics of historical eruptions is of paramount importance for understanding the dynamics of the on-going eruption and the causes of drastic changes in the eruptive dynamism. The large explosive events at stratovolcanoes are characterized by recurrent andesitic, vulcanian or subplinian phases, interspersed with rare dacitic, plinian phases, arguing for a complex combination of open-system petrological processes. Our approach focuses the magmatic processes recorded in the isotopic zonation of crystals. Core to rim isotopic profiles represent a record of magma evolution from crystal nucleation to eruption. Isotopic profiles and the relationship between isotopic composition and petrographic features may be used to constrain magma evolution pathways and to trace components that contribute to magmas.

In this work, we explore the origin of the magmatic processes that led the large plinian 1886 AD eruption of Tungurahua volcano. A recurrence rate of at least one pyroclastic flow- forming eruption per century has been estimated, placing Tungurahua amongst the most active volcanoes of the Northern Andes. This approach is based on BSE imaging, and major- trace element measurements coupled with *in situ* Sr isotope analyses of plagioclase crystals from three distinct samples, two from the pyroclastic flows deposits and one from the andesitic lava, representing the successive events during the 1886 AD eruption.

Preliminary results show that abrupt changes in $^{87}Sr/^{86}Sr$ ratios are correlated with distinct petrologic discontinuities such as resorption, coarsely sieved and oscillatory surfaces in crystals. The Sr isotope ratios and major-trace element data reveal that crystals last equilibrated in the same magma. However, their composition diverged from rim to core, and thus back through time, suggesting divergent histories. The $^{87}Sr/^{86}Sr$ ratios of the crystals cores has decreased through time until a primitive composition (0.7035±1), suggesting that injection of mafic magma carrying unradiogenic Sr triggered the 1886AD eruption.

S01.16 Poster

A Sea Level Influence on the Eruptive Style and Timing on the Santorini Volcano

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Hypotheses attributing changes in eruptive activity on island volcanoes to sea level changes have been discussed since the late 1960s. However, a lack of precisely dated volcanic stratigraphies and local sea level curves has so far prevented a rigorous comparison of the two. We present the first evidence of sea level influencing both the style and frequency of volcanic activity for an individual island volcano (Santorini). This evidence comprises a precisely dated sea level curve and a comprehensive eruptive record of an island volcano (constructed through integration of both proximal and distal eruption records). The eruptive history of the Santorini volcano, from ~ 224 ka to the Late Bronze Age (Minoan) eruption at ~3.6ka is chronologically compared with a local, Aegean sea-level curve using a Kernel Density Estimate for the number of eruptions of each type (Plinian, Interplinian Explosive, and Lava producing). The results imply that Santorini's eruptive frequency is sensitive to the crustal unloading and loading associated with Quaternary sea level changes. We also demonstrate that the style of eruptions varies with sea level changes; lava eruptions only occur when the sea level is at or below ~-60m below the present day sea level. Sea level is therefore proposed as a primary control on both the style and frequency of eruptive activity on oceanic calderas like Santorini, although the precise mechanisms connecting sea level changes to the plumbing system of the volcano have yet to be established.

S01.16 Talk

Youngest IBERSIMS SHRIMP U-Th-Pb zircon ages: dating an Ascension Island Pleistocene pyroclastic deposit and associated plutonic enclaves to yield insights into magmatic evolution in a complex composite ocean island volcano

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Ascension Island, south Atlantic, is a composite ocean island volcano, located ~100km west of the Mid-Atlantic Ridge. The last 1 Myr of subaerial volcanism (~850m), represents a fraction of the 6-7 Ma volcano (~3600m). Volcanic rocks on the small, 88km2, island are varied: alkaline basalt-rhyolite effusive-flows and explosive-falls. Similarly, associated plutonic enclaves range from gabbro-granite.

Recent Ar/Ar dating of subaerial volcanic rocks (1;2) has placed constraints on ages and stratigraphy. Furthermore, a new model for the magmatic plumbing system of Ascension has proposed small-scale, short-lived magma storage regions feed felsic eruptions, rather than large long-lived magma chamber(s) (3). These studies raise key questions about magma system periodicity, volume and source which, with effusivity-explosivity, are significant factors in assessing future eruptions' hazard and risk.

Here we consider source, timing and context of magma generation and evolution using field, petrography, geochemistry and geochronology results from plutonic enclaves and volcanic rocks. If each eruption represents a discreet magma pocket they may map source and crustal heterogeneities. Our first precise SHRIMP U-Th-Pb zircon ages are of two syenite enclaves and pumice from a Pleistocene mingled ash fall.

One enclave is the same age, 540±30 ka, within error, as the pumice, 600±40 ka.
Compositional (O and Hf isotopes) and textural study, will show whether pumice zircon grains are: magmatic microphenocrysts; cogenetic plutonic rocks antecrysts; or xenocrysts. Phenocryst ages would be indicative of synchronous volcanic-plutonic magmatism. Erupted products provide minimum estimates of potential magma volumes, identification of coeval plutonic components would augment this. Antecrysts and xenocrysts do not constrain volcanism timing. The other enclave, 1.03±0.20 Ma, reflects periodic conduit reactivation and tapping of older magma frozen at depth.

Our approach places constraints on: magmatic periodicity; source and storage region character; and crustal controls affecting mafic and felsic magma ascent.

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Tephra stratigraphy of a replenished, tapped and fractionated pyroclastic sequence: placing temporal constraints on magma chamber processes, Poás Volcano, Costa Rica

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Poás is a complex stratovolcano located in the Central Volcanic Cordillera, Costa Rica. Its activity is characterised by frequent, <10 yr repose period, low explosivity, VEI ≤ 2, eruptions. Prior to 2017, three main historical eruptions occurred: 1834, 1910 and 1953-1955.

On the 12th of April 2017 a new magmatic-phreomagmatic eruptive phase began. Pyroclastic flows and surges have spread eastwards to the tourist view point and eruptive columns ascended up to 5 km. Nevertheless, deposits have been mainly restricted to Poás National Park. Recent eruptions have nearly removed the effusive 1950s dome, an explosive scoria cone has formed in its place. The northern summit lake, Laguna Caliente, one of most acidic in the world, dried up from July-December, later refilled in January, then emptied again in February.

Recent fieldwork has constrained the relationship between successive layers of a well- exposed pyroclastic sequence: the youngest is from the 1953 eruption and one of the underlying deposits from 1910. Radiocarbon dating of older layers is currently underway to refine the stratigraphy.

Here we present field data, petrography and whole-rock major element data for the pyroclastic deposits and, for comparison, a 1953 lava and a bomb from the most explosive recent activity on 22nd April 2017. The rocks vary down sequence between basaltic andesite and rhyolite. Observed variations are indicative of repeated replenishment, tapping and fractionation of a small volume magma system.

Linking tephra stratigraphy ages with geochemical, petrographic and mineralogical changes between eruptive events will place temporal constraints on processes occurring in the magmatic plumbing system including, of particular interest, the sub-volcanic magma chamber.

Potential hazard and risk associated with future eruptions depend on periodicity, volume and the effusive-explosive eruptive style. The more information available about past behaviour of a volcanic centre permits development of better models of prediction and risk mitigation.

Chemical vapour deposition of metastable SiO_2 cristobalite in volcanoes

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The very fact that volcanoes erupt attests to them being systems in disequilibrium. One manifestation of this disequilibrium is the abundance of metastable minerals found in extrusive magma bodies. Quartz is the nominally stable form of SiO_2 at Earth's surface, but is relatively rare in volcanic rocks, and is typically restricted to high-silica rhyolites. Conversely, the high-temperature, low-pressure polymorph cristobalite is readily found in the pores of volcanic rocks with widely varying bulk silica contents. Explaining how and why cristobalite forms is important for predicting surficial dome explosivity, for determining if activity at a given volcano poses a respiratory hazard to people nearby, and it also provides an interesting analytical challenge to studying gas-solid reactions and metastable crystallization in natural systems.

We investigate the formation of vapour-phase cristobalite in a range of magma types, from andesite to rhyolite, and discuss how this has led to the use of a wide variety of cutting-edge microanalytical tools, including: microtomography (μ-CT), scanning electron microscopy (SEM), electron microprobe (EPMA), electron backscatter diffraction (EBSD), hyperspectral cathodoluminescence (CL), laser raman spectroscopy, atom probe tomography (APT), and transmission electron microscopy (TEM). Only when used together, can these techniques allow us to discuss the importance of impurities in the cristobalite structure (Al3+, Na+), and the role these have in allowing chemical vapour deposition of cristobalite formation in a wide range of volcanic settings.

S01.16 Poster

The inner workings of a volcanic complex: Holocene activity at Quetrupillán, Chile

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Quetrupillán is a little-known and poorly understood active volcanic complex in the Southern Volcanic Zone of Chile. It comprises an incomplete stratocone with a dispersed and fault-controlled volcanic field on its southern flanks. During the Holocene, this field has developed as a monogenetic field, with features including blocky lava flows, scoria cones and a maar. Using a combination of petrological, geochemical and textural studies, we are unravelling the Holocene eruptive history of this volcano, to determine its volcanic and magmatic evolution, and to anticipate potential future hazards.

Trachyandesitic lavas have been erupted from the stratocone, while products of the monogenetic field are mostly of a trachytic composition. Enclaves of basaltic andesite within trachytic lavas indicate magma mixing and mingling, which is supported by the presence of multiple populations of phenocryst minerals, including sieve-textured plagioclases and two populations of resorbed pyroxenes. Granitoid xenoliths indicate that crustal assimilation may have played a role in the generation of Quetrupillán's magmas. The proximity of two distinct volcanic centres at Quetrupillán (the stratocone and dispersed volcanic field) suggests that a complex plumbing system exists beneath this volcanic complex.

Quetrupillán's diverse volcanism poses issues for hazard mitigation, as an eruption from within the dispersed volcanic field is expected to have less impact on surrounding communities than an eruption from the summit of the stratocone. However, Quetrupillán is snow-covered for much of the year, and so any eruption is likely to lead to the formation of lahars, which may affect the many isolated settlements in the valleys on the flanks of the volcano.

S01.16 Talk

Using distal sedimentary archives to obtain better constraints on the timing, magnitude and dispersal of past eruptions in Japan

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The volcanic deposits preserved near their sources are typically used to establish the timing, magnitude and dispersal of the eruptions. This method is effective for recent eruptions that have well preserved deposits but is less reliable for events further back in time as their deposits are typically buried and often destroyed by younger activity. Distal records can be used to furnish the eruption record but the preservation can also be compromised by weathering and erosion. Here we present the detailed tephra record of a high-resolution sediment cores from a small tectonic lake in central Japan. These Lake Suigetsu sediments span ~150,000 years and record > 30 visible tephra layers. We have significantly expanded this tephra record by identifying non-visible ash (cryptotephra) layers using density separation methods in the laboratory. Indeed, the Holocene (<10 ka) sediments preserve four times more cryptotephra layers than visible tephra deposits. Glass compositions of tephra layers throughout the record reveal that they are sourced from volcanoes across Japan, Ulleungdo (South Korea) and Changbaishan (North Korea/China border). The incredibly detailed radiocarbon and varve (annually layered) chronology of the Lake Suigetsu record has also allowed us to determine precise eruption ages and repose periods between events at particular volcanoes. Even though Japan has the most complete record of past eruptions on Earth our detailed investigations have discovered new eruptions, identified that some volcanoes have multiple large eruptions over short periods of time, and greatly extended the dispersal of many small to moderate events, which have implications for hazard assessments.

New constraints on recent eruptive history of Montagne Pelée (Lesser Antilles arc) from marine drilling U1401A (340 Expedition IODP)

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To overcome the problem of poorly preserved outcropping and go further in detail on the eruptive history on volcanic island context in tropical climate, marine tephrochronology provides a good alternative to complete the volcanological history. Based on the tephrochonological study of a marine core from the site U1401, sampled during the 340 IODP expedition and located west off Martinique Island, 28 km from the coastline, we provide new constrains on the recent volcanological evolution of Montagne Pelée. The core (15 m long) was obtained over the debris avalanche deposits (DAD) associated to the last flank-collapse event that occurred on Montagne Pelée volcano. Although it was not possible to drill through the DAD because of the heterogeneity of the deposit and the presence of large blocks, the sediments and volcanic deposits that covered the DAD were sampled. On the basis of a detailed multiparameter study of the core U1401A - using geophysical data acquired on-board during the IODP cruise, lithological and geochemical data and temporal constrains through ^{18}O stratigraphy and ^{14}C dating - we propose a new age for the last flank- collapse event and a new volcanological history of Montagne Pelée. The last flank collapse is now dated at ~36 cal ka BP (older than previous studies). The flank collapse, even implying a low volume (2 km^3), had an important consequence on the magma plumbing system of Montagne Pelée and produced by threshold effect exerted on the plumbing system, abundant open-vent scoria eruptions (basaltic-andesite composition), during the period 36-25 cal ka BP. This activity was attributed on previous works as associated to the second flank-collapse of the volcano. This new age obtained for this third flank-collapse event has important implications not only for the post collapse activity, but permit also to revisit the whole volcanological history of Montagne Pelée.

Long-term prediction of large eruptions at Sakurajima Volcano using the crystal size distribution of plagioclase phenocrysts

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Sakurajima volcano has three large scale eruptions (> 1 km^3 in DRE volume) during this six centuries, which produced both plinian pumice and lava flow in similar volume. 100 years past since the last large eruption (Taisho eruption), meanwhile, the inflation of inferred source region continues as indicated by the geodetic observation. In this paper, we make an attempt to develop the method of long-term prediction using the textural features, CSDs (crystal size distributions), in the lava flows of the past eruptions. The phenocryst CSD has been interpreted by the open system dynamics in magma plumbing system, in which a slope of CSD is related to the residence time and effective crystal growth rate. The residence time can be converted to the magma ascent rate or flux of magmas. In historical eruptions, plagioclase phenocrysts have two different origins: felsic and mafic magmas as shown by bimodal An contents. We conducted CSD analysis for two distinctive plagioclase phenocrysts after measurements of core compositions. As a result, we found that plagioclase CSDs for the felsic origin have unchanged characters (slope and intercept), indicating the steady state in the physico-chemical condition, whereas the CSDs for the mafic origin indicate the monotonic increase in the values of slope, suggesting the increase in the flux from the mantle during three historical eruptions. Intervals between eruptions decreases with time from ca 300 to 135 years, and a smaller scale of eruption (Showa eruption) occurred 35 years after the last large Taisho eruption, followed by the current activity of mafic magmas. Assuming that the plumbing system maintains the geometry, the shortening of interval can be explained by the increase in input rate of mafic magma. Applying the estimated flux for the last large eruption allows us to infer the onset time of forthcoming eruption.

Untangling processes of magma origin and ascent for Cerro Overo mafic monogenetic volcanism, Chile

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Cerro Overo is a young (77 ka) basaltic andesite maar (54 wt % SiO_2, 7.4 wt % MgO) in northern Chile, and is the most mafic lava yet recognized in the Altiplano-Puna region of the central Andes. Silicate melt inclusion major element compositions range from basaltic compositions representing less-evolved trapped melts, through basaltic andesite identical to the bulk rock, to dacite which reflects trapped crustal melt. Micron-scale phosphorous zoning in olivine from Cerro Overo indicates crystallization by cyclical rapid skeletal growth followed by slower infilling crystallization, suggestive of relatively unimpeded, continuous crystallization, likely reflecting magmatic ascent from the lower crustal MASH zone with negligible stalling or magma storage. The $^{87}Sr/^{86}Sr$ compositions of forsteritic (Fo_{86}) olivine- hosted melt inclusions show a wider range (0.7038 – 0.7072) than whole rock values (0.70618 – 0.70645), and the least-evolved compositions (0.70376 – 0.70432) are the most primitive values yet reported for the Altiplano-Puna region of the central Andes. Located within the frontal arc, Cerro Overo represents a regional mafic end-member and approximates the composition of parental arc magmas derived from partially-molten lower crustal regions where mantle-derived magmas interact with the surrounding lithosphere and undergo density differentiation (MASH zones). Melt inclusions suggest mobilization of MASH magma by injection of basaltic melt, and modeling of olivine diffusion profiles yield ascent time frames of several hours and up to 2 weeks. The location of Cerro Overo maar along the Calama-Olacapato-El Toro crustal lineament, where it crosses the arc front, represent a large-scale zone of crustal weakness that may extend as deep as the base of the lithosphere. This may provide a pathway to allow melts derived from the MASH zone to ascend rapidly with minimal crustal contamination or evolution by crystal fractionation.

Temporal dynamics in Vulcanian explosivity as recorded by petrological, geochemical and geophysical observations at Santiaguito volcano, Guatemala

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Volcanic systems with eruptive longevities of decades-to-centuries facilitate the development of long-term, multi-parameter, monitoring strategies to better constrain volcanic unrest. Santiaguito dome complex, Guatemala, has continuously erupted since 1922, being characterised by cyclic effusive activity and regular, small-to-moderate explosions. In mid-2015, activity shifted to larger, less frequent explosions, which continued to escalate until mid-2016 as ash-rich plumes reached 7-10 km, impacting local air traffic and farming. Here, we present results of a multi-disciplinary study including geophysical observations, and a detailed petrological description of eruptive products throughout this transition period. Combined seismic and acoustic infrasound monitoring reveal progressively longer repose intervals between explosions as the magnitude of these events increased along with fragmentation depth. Concurrently, the erupted ash shows a marked increase in the percentage of grains that had undergone extensive devitrification to sub- micron crystalline silica, coinciding with a ~2 wt.% bulk SiO_2 increase. Differences in microlite crystallinities of the juvenile material (MND, shape, size) indicate contrasting ascent styles due to the complex interplay of decompression, volatile content, shearing and friction. Ejected bombs reveal late-stage mingling textures with isolated domains differing in microlite characteristics similar to variations observed in the ash, suggesting the presence of two magmas that experienced varied ascent histories, and interacted at shallow levels in the conduit (<500 m). Abundant disequilibrium textures and phenocryst chemistries suggest that these events were a consequence of deeper magmatic processes.

Plagioclase phenocryst core compositions from the 2015-2016 magma form a bimodal distribution (peaks at An_{50-55} and An_{90}), opposed to the single An_{50-55} peak recorded since 1940's [1], with amphiboles also revealing higher crystallisation temperatures of 970-1025°C. Our work at Santiaguito captures a unique petrological and geophysical dataset of its on-going activity, which we anticipate will greatly contribute in elucidating shifts in activity at long-active volcanoes.

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Tracking the persistent activity of Vesuvius from 19th Century collections

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From 1631-1944 Vesuvius was persistently active and attracted many visitors, eager to take away fresh samples of lava. As a result, there are numerous samples of Vesuvius lava of known age in museum and other collections across Europe. These include examples of lavas, some collected while still hot, that will preserve a record of the persistent 'background' state of the volcano. We have conducted a study of selected products from Vesuvius from the collections of Professor John Phillips, founding Keeper of the Oxford Museum of Natural History. We have focussed on the time period bracketed between the violent eruptions of 1794 and 1822, and have analysed the compositions of pyroxenes that are a ubiquitous phase in all of the eruptive products.

Major element analysis of clinopyroxenes show interesting patterns of secular change, that we can interpret in terms of the emptying and refilling of a shallow reservoir system. The products of the violent eruption of 1779 and 1794 are crystal-rich (>15 vol% larger than 1mm), and compositionally diverse with clinopyroxenes ranging from Mg#92 to Mg#68. In contrast, products of effusive eruptions in later years (1803-1809) are more crystal-poor (<5 vol% larger than 1 mm), but with clinopyroxene compositions that span a wider compositional range, extending to less magnesian compositions.

Pyroxenes from two sets of lavas fall away from this 'normal' pattern. These correspond to eruptions in 1804 and 1813 from eccentric vents. These lavas are crystal-poor and have distinctly fewer high Mg# clinopyroxenes, with modal compositions closer to Mg#65-70.

Work in progress on diffusion-timescales from clinopyroxenes will provide complementary information on the storage timescales of the shallow magmatic system. This pilot project illustrates the value of revisiting curated sample archives in the search for answers to new questions, and in the search for the ephemeral products of long-lost eruptions.

S01.16 Poster

Magmatic differentiation and crustal contamination at the Fossa cone, Vulcano, Aeolian Islands: insights from oxygen isotopes in crystals and glass

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The Fossa cone, Vulcano, is characterised by alternating periods of explosive events and lava flow effusion. It formed over 5.5 kyr, with many of the eruptions commencing with dilute pyroclastic density currents (PDCs) and tephra fallout capped by lava flows with a compositional range from shoshonite to rhyolite (52-74 wt.% SiO_2).
Here, oxygen isotopes are used in conjunction with petrological and textural analyses to constrain the role of crustal contamination processes and to determine if and where crustal contamination takes place in the magmatic system. Samples from selected lava flows and PDC deposits contain crustal xenoliths and magmatic enclaves and show abundant mineral disequilibrium textures, illustrating the importance of crustal contamination and magma mingling.

Preliminary oxygen isotope data for 14 samples from the Fossa cone are presented, comprising mineral separates (clinopyroxene, plagioclase) and volcanic glass from pumice, scoriae, breadcrust bombs, lavas and mafic magmatic enclaves. $\delta^{18}O$ values range from
+6.2‰ to +6.7‰ for clinopyroxene (Mg# 68-80), from +7.0‰ to +8.1‰ for plagioclase (An 39-55), and from +7.8‰ to +8.7‰ for obsidian glass. $\delta^{18}O$ values for clinopyroxene do not vary systematically with the degree of differentiation of the host rock, in contrast to the $\delta^{18}O$ values for plagioclase which appear to increase. The range in $\Delta^{18}O_{plag\text{-}cpx}$ for the Fossa cone is +0.4 to +1.8, suggesting isotopic equilibrium between the two minerals for most samples at the estimated crystallisation temperatures. Estimated $\delta^{18}O_{melt}$ values are higher than those of mantle-derived magmas, indicating that crustal contamination is ubiquitous in the Fossa magma plumbing system, accompanying fractional crystallisation and magma mingling processes. A better understanding of these processes at the Fossa cone has implications for hazard assessment at arguably the most hazardous volcano in the Aeolian Islands.

Mantle melting and OIB ascent in a slowly rifting lithosphere at the Azores Triple Junction

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The relationship between hot spots and mantle plumes is still a topic of lively debate. We use the case of the Azores Triple Junction (ATJ) to address this unresolved problem and investigate the processes that can explain the chemical heterogeneity of extruded magmas at a regional scale. Our model of the Azores magmatism combines detailed geochemical data on silicate melt inclusions from samples collected across the ATJ with tectonics and high-resolution seismic images of the mantle. Carbonated-silicic melts metasomatization, related to the recycling of an old oceanic crust, and partial melting (3 to 5%) of a FOZO-type mantle can account for the overall geochemistry of the magmas extruded during the last 20 ka. Melting occurred in the presence of water at a maximum pressure of 3.4 GPa and with a small difference of potential temperature from that one of the ambient mantle (ΔT=1-98 °C). This weak thermal anomaly does not presently support the dominant influence of a thermal plume in the shallow mantle beneath the region. Lithosphere extension may have promoted decompression melting assisted by fluids, and deep faults enhanced the ascent of primitive magmas from their ponding zones.

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S01.17 - Calderas unrest, eruptions, risk

Calderas: from unrest to magma transfer

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Calderas consist of broad depressions and are among the most active and dangerous volcanoes, producing the most devastating eruptions. Calderas commonly experience unrest, defined by enhanced seismicity, gravity changes, surface deformation and degassing. Although much caldera unrest does not lead to eruptions, every eruption is preceded by an unrest episode. Therefore, the proper description of unrest and the forecast of its possible outcome is a timely and challenging task.

A review of caldera unrest occurred in the last decades suggests that this can be described and contextualized considering the composition of the erupted magmas (felsic vs. mafic) and the amount of opening of the magmatic system (plugged, semi-plugged, open). Statistical analysis of caldera unrest shows that pre-eruptive unrest commonly lasts <10 months and is preceded by seismicity and degassing, providing useful constraints to forecast eruptions.

Pre-eruptive magma transfer is often controlled by the morphology of the caldera, determining the unloading due to the depression. Caldera unloading promotes the lateral propagation of magma through sills and dikes, as for example reconstructed before the 1538 AD eruption at Campi Flegrei caldera, Italy. Such a lateral transfer of magma, feeding non-central eruptions within calderas, is also commonly observed at recently erupting calderas, suggesting a widespread mechanism. When caldera unloading is significant (large and deep depression) and with moderate overpressure (related to basaltic magmas and shallow magma chambers) magma transfer becomes peripheral: in this case, tangential eruptions are promoted outside the caldera rim, as observed at the Galapagos volcanoes.

S01.17 Poster

Identification and characterization of the youngest eruptive products of the Chalupas Caldera, Ecuador: An update on the caldera

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The Chalupas caldera is located atop the Eastern Cordillera of Ecuador, 80 km southeast of Quito. The caldera formed due to a major rhyolitic eruption (~100 km³ of magma) whose single-event evacuation caused the collapse. The tephra deposit from this eruption is the non-welded "Chalupas Ignimbrite" (~211 kyr) which flowed over 100 km distance in a N-S direction. Inside the caldera's center is the resurgent andesitic volcano Quilindaña (~170 kyr).

The caldera's rim and Quilindaña were eroded by actions of several glaciations; the area of the youngest eruptive products was defined by analyzing orthophotographs and a Digital Elevation Model (3m/px special resolution).

Moraines of "The Last Glaciation Maximum" (~35 kyr) helped us to identify the youngest eruptive products: Buenavista Lava Dome (dacitic) and the Huahui lava (Andesitic-dacitic) flow. Then we made sampling surveys: the rocks and tephra samples were used to make thin sections and geochemical analyses (major and trace elements).

Geochemical analyses suggest that processes of fractional crystallization were dominant in forming the suite of rocks for the whole caldera. Petrographic descriptions also suggest that the youngest, most recent products were formed from a more evolved magma. A newly identified crystal-poor rhyolitic (75 %Wt. SiO_2) tephra layer from Buenavista provides possible evidence of formation of a silica cap ontop of a "crystalline mush" in the magmatic storage area. We derived a 14C age of 43,620+/-700 yBP from a peat layer under this ash layer. The source of this ash was discriminated from other nearby volcanoes, Cotopaxi and Chaupiloma, based on geochemistry and petrography. It is important to continue studying Chalupas caldera because shallow rhyolitic reservoirs with highly silicic tops and that have produced crystal-poor magmas, are easy to perturb and upon onset of unrest eruptions can occur in short order a year or so, like Pinatubo has taught us.

S01.17 Poster

Integrated analysis of magnetotelluric and borehole data applied to active volcanic areas: the example of Ischia Island (Southern Italy)

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The data obtained from magnetotellutic survey and drillings (temperature and stratigraphy), have been used to improve the knowledge of volcano-tectonic processes occurred in the Ischia Island and to assess the thermal-rheological state of the shallow crust (down to a depth of about 3 km). The Ischia Island (located in the Bay of Naples, Italy) represents a well-known case of exposed caldera that has experienced a large (>800 m) and rapid resurgence, accompanied by volcanic activity. The mechanism driving caldera resurgence is a crucial issue to investigate, because it is associated with potential eruptions and high risk to people living within and around such large active volcanic systems. To this aim, a magnetotelluric (MT) survey of the island was carried out along two main profiles through the central-western sector, providing an electrical resistivity map to a depth of 3 km. These resistivity cross sections allowed us to identify the presence of a very shallow magmatic intrusion, possibly a laccolith, whose top is located at a depth of about 1 km. This intrusion was responsible for both the resurgence and the volcanic activity at least since 33ka. The resistivity data is also compared with geothermal gradients and stratigraphy of deep boreholes (down to 1 km of depth) located in the western sector of the island. The tectonic structures bordering the resurgent area and the occurrence of a large thermal anomaly in the western sector of the caldera provided a signature in the resistivity cross sections, with the magma intrusion producing advection of hot fluids with high geothermal gradients (>150 °C/km) in the southern and western sectors. Furthermore, the boreholes temperature data allow us to assess the possible rheological state of the magmatic source. This is fundamental to account for the transition from magma eruption to accumulation.

S01.17 Poster

Source Mechanism of Ischian Earthquakes: Stick-Slip or Magma Pushing?

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The earliest sources on the seismicity of Ischia date back to the Greek colonization of the Island in the eighth century BC. Until the eruption of 1302, seismicity was widespread across the whole Island, while thereafter it was concentrated in its northern part. The two major earthquakes that hit Casamicciola on 4 March 1881 and 28 July 1883 caused irreparable damages. Buildings were pulverized, the street network was wrecked, and the morphology of the area was altered by landslides.

The 1883 earthquake of Casamicciola has an important place in the seismic history of Italy, both because it is the first major earthquake to have occurred after the unification of Italy and because of the seriousness of the damages.

The Ministry of Public Works reached the scene of the disaster promptly to bring rescue to the local population. Hazard seismic maps were drawn and high risk zones of the territory were clearly defined to avoid the reconstruction in these places. New settlements were designed along the shoreline of Casamicciola where the level of expected seismic hazard resulted at lowest rank. Furthermore, to monitor the seismicity of the Island, the Geophysical Observatory was built up at “Grande Sentinella” in Casamicciola.

The characteristics of earthquakes on Ischia is that they occur very near the surface (1-2 km). At this depth the seismic cut-off is due to the brittle-ductile transition for high geothermal gradient in the Island (180°C/km). The earthquakes source in the Island may be attributed to the regional tensile tectonics, accompanied with stick-slip process, as well as to the magma pressure of a shallow magma body, or to the both mechanisms. It has to rule out the active contribution of magma to the occurrence of earthquakes after the last eruption on 1302, which was followed by the slow sinking of the Island.

Forecasting vent location at Campi Flegrei by inversion of local 3D stresses

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Vent locations at calderas are currently forecast based on the empirical distribution of previous vents, sometimes combined with additional information, e.g. the distribution of fractures or degassing vents and other mechanical weaknesses. Our aim is to define a testable, physics-based method to produce vent maps based on the mechanics of magma transport. We adapt the method of Corbi et al. (this conference) to 3D.

A 3D boundary element code is used to simulate magma propagation paths through a heterogenous stress field. This is used to model the stress state due to caldera excavation and the far field tectonic stresses. Then, using this calculated stress field, we approximate dyke trajectories through the crust by aligning these parallel with the most compressive stress in the system. Our model is an end member, where the path is not deflected due to magma buoyancy or internal viscous flow. A dyke is seeded at a point with a given start depth and its trajectory to the surface is calculated.

This model combined with a Markov Chain Monte Carlo algorithm resolves which input parameters result in the observed vent locations and alignments in the Campi Flegrei caldera. Splitting the observed volcanism into different periods, we examine how the inverted parameters evolve through time and compare this to the geological observations. Further, using knowledge of the recent geological evolution, we calculate a forecast of the likely vent locations in the future.

Finally, we compare the results of our physics-based model to the results of statistical methods based on the distribution of previous vent locations. In spite of the many assumptions and dramatic simplifications both on the physical process and the input parameters, the model provides a new framework to both better understand how the evolution of the stress field has controlled migrations of the vent pattern.

S01.17 Poster

The Campi Flegrei Deep Drilling Project: results from the pilot hole

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The Campi Flegrei Deep Drilling Project was aimed to study the shallow and deep substructure of the Campi Flegrei, in order to reconstruct the erutpive history, the thermal state and the physical properties of the rocks. The first step of the project, namely the drilling of the pilot hole, 500 meters deep, has been performed in 2012. The pilot hole shed light on the volcanic history of the most important and less known part of the caldera, namely the Eastern border containing part of the city of Naples. The pilot hole stratigraphic results allowed to definitively assess that the Campi Flegrei caldera Easternmost border ends at the Posillipo hill, and does not enclose the whole city of Naples as hypothesized for decades. Furthermore, it questioned that the largest eruption ever occurred in Europe, namely the Campanian Ignimbrite (39.000 y BP) had occurred from Campi Flegrei, forming the caldera. This important finding, confuting most of the volcanological theories accepted till now, has been further investigated by a geological campaign aimed to sample the Campanian Ignimbrite products in several shallow holes drilled at several sites in the Campania Plain. Besides such important stratigraphic results, the pilot hole has been also used to determine in situ properties of volcanic rocks, allowing to constrain the permeability and the amount of regional stress. These parameters have been crucial to constrain models for caldera unrest. Finally, the pilot hole has been equipped with innovative borehole sensors, thus constituting the first nucleus of the Campi Flegrei Deep Observatory, a network of innovative borehole sensors installed in the period 2013-2016.

S01.17 Poster

Magma and Hydrothermal Reservoirs as a Single System, Krafla Caldera, Iceland

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The storage and evolution of magma depends much on adjacent hydrothermal circulation, the dominant mechanism of heat loss. Likewise, the evolution and sustainability of a geothermal system depends upon the heat source, which for high-temperature systems is magma. Drilling in Hawaii, Kenya, and Iceland unexpectedly discovered silicic magma immediately below geothermal systems. Iceland Deep Drilling Project well IDDP-1 revealed < 30 m separation between the two under Krafla Caldera. New laboratory experiments show thermal fracturing beginning 100^{o}C below the solidus. For Krafla then, the vertical separation between silicate and aqueous fluids could be only 5 m, implying that a perturbation in the circulation of one fluid will affect the other in less than a year. That the magma is convecting, thereby replenishing heat lost to the geothermal system, is implied by the absence of evidence of crystallization at the magma ceiling. Both fluids transport thermal energy to the surface and geothermal production is a significant factor. At the surface of Krafla, the current geothermal output is 500 MWt and eruption output averaged over the Holocene is 100 MWt. Proximity of the two convecting fluids offers two opportunities: 1) Sustainable production of high-enthalpy aqueous fluid from immediately above the magma, thereby increasing electric power capacity 10 fold; 2) Emplacement of sensors near and directly in magma providing, for example, pressure and temperature measurements that could be used to forecast eruption. A scientific research/engineering development borehole is being planned as the first phase of the Krafla Magma Testbed, envisioned as an international infrastructure for probing magma-hydrothermal systems. KMT-1 will provide the first core samples of the interval from brittle rock to liquidus magma and the first heat flux measurements in the roof of a magma body.

The role of magma evolutionary processes and cumulate melting in the Campanian Ignimbrite and Neapolitan Yellow Tuff caldera-forming eruptions (Campi Flegrei, Southern Italy)

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Understanding the mechanisms responsible for the generation of chemical gradients in high-volume ignimbrites is key to achieve information on the processes that control the maturation and eruption of large silicic magmatic reservoirs. Over the last 60 ky, two large ignimbrites (i.e., the Campanian Ignimbrite, CI, ~ 39 ka and the Neapolitan Yellow Tuff, NYT, ~ 15 ka) were emplaced in large part of the Campanian Plain and produced two different caldera collapses in the present Campi Flegrei area. They show different types of zoning. In the CI, petrological investigations reveal linear compositional, thermal and crystallinity gradients that suggest a magmatic evolution controlled by fractional crystallization occurring in a mushy reservoir. The pyroclastic sequence represents the inversion of the zoned magma chamber, trachytic-to-trachyphonolitic in composition. The early erupted crystal-poor units reflect highly evolved melts extracted from an upper crustal mush system and the late erupted crystal-rich units correspond to remobilized and partially re-melted portions of the cumulate mush, rejuvenated after mafic recharge. Conversely, the NYT is a pyroclastic sequence characterized by remarkable compositional variations (trachyandesite to phonolite), with dominantly crystal-poor units that reveal a more complex zoning in the magma reservoir and dynamics of magma withdrawal. Detailed analyses of matrix glasses and mineral phases indicate that such variability results from mixing/mingling between three different magmatic components: (1) a resident evolved magma representing the melt extracted from a relatively refractory cumulate mush; (2) a hotter and more mafic magma from recharge and (3) a compositionally intermediate magma derived from remelting of fusible portions of the cumulate crystal mush. The models proposed for the two high-magnitude explosive eruptions provide a framework within which to understand the importance of crystal mushes in the evolution of upper crustal reservoirs and they capability of becoming eruptible upon recharge.

Caldera resurgence driven by magma viscosity contrasts

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Calderas are impressive volcanic depressions commonly produced by major eruptions. Equally impressive is the uplift of the caldera floor that may follow, dubbed caldera resurgence, resulting from magma accumulation and accompanied by minor eruptions. Why magma accumulates, driving resurgence instead of feeding large eruptions, is one of the least understood processes in volcanology. Here we use thermal and experimental models to define the conditions promoting resurgence. Thermal modelling suggests that a magma reservoir develops a growing transition zone with relatively low viscosity contrast with respect to any newly injected magma. Experiments show that this viscosity contrast provides a rheological barrier, impeding the propagation through dikes of the new injected magma, which stagnates and promotes resurgence. In explaining resurgence and its related features, we provide the theoretical background to account for the transition from magma eruption to accumulation, which is essential not only to develop resurgence, but also large magma reservoirs.

S01.17 Talk

Non-eruptive unrest at the mafic caldera of Alcedo (Galápagos, Ecuador) revealed by InSAR analysis and numerical modelling

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Despite the fact that no eruptions have occurred at Alcedo (Galápagos, Ecuador) in the last 50 years, its mafic caldera has been recently and repeatedly characterized by non-eruptive unrest episodes, with ground deformation and degassing. Here we investigate the volcano- tectonic evolution of Alcedo from 2007 to 2011. InSAR data show an asymmetrical intra- caldera uplift of ~30 cm from 2007 to 2009. Then, in the following six months, there was a small subsidence of the previously uplifted part, while the NW portion of the caldera underwent few cm of uplift. Finally, from 06/2010 to 03/2011, the subsiding area inflated again. We have inverted the ground deformation for plausible sources using the GBIS software. The first deformation event can be explained by the emplacement of a sill and the (re-)activation of an intra-caldera ring fault. The second event is consistent with lateral migration of magma from the previously inflated sill. The third event is consistent with new inflation of the sill. Despite the new magma supply, no eruption occurred, probably because the intruded magma was not sufficient to reach the critical overpressure for triggering an eruption.

S01.17 Poster

Accumulation of rhyolite magma prior to the caldera-forming eruption of Aira caldera

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Accumulation of large-volume silicic magma in a chamber at shallow level of the crust is one of the fundamental precursory processes for catastrophic ignimbrite eruption. Temporal variation of erupted magma during “pre-caldera” stage will provide the key information about the growth of magma chamber for catastrophic ignimbrite eruption. Aira Caldera, in the southern Kyushu, Japan, is one of the most active calderas, with eruption of VEI~7 Ito ignimbrite at ~30 ka and the activities of post-caldera Sakurajima volcano. Prior to the Ito ignimbrite eruption, the Aira caldera repeated several VEI 4-6 class eruptions from the caldera. Petrochemical investigation of these pre-caldera and syn-caldera products reveals that rhyolite magma with relatively-homgeneous composition erupted for ~30,000 years prior to the caldera-forming eruption. The petrographical characteristics and chemical compositions of these pre-caldera rhyolites overlap that of the Ito ignimbrite, which is the main ignimbrite of the caldera-forming eruption. The water contents in the glass inclusions in the phenocryst minerals, mainly plagioclase and orthopyroxene, concentrated between 4 and 7 wt% for all pre-caldera products. This water concentration corresponds to the saturating concentration at 100 – 200 MPa. Phase relationship of phenocryst minerals and groundmass glass of these pre-caldera rhyolites also suggest the equilibrium condition at at 100 – 200 MPa. These observations support the accumulation of rhyolite magma ~5 km beneath the caldera for at least ~30,000 years prior to the caldera-forming eruption. A part of the accumulated rhyolite magma leaked as smaller pumice eruptions and lava effusion. Temporal change of the erupted magma toward caldera-forming eruption can provide a key to understand the evolution of magma reserving system beneath a caldera candidate.

Magma vs Gas: unravelling the driver of caldera breathing

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Understanding the processes that govern the inter-eruptive dynamics of volcanic calderas (e.g., Campi Flegrei, Yellowstone) is crucial to better forecast their activity. This is an important concern to monitoring agencies because calderas represent major hazards to modern societies, both at local and global scale. One of the most intriguing caldera-related phenomena is the so-called breathing, i.e., continuous inflation-deflation cycles on the order of up to 10s of centimeters per year and with characteristic periodicities ranging from a few years to decades. In this study, we explore the breathing activity of Domuyo volcano, a dacitic caldera in the Southern Andes whose most recent eruption occurred >10,000 years ago. Breathing activity is explored using geodetic data (retrieved from the synthetic aperture radar -SAR- sensors onboard ALOS, ALOS-2, Radarsat-2, and Sentinel-1 satellites) and thermal data (retrieved from the moderate resolution imaging spectroradiometers - MODIS- onboard Terra and Aqua satellites). Our main findings are: Domuyo is inflating at ~11 cm/year since 2014; and diffuse heat emissions, associated to diffuse outgassing, is phase shifted with respect to deformation. To interpret these results, we develop a numerical model based on mass and momentum conservation that couples the permeable flow of gases through the shallow crust, the exsolution and accumulation of volatiles inside a shallow magma reservoir, and viscoelastic deformation of the crust. Our preliminary results show that the pressure inside magma reservoirs can oscillate spontaneously during quiescent degassing at the typical breathing timescales, thus suggesting that rise and fall of calderas is not necessarily associated to the flow of magma beneath the surface. An important prediction of our model for forecasting purposes is that, if deformation and diffuse outgassing are time delayed, caldera inflation is likely not driven by magma flow.

S01.17 Poster

Lessons from the Bárðarbunga 2014-15 caldera collapse: Implications for magma reservoirs and collapse mechanisms

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The Bárðarbunga 2014-2015 caldera subsidence and its connection with eruption in Holuhraun throws new light on the existence and form of magma bodies in the crust, a long- standing, only partly solved problem in earth sciences. Geophysical imaging aimed at detecting magma bodies under volcanoes has been elusive, providing only weak constraints. Caldera collapses, however, provide better constraints, including minimum volumes of magma present at the start of collapse. During the Bárðarbunga 2014-2015 caldera collapse in Iceland, a subsidence bowl (a down-sag caldera) formed, up to 65 meters deep and over 100 km^2 in area during eruption of 1.4 km^3 of lava and intrusion of ~0.5 km^3 of magma. Seismicity and modeling indicate a piston collapse at depth along a pre-existing ring fault and into a magma reservoir at ~10 km depth. This body extended over 30-55 km^2 with a thickness not less than ~0.1 km and a volume of at least 1.8-2 km^3. The discharge of magma displayed an exponential decline. Magma chemistry did not change during the eruption and it had a crystal content of only a few percent. These observations are consistent with a single, liquid and convecting magma body. There are many similarities with the Laki eruption of 1783, often considered to have originated from a crustal magma reservoir under Grímsvötn. Given the size of the Grímsvötn caldera, a subsidence of a few hundred meters is required to account for the volume erupted in 1783. The geochemistry of Laki is consistent with a mostly liquid, convecting and interconnected magma body. Other large eruptions may have a similar explanation. Apparently, liquid magma bodies in the crust, of volumes of 2-20 km^3 are required to explain these large basaltic eruptions in Iceland.

Understanding caldera complexes by geochemical correlation of pyroclastic outflow sheets: A case study from the ancient nested Scafell and Langdale calderas, U.K.

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Caldera-forming eruptions are some of the most severe hazards on Earth. Understanding how caldera volcanoes erupt is hampered by poor exposure of proximal deposits at modern caldera volcanoes. Ancient dissected volcanoes can provide us with much needed comparative information. The Scafell nested caldera complex of the Ordovician Borrowdale Volcanic Group, N.W. England, is one of the world's best exposed caldera volcanoes. Several calcalkaline and high-K ignimbrites and other pyroclastic units are associated with the well- studied >140 km^2 Scafell caldera and the more poorly understood Langdale calderas of the nested complex. In the exceptional Scafell example, exhumation and glacial erosion have revealed the entire succession including pre-caldera volcanics, caldera-fill deposits and post-caldera lake sediments, along with the caldera floor faults, vents and domes.

However, the large number of units, multiple source calderas, prehnite-pumpellyite regional metamorphism, cleavage and thrust fault development during the Acadian orogeny have hampered correlation of the ignimbrites from intra-caldera to outflow facies.

In order to correlate outflow facies to proximal units of Scafell and Langdale calderas, trace- element geochemical fingerprinting was utilised in combination with detailed stratigraphic mapping and textural interpretation of the andesitic to rhyolitic caldera-forming successions.

The improved correlation of outflow sheets is enhancing our understanding of ignimbrite volumes, eruption parameters, relative age relationships of ignimbrite eruptions, caldera collapse events and intracaldera lacustrine sedimentation in the caldera complex. Detailed correlations of individual outflow sheets to caldera fill could ultimately lead to the correlation with individual vents. Results also show that some outflow sheets can be traced to their sources, whereas others are 'exotic' and derived from as yet unidentified sources. This study illustrates that such understanding of the pyroclastic and sedimentary stratigraphic successions is of fundamental significance not only for our understanding of ancient volcanic complexes, but also for modern caldera volcanoes.

S01.17 Poster

Contrasting volcanism at Aso volcano, SW Japan, before and after the caldera formation: Petrological effort to find difference in magma supply system

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Aso volcano in Kyushu Island, SW Honshu arc, Japan has three contrasting stages of activities: i.e. pre-caldera, caldera-forming and post-caldera stages. Pre-caldera volcanism is represented by scattered occurrence of lava flows and lava domes, most of which are found on Aso caldera walls or outside caldera. The reported ages of pre-caldera peak activities are between 400 ka and 800 ka. Caldera-forming stage is represented by four large-scale pyroclastic eruptions, called as Aso-1, Aso-2, Aso-3 and Aso-4, the estimated age of which are 266 ka, 141 ka, 123 ka, and 89 ka, respectively. Large-scale pyroclastic eruptions were intervened by intra-caldera volcanism of lava flows and moderate explosive eruptions producing tephra. Precursory lava effusion event before large-scale eruptions Aso-1, Aso-2 and Aso-4 were found. Post-caldera volcanism is a collection of cones, lava flows and silicic explosive events to form central cone complex inside the caldera.

Olivine and/or hornblende bearing andesite are dominant among pre-caldera lavas. Caldera- forming pyroclastic flows contains abundant dacite pumice with or without hornblende phenocryst. Some pyroclastic flow units contain basaltic scoria and banded pumice with hornblende or with hornblende + olivine. Intra-caldera lavas and tephra are pyroxene andesite and hornblende decite. Post-caldera volcanic products are represented by olivine basalt, olivine basaltic andesite, and pyroxene andesite, pyroxene dacite, and pyroxene rhyolite. Hornblende is rare among post-caldera products.

In summary, Aso volcanic system is controlled by the interaction between silicic shallow magma reservoir and basaltic magma of deep origin. Hornblende and olivine is a key phase to describe such interaction. Distinct composition and mineral assemblage among three stages indicate different magma supply systems. Transition to caldera-forming stage from another, or from caldera-forming to another is better described by the estimation of temperature, pressure and water content in magmas.

Ground deformation, seismicity and underground structure of Aira caldera, Japan

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Aira caldera is located in south Kyushu Japan, and a caldera forming eruption occurred 29k years BP. There are two volcanoes in the caldera; Wakamiko submarine volcano, and Sakurajima, of which eruptivity started 26k years BP, as a post-caldera cone. The ground of south Kyushu widely subsided associated with a plinean eruption of Sakurajima in 1914. The center of subsidence was located in Aira caldera, with the maximum reached 0.8 m in land area. After the eruption, the ground turned uplifting. The uplifting of the ground amounts 0.73 m until now. Major magma reservoir of Sakurajima is located in the center of Aira caldera. Eruptive activity of the volcano is tightly related to storing magma in the major reservoir. Pressure source is estimated to be located at depths 10-13 km in the center of Aira caldera by using data of dense precise leveling and cGNSS. Amount of uplifting corresponds to magma volume of 2 km^3.

VT earthquakes distribute in the direction from NE to SW in the caldera. Most of the earthquakes are concentrated in Wakamiko and Sakurajima volcanoes with depths shallower than 5 km. Deeper VT earthquakes are located SW part of Sakurajima. Seismicity of deep LF at depths 20-40 km are active beneath the Wakamiko volcano and Sakurajima's SW part, where the seismicity of dLF is the most significant. 3D tomography of Vp and Vs and receiver function analysis show that anomalous structure corresponds to hypocenter and pressure source. At depth shallower than 10 km, Aira caldera is mostly occupied by low velocity zone, however, VT earthquakes are located in higher velocity zone. Contrast of Vp and Vs is clearer in deeper than 10 km. Low Vs zone is located in the center of Aira caldera, and this corresponds to pressure source beneath the Aira caldera.

The problem of ghost magma chambers under calderas

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Monitoring crustal deformation at active calderas gives us insights into the subsurface processes within the volcanic edifices. Several subsiding calderas (e.g., Wolf and Fernandina, Galápagos) show similar complex patterns of ground deformation revealed by space-borne radar interferometry. These patterns often consist of a broad deflation signal affecting the entire edifice and a localized subsidence signal focused within the caldera. While analytical and numerical models with multiple magma chambers at different depths have typically been used to explain these signals, ring-faults and other structures beneath the calderas have usually been ignored in the modeling. This raises questions about how realistic models of multiple magma chambers are, even though they may be able to reproduce the observed deformation patterns.

Here we explore alternative mechanisms that can produce the observed complex deformation patterns. Using two complementary methods, we study the three-dimensional geometry and kinematics of caldera deflation processes evolving from an initial downsag subsidence to later collapses. First, we analyze analog experiments with structure-from- motion photogrammetry (SfM) and particle image velocimetry (PIV) to relate surface deformation to subsurface structures. Second, we use numerical modeling based on the boundary element method (BEM) to characterize the sources that can produce the observed deformation patterns.

Our results show that the broad deflation signal is mainly caused by the emptying of a deep magma chamber, whereas the localized subsidence signal on the caldera floor can be related to the shallow ring-fault activity. The ring-fault architecture to a large extent determines the ground deformation localization. Since there is clear evidence for ring- faulting at several subsiding calderas, we highlight its key role in shaping the observed deformation. Ignoring ring-faulting in models of subsiding calderas and instead using multiple point/sill-like sources will result in erroneous estimates of magma chamber depths and volume changes.

S01.17 Poster

A time-scale leading to the climactic pyroclastic flow phase in the 7.3 ka caldera-forming eruption at Kikai caldera, Japan

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Many explosive caldera-forming eruptions are represented by two major phases, the initial plinian and the following climactic PDC phases. A time-scale between the two phases is a key to understand how caldera-forming eruptions evolve. The 7.3 ka eruption at Kikai caldera, Japan, is a good example to study this issue. The deposits from this eruption are characterized by four major units; plinian fallout (Unit A) and intraplinian PDC deposits (Unit B), the climactic ignimbrites (Unit C), and co-ignimbrite ashfall deposit (Unit D). We focus on the depositional features of Units B and C and its boundary structure, and then discuss the time-scale between these units. Unit B shows various degree of welding due to high-temperature emplacement condition. At some locations near the caldera, fragments of welded Unit B are incorporated into Unit C. The field observation suggests that the uppermost part of Unit B was sufficiently cooled and then eroded by climactic PDCs. In order to estimate the time-scale of Unit B formation, a thermal history of the deposit was evaluated using the one-dimensional heat transfer and deformation model that includes the effect of changes of viscosity and pore fraction due to compaction. Given possible ranges of emplacement temperature, initial thickness, and physicochemical properties of pyroclasts, parameter studies were carried out. Then we obtained thickness changes, density profiles of the deposit, and time-scale to achieve glass transition temperature that may cause brittle failure of welded tuff. The results suggest that the time of days or weeks, rather than hours, are required to explain the deposit features. Therefore it might be a time- break with days or more between the plinian and climactic phases in the 7.3 ka Kikai caldera eruption. This discontinuous eruption sequence may be different from historical smaller-scale caldera-forming eruptions at Krakatau in 1883 and at Tambora in 1815.

Unrest at caldera systems: do we really know what happens?

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Many active silicic caldera systems have undergone or are currently undergoing unrest episodes of magmatic or hydrothermal origin or both, which may have ended or may end with an eruption or not. Deciphering the causes of such unrest episodes is not always easy due to the internal heterogeneity and anisotropy of such systems caused by a high degree of fracturing and presence of numerous stratigraphic and structural discontinuities. This allows magma and geothermal fluids to be present in multiple zones and to interact among them in different ways. The structure of the subvolcanic systems that allowed the formation of these calderas have been totally transformed due to the collapse event, so the installation of post-caldera volcanism may be controlled by a completely different shallow plumbing system mostly defined by the fractures network that driven caldera collapse. The presence of post-caldera basaltic volcanism in most of these calderas demonstrates that the pre- caldera silicic shallow magma chamber does not longer exist, so unrest episodes should not be related to such magma reservoirs. Geophysical imaging of the interior of calderas is not always precise enough to distinguish between fresh magma and/or geothermal fluids and to constraint the size and geometry of their potential accumulation sites. This results, sometimes, in rather speculative models on the interior of caldera systems and on the causes of such post-caldera unrest events. In this contribution I reflect on the internal structure of caldera systems and the controls of post-caldera volcanism by reviewing several case studies representing a wide range of active calderas.

Unrest at Long Valley Caldera from a Geophysical Perspective

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Long Valley Caldera is a well-monitored and restless caldera in Eastern California at the tectonic step-over between the eastern California shear zone, and the Walker Lane. Long Valley has been restless at least since the initiation of focused geophysical instrumentation following a series of M6 earthquakes in 1980, with frequent earthquake swarms, inflation under the resurgent dome, and changes to the geothermal system. Comprehensive geological studies (e.g. Hildreth, 2004, 2017), are complemented by a long history of geochemical and instrumental geophysical observations including geodetic, seismic, gravity, and magnetotelluric data. However, an interpretation relating these data to subsurface processes is uncertain. Geological investigations indicate there has been no substantial silicic volcanic activity in the Long Valley Caldera in the last 200,000 yrs (there was recent activity in the Mono-Inyo chain and Mammoth Mountain), leading to the conclusion that Long Valley is a moribund volcano, and the restlessness is the result of second boiling of the cooling reservoir. Observations from a geophysical perspective include episodic inflation characterized by both uplift and significant horizontal extension under the resurgent dome, which may be described as tumescence, or swelling, with minimal subsidence. Gravity surveys indicate it is likely that the deforming reservoir has a density consistent with magma, however, there is poor water table resolution leading to uncertainty in the density estimate. Several studies have reported evidence for a low-velocity layer at ~8-10 km depth that might indicate the presence of partial melt, and the roof of a large midcrustal magma reservoir was imaged using teleseismic and ambient noise tomography. Magnetotelluric studies find evidence for the shallow geothermal systems, and possible deeper partial melt. The geophysical observations leave open the possibility of recent magmatic intrusion underlying the unrest at Long Valley, but also suggest further experiments are needed to differentiate the mechanisms driving unrest.

S01.17 Talk

Theoretical model constrained by analogue experiments for modeling the storage of silicic magmas in the continental crust

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Physical mechanisms by which silicic magma stops rising and makes space for itself in the continental crust remain controversial. In extreme cases, silicic magmas generate so called super eruptions, and in so-doing form vast calderas. Understanding storage mechanisms and stresses exerted on the crust is important. Beneath large, active volcanic systems, the lower continental crust is anomalously hot and behaves ductilely, whereas the uppermost crust remains brittle. We hypothesise that upward progress of silicic magma is stopped by the brittle-ductile transition in the crust, which is expected to be at shallow depths when crust is very hot as suggested for Uturuncu volcano in Bolivia, Yellowstone volcano in USA and Campi Flegrei in Italy. Petrological evidence indicates pre-eruptive magma storage at shallow depths (< 10 km), which for these three cases is also similar to the brittle-ductile transition depth. Whereas most models put the deformation source in an elastic or viscoelastic half-space, we propose a physical model in which buoyant magma accumulates beneath an elastic plate and deforms it due to buoyancy forces. A theoretical model and numerical code are used to predict surface deformation and compare with observations. Laboratory experiments are also performed. In a tank a layer of aqueous sugar solution (representing ductile lower crust with liquid rheology) is overlain by an elastic plate of gelatin (representing brittle upper crust). At the bottom of the tank a positively-buoyant colored-liquid was injected in small increments. Liquid distribution beneath elastic plate is deduced using a colorimetric technique, while surface deformations are determined with a Moiré method. The experiments give surface deformations and associated source shapes which are used to test the model. After confirming experimentally the calculations results, we apply the model to deformation pattern observed at Uturuncu volcano by satellite geodesy.

The unrest dilemma (hydrothermal vs magmatic) at Campi Flegrei caldera and the role of geochemical data and modelling

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At closed-conduit volcanoes with large hydrothermal systems, an intrinsic ambiguity characterizes the interpretation of unrest phenomena, particularly the identification of the source (magmatic vs hydrothermal) of detected anomalies. Geochemical data can be effective in reducing ambiguities, but assumptions about redox state and phase coexistence have a large impact on the computation of P-T properties, as well as on mass balances of major components. High uncertainty generally remains also in those environments, like Campi Flegrei caldera (CFc), where excellent geochemical databases have been established since decades. We show here this has occurred so far because 1) the thermodynamic treatment of fumarolic gas data was biased by ‘a priori’ assumptions about the redox-state and the imposition of liquid-vapour coexistence, and 2) thermomechanical modelling provided in the literature was poorly constrained with respect to the energy required by the whole hydrothermal process.

Our results allow rethinking how far data from fumaroles can be used to understand caldera-scale processes and, in agreement with independent geophysical (seismic and geodetic) evidences and arguments, represent an instructive restart to understand CFc unrest and its causes. In particular, the role of CO_2-induced drying of the deep hydrothermal system is shown for post 1984 phenomena; including the ongoing unrest, whereas magma emplacement contributed to the 1982-84 large unrest episode.

S01.17 Talk

Supercharging a Pyroclastic Density Current with Caldera Hydrothermal Fluids: Campanian Ignimbrite, Italy

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The largest eruption of the Campi Flegrei caldera produced the 39 ka Campanian Ignimbrite (CI), a very mobile PDC that travelled outward at least 80 km from the vent, covering >30,000 km^2 and overtopping ridges >1400 m high, before lofting into the air to deposit a large co-ignimbrite fallout around eastern Europe. No evidence of a collapsing Plinian column is seen in the main CI. The PDC was dilute and close to a kilometer thick, but deposits were emplaced at temperatures above 580 ºC (magnetite blocking temperature; estimated magmatic temperatures 800-950 ºC). This limits the amount of atmospheric gas incorporated into the current, consistent with geometric arguments for limited access of air into the flow. We propose that supercritical fluids from the Campi Flegrei caldera hydrothermal system provided excess hot volatiles for the eruption. Previous CI melt inclusion data (Marianelli et al. 2006) show normal ranges of H_2O contents (2-6 wt%), but a hot hydrothermal system exists under the Campi Flegrei today and the Breccia Museo, a proximal deposit of the CI eruption, records the explosive ejection of a hydrothermal system. The Campi Flegrei is close to sea level, with half the caldera below water. Lacalamita et al. (2017) suggest a Na-rich fluid, consistent with the probable composition of the Campi Flegrei hydrothermal fluids, passed through the CI while it was hot. Such supercritical fluids expand to gas without requiring heat of vaporization, so would only minimally cool the PDC, and the addition of this hot gas could produce a large, dilute, hot PDC. A large proportion of the CI current was deposited in distal regions as co-ignimbrite fallout.

S01.17 Talk

Ignimbrite depositional facies of El Aguajito Caldera Complex in Baja California Sur, México

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The Aguajito Caldera Complex (ACC) is located in the central part of Baja California, México. A detailed revision of the stratigraphy based on extensive field work and $^{40}Ar/^{39}Ar$- U/Pb ages allowed to understand the volcanic evolution and timing of the caldera collapse. The caldera-forming eruption consists of two parts: the basal part is composed of a fall deposit (PF) and a pyroclastic density current (BpPF). The upper part consists of a lag breccia facies (mlBr) and an ignimbrite enriched in lithics that grades from unconsolidated to welded facies (wPFpf). The initial pyroclastic fall, is interpreted as a decompression event that formed a sub-plinian column followed by radial dense pyroclastic density currents flows. This stage was followed by the onset of the caldera forming phase. The collapse produced a ~5 km wide irregular caldera depression bounded to the west by the active N-S Cimarron Fault and to the east by lithic breccias, and domes giving to the crater a "D" shape form. The Aguajito ignimbrite covers an area of ~400 km^2 with a maximum thickness of 70 m and a minimum total volume of ~7 km^3. A sequence of lava flows and pyroclastic deposits (~0.9 Ma) cover the Aguajito ignimbrite. This sequence is exposed at the center of the caldera representing two stratocones that filled the caldera depression after which they were destroyed and dismantled by erosion. The youngest rhyolitic domes (0.6 to 0.4 Ma) of Aguajito occur along and around the caldera rim and aligned in a NW-SE direction.

S01.17 Poster

Post-unrest volcanic activity at Santorini (Greece) detected by remote sensing

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Santorini (Greece) comprises the most active volcanic centre in the Aegean Sea, and it is documented to have given one of the largest volcanic events known in historical time, the so-called Minoan eruption, which occurred in the late 1600s BC with major catastrophic effects. Post-Minoan volcanic activity of multiple caldera collapses and magma depositions, was almost entirely confined within the caldera, in the central part of which Palea and Nea Kameni volcanic centres emerged. Since its last eruption in 1950, a deflation occurred at Nea Kameni, as measured during 1992-2010 by satellite Synthetic Aperture Radar Interferometry (InSAR) with rates of 5–6 mm yr^{-1}, as well as the absence of seismic activity within the caldera. However, at the beginning of 2011 the volcano showed signs of unrest with increased seismic activity and significant ground uplift, reaching 14 cm within a year (March 2011 – March 2012). Joint inversions of InSAR and GPS velocities indicate a pressurized spheroidal magmatic source located offshore at about 1 km north of Nea Kameni at 3.8 km, whose estimated volume variation rate is 9 10^6 m^3 yr^{-1}. A gradual slowing trend in the inflation rate took place within the 2012 as observed by ENVISAT data. The continuation of the deformation monitoring after the unrest event was deemed necessary, in order to monitor the post-unrest state of the volcano and to recognize potential ground deformation signals. A multi-temporal InSAR analysis from Sentinel-1 mission was performed to retrieve the actual deformation state of the volcano during the repose period 2014-2017. The results indicate subsidence rates on Nea Kameni of about 8-9 mm yr^{-1}, double than before the 2011-2012 unrest, implying a gradual deflation of the magma chamber, while Thera, the main island, appears almost stable with negligible deformation.

S01.17 Talk

Geology of the Acoculco Caldera Complex at the eastern sector of the Trans- Mexican volcanic belt, México

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The Acoculco Caldera Complex (ACC) is located in the eastern part of the Tans-Mexican Volcanic Belt in the State of Puebla. It is a potential source of geothermal energy catalogued as a high-dry rock reservoir. The complex is located at the intersection of NE-SW, NW-SE, and E-W fault systems accommodated by a N50°W extensional regime. These fault systems have controlled the caldera collapse and exerted the main control on the location of post- caldera vents. The complex was built upon a basement formed by Cretaceous limestones, the Zacatlán basaltic plateau and the Miocene pre-caldera domes and lavas (10-3 Ma). The caldera-forming eruption occurred 2.7 Ma ago with an explosive event that dispersed pyroclastic density currents and emplaced the Acoculco andesitic ignimbrite with a volume of ~127 km^3. The volcanic activity was renewed mainly inside the caldera complex producing several volcanic units that formed the early post-caldera volcanism (2.6-2.1 Ma). This volcanism consists of lava and domes dominantly of basaltic trachyandesite to basaltic composition with an erupted volume of 32.8 km^3. The activity migrated dominantly to the periphery provoking the emplacement of 70.6 km^3 of late post-caldera domes and lavas, and the Encimadas ignimbrite, all with rhyolitic composition (2.03-1 Ma). Finally, extra-caldera activity occurred between 0.9 and 0.06 Ma through venting of scoria cones and lava flows that erupted basaltic trachyandesites to basaltic andesites with a volume of 31 km^3. Aeromagnetic data revealed the presence of at least four intrusive bodies at depths of >2 km hosted in the Cretaceous limestones. These bodies and the occurrence of an aplitic dike dated at 183 ± 36 ka at the bottom of the EAC2 drill hole at depths of >1.8 km below the surface suggest that these intrusions may provide the heat for hydrothermal manifestations and a geothermal potential still to be explored.

S01.17 Poster

Geology of the Late-Pliocene Yolo Volcanic Complex, North of the Acoculco Caldera Complex, Hidalgo State, México

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The Late-Pliocene Yolo Volcanic Complex is located east of the Tulancingo city, at the northernmost part of the eastern Trans-Mexican Volcanic Belt. The area is located ~450 km from the Middle America Trench where the Cocos Plate subducts beneath the North American Plate. The Yolo Volcanic Complex is built upon a basement formed by Cretaceous limestones from the Sierra Madre Oriental and the Oligocene-Miocene Zacatlán basaltic plateau. Yolo belongs to the pre-caldera volcanism of the Late-Pliocene - Pleistocene Acoculco Caldera Complex and consists of eight rhyodacitic to rhyolitic lava domes, two of them with associated rhyolitic PDCs. Yolo is overlied by the 2.7 Ma Acoculco Caldera Complex (southeast), the Plio-Quaternary Apan-Tezontepec Volcanic Field (southwest) and the Quaternary lacustrine sediments of the Suplitán Lake (west). Yolo is situated within the NE-oriented Apan Graben that forms part of a regional orthogonal arrangement of horsts and graben-like structures, mainly ruled by the intersection of two fault systems present in this region. The NE-striking Apan-Piedras Encimadas Fault System and the NW-striking Taxco-San Miguel de Allende Fault System. These tectonic faults control the distribution, development and geometry of some volcanic structures and sedimentation in the region.

S01.17 Poster

Constraints on magma accumulation, storage and extraction in gravitational viscoelastic Earth: Understanding the Bardarbunga 2014-2015 caldera collapse

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Large effusive basaltic eruptions (>1 km3) provide a challenge for common mechanical volcano models. For elastic host rock rheology, large build-up of overpressure is typically required to generate large eruptive volumes – exceeding the tensile strength of the Earth (not realistic). However, for viscoelastic host rock rheology, large magma volumes may accumulate over long periods without large overpressure, as stresses due to overpressures are relaxed. For buoyant magma large underpressure may in certain situations develop in magma bodies feeding large eruptions, which is possible as long as a feeder channel towards the surface can remain open. This model is challenged, however, by the elastic theory that a feeder channel closes as overpressure goes to zero, which may be the most common situation. Exceptions are few cases when inelastic processes dominate such as during caldera collapses or when draining of large magma volumes occurs. Erosion of a crystal mush, delivering crystals to a carrier liquid, may help sustain an open magma pathway from the feeder body towards the surface. Solidification of thin borders of a feeder dyke due to cooling at the host-rock interface may also create strength to help keep open the wider parts of a dyke. We present a model of these processes for the Bardarbunga 2014-2015 caldera collapse, Iceland, where buoyant magma was drained from a magma body embedded in viscoelastic crust below the brittle-ductile transition.

S01.17 Talk

The Campi Flegrei Conundrum: Accounting for the Change in Unrest Dynamics in 1982-1984

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Campi Flegrei caldera, Italy, has been in a state of unrest since 1950 that is similar to behaviour in the 100 years before the last eruption at Monte Nuovo in 1538. Between 1950-1984, three short-term rapid uplifts (c.1 m yr^{-1}) elevated the centre of the caldera by c.4 m. The similarity in the characteristics of the uplifts implies a common source mechanism. However, the 1982-1984 episode was followed by a subsidence (c.0.6 m) that persisted until 2000. This deformation has since been virtually recovered by slow uplift since 2005, which we infer from the geometry and rate of deformation to represent a reversal of the subsidence process.

Critical to the effective management of unrest is the ability to differentiate between uplift due to magma from that caused by the hydrothermal system. Conventionally models have focused on ground movements post-1982 and uplifts have been variably attributed to either magma, pressurisation of the hydrothermal system or both. None can account for both the net-uplift since 1950 and the emergence of the slow ground oscillation after 1984.

Contrary to previous models, we consider unrest since 1950 as a single sequence whereby the controls on ground movements are dynamic and can change overtime in response to mechanical changes in the crust. We propose that the 1982-1984 uplift marks a transition from a magmatic to hydrothermal control on ground movements and that the appearance of the hydrothermal signal is the result of a critical permeability change caused by repeated stretching of the crust during successive sill intrusions between 1950-1982. Two end-member scenarios for the post-1984 sequence are recognised depending on when crustal equilibrium conditions are assumed. The primary implication of the model is that past uplift episodes may not provide a reliable basis for defining future unrest scenarios without consideration of long-term cumulative changes in the crust.

Statistical approaches to better constrain eruption probability and future vent location at Campi Flegrei caldera

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Campi Flegrei has had more than 60 intra-caldera eruptions since its last major episode of collapse, virtually all located within an annular zone defined by the caldera ring fault. Non- eruptive episodes of caldera-wide uplift since 1969 are consistent with the intrusion of magmatic sills 2-4 km beneath the volcano. An important goal for hazard mitigation at Campi Flegrei is to develop reliable methods for relating the potential for eruption to the behaviour of caldera unrest.

The probability of an eruption can be defined as: P(eruption) = P(bulk failure of the crust) x P(magma reaches surface through failed zone). Empirical expressions governing elastic- brittle deformation of the crust around a pressurizing magma body have frequently been used to constrain the likelihood of bulk failure and, hence, the first term on the right-hand side of the equation. To better constrain the second term at Campi Flegrei, we have developed Monte Carlo simulations to investigate the probability of an intruded sill intersecting the zone of ring faults as a necessary step before eruption.

Maximum probabilities of sill-ring fault interaction were typically found to be about 40% or less, which may explain why episodes of uplift do not always lead to eruption. Given the preferential location of sill intrusion at Campi Flegrei, we also find that the probabilities vary spatially along the fault structure. The results agree with spatial analyses exploring the density of post-caldera vents. Thus, relative probabilities of sill-ring fault interaction appear highest along the north-eastern sector of the ring fault, consistent with the zone of greatest vent density; the lowest probabilities in contrast appear offshore to the south, where few eruptive vents have been mapped. Combining these results with models of elastic-brittle deformation provides a first-order constraint on estimating the probability of an eruption during future unrest, and its preferred location.

S01.17 Poster

Explosive Volcanic History of Ilopango Caldera, El Salvador: indispensable geologic data for future volcanic hazard assessment

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Ilopango caldera is located next to the two million people city of San Salvador and within El Salvador Fault Zone, where the deep strike-slip faults are controlling the volcanism of the caldera. Ilopango is a 17 x 13 km volcano-tectonic structure filled by an intracalderic lake. This caldera has experienced many collapses during its episodically formation. The first three phases (lower member) produced large explosive eruptions that deposited: the Olocuilta Ignimbrite (1.78 ± 0.01 Ma), Colima Ignimbrite (1.56 ± 0.01 Ma) and Apopa Ignimbrite (~ 1.34 Ma), with volumes of at least 50 km^3 DRE per unit (VEI ~ 7). Ilopango caldera generated at least 6 more explosive eruptions during a time span of 1.34 Ma – 57 ka (middle member), producing dangerous pyroclastic density currents, plinian falls and phreatomagmatic explosions. The last four explosive eruptions of Ilopango happened during the past ~57ka and are known as Tierras Blancas (TB, upper member): TB4, TB3, TB2 and TBJ. The largest of these younger eruptions was the Holocene TBJ (39 km^3 DRE), which occurred c.a. 1600 years ago catastrophically affecting the Mayan population in the region.

We present here the newly geological study carried out to identify and characterize the 13 large explosive eruptions produced by Ilopango caldera in order to understand the entire volcanic history of this long-lived caldera. Acquiring this kind of geologic data in poorly known volcanoes is the first step for future volcanic hazard assessment. This is particularly crucial in vulnerable countries like El Salvador, where even the emplacement of a small intracaldera dome in 1879 provoked serious damages in the San Salvador Metropolitan Area.

This study was financed by CONACYT-CB grant 240447 and logistically supported by MARN and PNC-El Salvador.

S01.17 Talk

Interaction between Aso volcano system and the terminal parts of strike-slip faults during the Kumamoto earthquake

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NE-SW trending ruptures appeared on the ground from about 25 km west of Aso caldera rim, to inside of Aso caldera during the Kumamoto earthquake, which occurred in the central part of Kumamoto Prefecture on April 16, 2016. The eastern terminal of those ruptures appeared on Aso central cones, and was divided into three rupture bands, all having an E-W trend with marginal shear zones. Those rupture bands reached the west end of Nakadake volcanic crater, one of the most active volcanoes in Japan. Our previous study showed how distributions and displacements of faults generated by the Kumamoto earthquake affected the central cones of Aso volcano. This study shows a correlation between long-term and present volcanic structures, and fault structures created by the Kumamoto earthquake. The present volcanic complex started at 90 ka after Aso-4 caldera- forming eruption and developed in three stages, when consistent fault structures appeared as the result of Kumamoto earthquake.

The eastern end of the earthquake ruptures formed graben structures in the concentration zones on the edifice of Aso volcano. The locations of volcanic cones younger than 90 ky controlled the faulting structure of terminal parts of the Futagawa fault segment, while they gradually shifted to north. Activities of stratovolcanoes from the central cones shifted from east to west, which correlates with the terminal part of the Aso graben. In the last stage, the Nakadake crater erupted for a long period of time using stable conduit system. Three dimensional volcanic structures were deduced using seismic velocity profile and fault texture. Those results agree with tectonics: a terminal pull-apart structure in shallow crust controls the shape of volcanic edifice on the Aso volcano.

S01.17 Poster

Interaction between calderas and rifts along divergent plate boundaries: an example from Askja volcano, Iceland

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Understanding the distribution of the volcanic activity at calderas and its relationship with local and regional tectonic structures is a key feature to mitigate hazards related to locations and styles of future eruptions.
Here, we focus on the Askja central volcano located within the NNE-SSW trending rift along the magmatic divergent plate boundary (MDPB) of Iceland. It is formed by three overlapping calderas (Kollur, Askja and Öskjuvatn) within an older hyaloclastite massif. Volcanic activity occurred both along the rift and in the central edifice.
In order to better understand this complex volcano-tectonic framework, we analysed the distribution of the volcanic activity at the surface, the relationship among the three calderas and the interplay between rift-related and calderas-related faults.
We performed a structural field survey supported by mapping vents and tectonic-lineaments using aerial and satellite imagery.
Our results show that volcanic vents and dikes are preferentially distributed along the caldera ring faults and along the NNE-SSW regional trend, when located outside the calderas. In particular, closer to the central volcano, the volcano-tectonic structures are: 1) NNE to NE oriented in the eastern portion of the hyaloclastite massif, 2) parallel to the caldera rim and NNE oriented cross-cutting on the western side around Askja caldera, 3) caldera rim parallel around Öskjuvatn caldera.
We suggest that Askja volcano holds both regional (rift-related) and local (calderas-related) volcano-tectonic structures, thus depending on two distinct regional and local stress fields interacting together. This balanced effect of regional and local deformation controls the propagation of magma and thus the eruption locations in the whole area.
This setting differs from Krafla volcano (north of Askja), dominated by regional structures, and Grímsvötn (south of Askja), likely controlled by local structures – that may reflect a northward increase of the spreading rate along the Icelandic MDPB.

S01.17 Talk

The use of the Electrical Resistivity Tomography to image volcanic structures: an application to the Solfatara – Pisciarelli complex (Campi Flegrei caldera, Italy)

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Geophysics is considered a powerful tool both for modeling the structure and controlling the dynamics of active volcanoes. In particular, the application of the Electrical Resistivity Tomography (ERT) is a topic of great interest, given the strong dependence of the electrical resistivity on the shallow and deep physical characteristics of a volcanic apparatus. ERT is able to furnish a high affordable imaging of the subsoil, through the use of an artificial source. However, its relevance in volcanological applications greatly depends from the depths of the investigated formations. This latter strongly depends from the physical and logistic conditions characterizing the data acquisition phase, as the power source intensity, an electrical current injected into the ground, and the electrode arrangement, which deployment often implies hard problems due to the harsh nature of the volcanic environments. The actual progresses of the technologies offer ways to bypass these limitations: the modern instruments permit the realization of a sort of wireless electrodic arrays, whereas the easiness of use of the actual power generators represents a further notable element. The ERT imaging could now represents an optimal tool also in the imaging of structures buried at intermediate depths (several hundreds of meters).

We present a study concerning this capability, applying the deep ERT imaging to the Campi Flegrei caldera (Italy) that is among the most surveyed active volcanoes in the world for the great concern due to the high level of urbanization. 12 wireless ERT stations have been distributed around the Solfatara crater and the near Pisciarelli area, the most active part of the caldera in terms of gaseous emissions and seismicity. The imaging details the main formations and structures of the shallower part of the subsoil, furnishing useful elements to highlight the fluid dynamics in an area with hazard related to possible phreatic events.

S01.17 Poster

Electromagnetic imaging of the deep Campi Flegrei caldera structure (Southern Italy)

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The Campi Flegrei caldera (CFc) is the most hazardous volcano in Europe. Enormous investigative efforts have been done aimed to share its inner structure and to understand its unrest dynamics, making the CFc one of the main subjects of interest of modern volcanology.

Due to the destructive potential and the active geothermal system, the CFc geological structures have been investigated through many different methodologies. A key role belongs to the applied geophysics that allows to gain knowledge about the volcanic setting and consequently to understand the dynamics of this active caldera system.

So far, the main CFc structures have been not yet clearly defined. The geometry and configuration of the CFc plumbing system are still largely undefined, although seismic surveys nowadays detected findings of melt-bearing rocks, at least locally.

Here a deep electromagnetic (EM) imaging the CFc is presented. Two Magnetotelluric (MT) profiles have been carried out, ideally intersecting the main recent volcano-tectonic structures. The peculiar sensitivity to subsurface fluids and melts, associated with huge electric conductivity contrasts, make the MT particularly well suited to be applied in active volcanic settings.

The obtained results highlight the buried structures down to 10 km of depth providing an interpretative key into the overall caldera dynamics. In particular, the deep magmatic source is revealed, as well as the main ascent pathway of magmatic fluids and the related structures which critically contributing to the shallower-level of deformation at CFc.

Radial Interpolation Method (RIM) of ground displacement data in active volcanic areas: analysis of the recent deformation patterns of Campi Flegrei caldera (southern Italy)

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This study presents a new method to interpolate data characterized by a radial pattern around a relatively constrained central zone, such as the ground deformation patterns shown in many active volcanic areas. The method is applied to a large dataset collected at the Campi Flegrei caldera during the last 38 years, including leveling, Geodetic Precise- Traversing measurements and Global Position System. Interpolated maps well identify and display the circular and elliptical patterns resulting from uplift and subsidence episodes in the central portion of the Campi Flegrei caldera. Resulting elliptical shapes are characterized by WNW-ESE and secondarily NNE-SSW long axes. Ground deformation boundaries depict an active area nested within the larger pre-existing depression resulting from the two caldera-forming eruptions of Campanian Ignimbrite (~40 ka) and Neapolitan Yellow Tuff (~15 ka). The interpolated maps of horizontal displacement show maximum values lying along a semi-circular annular region with a radius of about 2-3 km in size, centered in the town of Pozzuoli, where the maximum value of vertical ground displacement is measured. This semi-annular area represents a good proxy of the localization of the main surface extensional deformation marked by meso-scale structures such as faults, sand dykes and fractures. This area could be ideally extended into the Gulf of Pozzuoli so depicting an elliptical-shaped region including most of the epicenters of the 1972-2015 earthquakes. Interpolated vertical displacement maps were used to evaluate the volume of displaced rocks both for uplift and subsidence episodes. The scatter plot of the displaced volume vs. maximum displacement indicates a linear relationship that was used to estimate the displaced volumes also for the uplift episodes of 1950-1952, 1968-1972 and 2005-2018.

Seismically-induced sand liquefaction and soft-sediment deformation phenomena during the volcano-tectonic activity at Campi Flegrei caldera in the last 15 ka (southern Italy)

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We report, for the first time in an active volcanic area, the field evidence of seismically- induced deformations. Structures such as sand dykes, sand volcanoes and slumps, are hosted in a marine-transitional and continental successions in the central area of the Campi Flegrei (CF) caldera (southern Italy). A detailed structural survey in an area bounding the coastal terrace of La Starza, including the excavation of a 1 km long tunnel, allowed us to constrains the formation of these sand dykes and sand volcanoes occurred between two major eruptions occurred at 4.55 ka (Agnano-Monte Spina) and 4.28 ka (Averno-Solfatara), respectively. These peculiar structures resulting from liquefaction processes which were allowed by the peculiar rheological and lithological characteristics of the volcanic and sedimentary filling of the CF caldera in the last 15 ka. In fact, this sequence is broadly defined by the superposition of three layers with different rheological behaviours: a basal thick massive tuff deposit (Neapolitan Yellow Tuff, 15 ka), a marine-transitional sequence of La Starza unit (15-4.9 ka) and an uppermost level of continental volcanosclastic deposits (4.9ka-AD 1538). We envisage that the lower and upper levels mainly deformed by means of an elastic and brittle behaviour, during phenomena of unrest predating major eruptions which include ground deformation and seismic activity,; on the contrary the middle level, characterized by water-satured loose sands, if subject to seismic shacking it can liquefy and consequently trigger the formation of both sand dykes capable to tilt and spreading laterally the overlying rigid layer and sand volcanoes in the subaerial surface. This sand liquefaction and soft-sediment phenomena can represent an additional hazard related to significant unrest crisis at Campi Flegrei caldera.

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S01.18 - Phreatomagmatic eruptions how do you know and how does it matter

The 16 March 2017 phreatomagmatic explosion at Mt Etna, Italy

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On 27 February 2017, an eruption started at Mt Etna from the large cone hosting the South- East and New South-East Craters, initially characterized by lava effusion and Strombolian activity and, on 15 March, by the effusive vent opening in the southern slope of the cone. Heralded by increasing steam emission and ash puffs in the lava field, on 16 March the interaction of a slowly advancing lava lobe with the snow cover produced a sudden and unexpected short-sequence of explosions, lasting less than 1 minute. White vapor, brown ash and coarse material ascended rapidly, and the ejected products hit a group of people (tourists, volcanologists, volcanological guides, and a BBC crew), who reported mild to serious injuries.

Surveys were promptly aimed at collecting representative samples and data on the dispersal area, thickness, and grain-size of the deposit of the explosion before possible coverage by new tephra/lava deposits. Coarse lapilli and coarse ash were also classified on a textural and morphological basis. The ballistic material reached up to 200 meters away, forming a bilobate fan-shaped area due to multiple explosions. The proximal deposit was poorly sorted and formed by a continuous mantle of ash, lapilli and decimetric-sized bombs varying in thickness. The mass loading per square meter and the grain-size of the coarse deposit (coated by wet ash) decreased gradually up to 50-60 m away from the "lava flow edge", further away becoming scattered decimetric to pluri-centimetric clasts. An estimation of the total deposit provided a mass of $\sim 10^5$ kg.

Improving our understanding of lava-snow interaction is crucial at Etna - a volcano recording up to thousands of visitors per day attracted by the high frequency of its eruptions - in order to improve the assessment of associated hazards and prevent similar accidents to the 16 March event.

Subsurface magma-water interaction: physical constraints from numerical modeling

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The inlet of phreatic water into volcanic conduits has been proposed as a major modifying agent of the dynamics of explosive eruptions, strongly influencing magma fragmentation, explosiveness and dispersion of pyroclastic products. Although several external water sources and interaction mechanisms have been proposed, the nature and effects of magma- water interaction are still largely unclear. A common postulate for phreatomagmatic activity to occur, is that pressure in a conduit crosscutting a subsurface aquifer drops below the pressure in the aquifer, which depends on the physical properties of the ascending magma and aquifer. In agreement with most phreatomagmatic eruptions, here we show that the injection of significantly large mass fractions of external water (here assumed corresponding to >3 wt.%) is only physically feasible for low eruption rate events; while high-intensity eruptions with evidences of magma-water interaction are probably related to other external water sources and/or interaction mechanisms, such as the involvement of large bodies of superficial water or the injection of ground water due to the destabilization of aquifer-hosting rocks during caldera collapse processes. Based on modeling findings, it emerges that favorable conditions for the access of external water in the conduit are generally reached above the fragmentation level. Consequently, magma-water interaction seems not able to induce dramatic changes to the features of a primary 'dry' vesicularity, as commonly claimed. Hence, the low vesicularity indexes traditionally attributed to phreatomagmatic eruptions appear difficult to be explained by the quenching effect of external water on a not fully developed vesicularity. Instead, they may be related to the low eruption rates required for effective magma-water interaction, which generally result in eruptions where the magma ascending in narrow conduits is characterized by significant lateral gradients of vesicularity.

Phreatomagmatic versus magmatic fragmentation: Insights from juvenile particle analysis

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Juvenile pyroclasts offer unique insights on the style of magma fragmentation. Observed variations in their morphology (e.g., fluidal versus blocky), crystallinity, vesicularity, and surface features (e.g., stepped features, etc.) have been used to distinguish phreatomagmatic from magmatic explosive activity. This distinction is of primary importance in hazard assessment. However, there is no widely accepted methodology for the characterization of juvenile pyroclasts to investigate magma fragmentation. To contribute to the development of such a unified methodology, we characterize known phreatomagmatic and magmatic juvenile pyroclasts from fragmentation experiments and the well-observed 1977 Ukinrek maar eruption in Alaska.

A test was carried out on phreatomagmatic and strombolian samples from the Ukinrek eruption in order to identify which grain sizes best record the fragmentation signature. Polished grain mounts were produced for size fractions from 0 to 4φ, and observed with optical and electronic microscopy. Selected 2D shape parameters such as axial ratio (form), solidity (morphological roughness) and convexity (textural roughness), along with crystallinity and vesicularity, were quantified from particle cross-sections for each size fraction and the results compared.

Experiments at the *Physikalisch Vulkanologisches Labor* in Würzburg (Germany) allowed us to reproduce both magmatic and phreatomagmatic fragmentation processes, using volcanic material of olivine-melilitite to basaltic trachyandesite composition, remelted at magmatic temperatures. High-speed video recordings allowed direct investigation of free air expansion of the melt. Artificial pyroclasts collected from each run were prepared for 3D and 2D image analysis. Preliminary results show that during magmatic fragmentation, magmas having similar equilibrium viscosities behave quite differently due to non-Newtonian behavior, and this has major influence on particle shape. Work on both the Ukinrek test and the experimental products is currently in progress, and the results will be presented at the conference.

Phreatic eruptions without unrest?

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Volcanic eruptions are typically heralded by unrest, which has extremely variable patterns and duration. Some eruptions are preceded by years of inflation and seismic swarms (Rabaul in 1994), others by days or weeks (Kelut in 2014). However, whether unrest occurs prior to phreatic eruptions is ambiguous, particularly for volcanoes that have had a hiatus of eruptions of a few years or more. Recent examples with no unrest detected (monitoring networks existed) prior to significant phreatic eruptions include Mayon in 2013, Ontake in 2014, and Merapi in 2018. Given that such events appear to happen with no warning and at any time, they are particularly dangerous and have the potential to cause significant harm and fatalities. A posteriori detailed analysis has, in some cases, shown that there were subtle changes in seismicity or thermal anomalies a few minutes or hours before the onset, too short to issue warnings and effective alerts levels. We have done a literature review (including data from GVP, WOVOdat, and other literature sources) of ~160 cases of no reported unrest (or shorter than a few hours) prior to phreatic eruptions in the last 20 years. We found that more than 70% of the phreatic eruptions lack evidence of unrest (<24 h prior). Towards better anticipation of such events, we suggest the implementation of a real-time automatic system to detect changes in high-sampling-rate seismic, deformation, and gas data, as well as the operation of an alarm system in the vicinity of the volcano. The absence or short duration (few hours) of unrest requires re-evaluation on how to represent an event tree to properly address this issue. We propose a variation of Newhall & Hoblitt (2002) with an event tree structure that starts with an initial node "normal", unrest in the second node, follow by genesis, outcome, etc.

S01.18 Talk

Assessing the hazard from phreatic/hydrothermal explosions at the Solfatara-Pisciarelli complex through 3D numerical simulations

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Volcanism at the Campi Flegrei caldera has included phreatic to phreatomagmatic explosions and both magmatic and effusive eruptions. The past eruptive history in the region, and the recent (post 2005) evolution of the activity in the area, suggest that the Solfatara-Pisciarelli sector of the Campi Flegrei caldera has a high probability of reactivation, and that several different eruptive scenarios are possible, including episodes or sequences of phreatic/hydrothermal explosions. The recent eruptions at Upper Te Maari Crater, Tongariro volcano (2012) and Mt. Ontake volcano (2014) have shown that such events are extremely difficult to anticipate and can pose a significant hazard in areas proximal to the eruption vents, mostly associated to intense ballistic ejection, even in the case of relatively small (i.e., less than 1 Mm^3 of ejecta) eruptions. This is particularly critical in a site with high density of inhabitants, such as the Solfatara-Pisciarelli area.

In this work, we model and simulate numerically, in 3D, a explosion driven by the sudden decompression of a shallow hydrothermal (non-magmatic) body, with the aim of providing to the Italian Civil Protection preliminary hazard scenarios in the Solfatara-Pisciarelli area. The model assumes that fragmentation of the hosting porous/fractured medium is immediate and produces an expanding gas-particle cloud, accompanied by a ballistic shower of coarse lithic fragments, initially accelerated by gas pressure gradient and drag. We explore, by a parametric study, the effect of the different model parameters, in particular the specific available mechanical energy (associated to pressurization), the temperature and the particle grain size distribution. Results show that the areal extension of associated pyroclastic currents and ballistic impacts is mostly controlled by the initial pressure in the system, although the geometry of the exploding volume plays an essential role in the azimuthal distribution of the products and in the initial decompression dynamics.

Progress towards realistic modelling of phreatomagmatic eruptions

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Phreatomagmatic eruptions, where magma fragmentation is largely dictated by water- magma interaction, are frequent and highly dangerous volcanic events. While phreatomagmatic eruption sequences often comprise complex and highly unsteady successions of generations of plumes, jets, ballistics and pyroclastic density currents, stratospheric disturbances caused by phreatoplinian eruptions have been proposed to influence climate. In contrast to dry magmatic eruptions, the dynamics of phreatomagmatic plumes and our ability to simulate these in numerical models remain incomplete. Recently Van Eaton et al. (2012) highlighted the importance of surface water and the role of phase transitions on the ascent dynamics and plume stability.

In this work, we report progress towards accurate and realistic modelling of phreatomagmatic eruptions. We modify the existing ASHEE (ASH Equilibrium Eulerian) model to include the effects of water phase changes (vapour, liquid, solid), resulting in a “wet” ASHEE eruption simulator. This additional microphysics is necessary when the mass fraction of water in the mixture exceeds 10%. Realistic thermodynamic functions are used to model the saturation pressure and the heat capacities in the wide temperature window explored by volcanic eruptions.

Using the “wet” ASHEE code, we run test numerical experiments to assess the effect of water phase changes on the ascent, steadiness and stability of eruption columns, while also collecting data on the dynamics of tephra and water dispersal and sedimentation. Simulations with a variety of mass eruption rates, water contents, and particle size distributions, are trialled and their dynamics assessed and compared. New fieldwork data on the initial phreatomagmatic phase of the 232 AD Taupo eruption are presented also and discussed in light of the numerical results. We discuss future modifications to the model, including the addition of Lagrangian particle phases coupled to the rest of the eruption column to assess how the presence of large clasts modifies the eruption dynamics.

Magma sediment mingling recorded in pyroclasts from 71 Gulch Volcano, Idaho, USA

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Phreatomagmatic explosions resulting from the interaction of magma and water/water- saturated sediments occur in all volcanic environments. Interpreting the geologic record is an important method for constraining the number, location, and conditions which produce these explosions. The sub-lacustrine 71 Gulch basaltic fissure structure in southwestern Idaho has been eroded to expose the shallow (<15 m below surface) volcanic plumbing system while preserving some of the eruptive products. This provides an opportunity to investigate the subsurface conditions that contributed to explosive and effusive activity. A detailed characterization of the deposits in the near surface and the preserved eruptive deposits highlights the variety of sediment and magma interactions from classic peperites to convoluted dikes, and cored bombs. Of particular interest at 71 Gulch are anomalous light grey colored vesicular lapilli and bombs that occur in two horizons of the preserved eruptive deposits. These clasts occur within poorly sorted and weakly bedded tuff breccias with low vesicularity basaltic lapilli and bombs in an ash matrix. The light colored pyroclasts display centimeter to millimeter mingling of weakly vesicular (30-50%) basaltic material with lighter more vesicular (70-90%) material and the clasts frequently have a fragile outer coating of basalt. Major element geochemistry of the light colored material indicates that the pyroclasts have distinctive major and trace element chemistry relative to the dominant basaltic magmatic composition. While some major element trends are consistent with hydrothermal alteration, enrichment in trace elements indicates that post emplacement alteration is not enough to explain the origin of these pyroclasts. These rare clasts may reflect melting of the lacustrine sediment during or preceding an explosive phase of the eruption. Relating these and other mingling products to magmatic, phreatomagmatic, and non-explosive processes is critical to understanding the conditions that lead to phreatomagmatic explosions and our ability to reconstruct eruptions from their deposits.

S01.18 Poster

Surtsey phreatomagmatism, early results of the SUSTAIN ICDP 2017 drilling

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The island of Surtsey has been the type locality for Surtseyan and emergent basaltic volcanism, since its formation in 1963-67. It was constructed from a depth of 130 m, upon a sea floor composed of volcanic and glacial sediments. The initial explosive eruptions in November 1963-April 1964 lasted four and a half months before effusive eruptions began. The formation of Surtsey was exceptionally well documented and its structure can be reconstructed, partly on the basis of eruption history, partly on drill cores and partly from surface geophysical surveys. A first core was extracted in 1979 from a 181-m-deep hole (SE-01) on the eastern rim of the main explosive vent active in November 1963-January 1964 (Surtur I). Two new vertical cores (SE-02A, SE-02B), 152 and 192 m deep, were extracted close to the 1979 hole in 2017 by the ICDP-supported SUSTAIN drilling project. Preliminary results indicate that the basaltic lapilli tuff produced by the 1963-1964 eruptions has further altered and consolidated since 1979; there are also a few minor basaltic intrusions. A third core, inclined 35° from vertical, confirms the existence of a diatreme that cuts into the seafloor sediments. The island's interior hosts a geothermal zone, with maximum reservoir temperatures detected in 2017 of at least 120-125°C. The upper 100 m of the diatreme still has an elevated temperature relative to the surrounding sea floor, 50 years after eruptions terminated.
The new drillholes did not intersect any pillow lavas and no pillow fragments are found in the cores, suggesting an absence of these deposits at the base of the edifice. Thus, it appears that magma fragmentation was dominant from the start of the eruptions at a confining pressure corresponding to 130 m water depth.

Groundwater monitoring around the Ebino Plateau, Kirishima volcanic group

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The 2013 reactivation of the Ebino Plateau, of the Kirishima volcanic group, has led to increases in seismic activity and volcanic tremors in the area, as well as a series of ground deformations. A noticeable phreatic eruption accompanied by a small ash emission occurred on May 8, 2017, after which volcanic tremors, seismic activity, and ground deformations have been repeating at different intensities. On April 19, 2018, an explosive phreatic eruption, ejecting small ballistic projectiles and ash, occurred on the southern side of the summit crater, generating a hot lahar, which flowed down into the Nagae River. A more recent phreatic explosion, which occurred in the evening of April 26, 2018, led to the formation of new fissures at a lower elevation of the crater.

To help understand the behavior of groundwater systems within the Iou-Yama in order to contribute to volcanic mitigation, a series of continuously monitoring sensors of electrical conductivity and temperature were installed, one as close as 200 m from the fissure formed on April 26, 2018. These have been collecting groundwater samples from a number of locations since June 3, 2017 to continuously analyze their chemical composition.

Temporal variations of the chemical composition of the groundwater were observed in all samples from eight discharge points at three sites where data loggers were installed, variations specifically with respect to cations and anions. After September 22, 2017, the samples have showed an upward trend in major ion concentrations, including Ca+, Na+, SO42-, and Cl-, particularly at a site located close to a new fissure (i.e., site No. 1). Currently, further examinations on volcanic activity and its effect of local weather are being carried out.

Modeling potential directed explosions and ballistic ejection, pyroclastic density currents and partial edifice collapse from non-magmatic hydrothermal eruptions at La Soufrière of Guadeloupe (Lesser Antilles): new insights in the context of the ongoing increased deep-sourced unrest

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The current unrest developing at La Soufrière of Guadeloupe that reached between February and 27 April 2018 unprecedented levels of seismic energy release in the last 42 years. We use exegesis and re-analysis of historical chronicles, new knowledge on the structure and hydrothermal fluid circulation in the dome, new field data and current monitoring data to perform numerical simulations of the main expected hazards from a potential non-magmatic explosive hydrothermal eruption at La Soufrière of Guadeloupe. Indeed, recent eruptions of Ontake (2014) and Tongariro (2012) underscore the hazards and risks associated with sudden, often unpredictable hydrothermal eruptions at volcanoes characterized by long-lasting non-magmatic unrest. Reappraisal of historical data has shown that 3 of 6 historical non-magmatic hydrothermal eruptions (1797-1798, 1836-1837, 1976-1977) have produced: 1) extensive ballistic fallout; 2) small-volume laterally-directed explosions; 3) small-volume high-energy turbulent pyroclastic density currents (PDCs); 4) small-volume collapses of the dome with associated rockslides and/or debris avalanches; and 5) the exurgence of pressurized warm to hot acid hydrothermal fluid. We use these data and the current unrest parameters to constrain temperature and pressure in the hydrothermal system as well as the source of overpressure. These data allow us to parametrize the simulations of directed explosions (with associated turbulent PDCs and ballistic fallout) as well as those for partial edifice collapse (with associated granular debris avalanches). Results show that debris avalanches and PDCs could reach several kilometers from the dome into populated areas of the southern flanks of the volcano. Given that flank instability of hydrothermally altered and pressurized regions of a volcano can be triggered by seismic, hydrothermal, magmatic, and meteorologic forcings, our results have implications for hazard and risk assessment as well as for continuing multi-parameter monitoring strategies on La Soufrière of Guadeloupe volcano currently in a state of significant unrest.

S01.18 Poster

Enhanced potential for phreatic eruptions due to thermal breakdown of hydrous minerals in the advanced argillic environment

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Non-juvenile eruptive produ
cts in phreatic and phreatomagmatic eruptions frequently contain hydrous materials such as amorphous silica (opal), alunite, and kaolinite. All three can contain 10-15 wt.% H_2O as do many other clays found in the advanced argillic environment. All of these hydrous materials are unstable and will dehydrate upon heating. For any such alteration product with 13 wt.% H_2O, devolatilization in the uppermost km will generate many cubic meters of steam for each cubic meter of rock. If magma is nearby, the additional heat will increase the relative overpressure. Any porewater near its boiling point will further exacerbate the situation. Depending on the permeability of the overlying rocks, significant overpressures might be generated by even partial thermal decomposition of hydrous alteration products.

Calculations for materials on the boiling curve at 5MPa indicate that the effect of thermal pressurization due to magmatic intrusion will be up to four times greater in acid-altered rock than in unaltered volcanic terrain containing water-saturated lavas, pyroclastic rocks, etc. Advanced argillic environments are almost always at elevated temperatures beneath active volcanoes because they are created as hot volcanic gas dissolves within shallow groundwater. As magma migrates through this environment, heated water may flow away, but hydrous minerals cannot move. New intrusions of magma will disturb acid-altered hydrothermal systems, can destabilize hydrous minerals, and may result in hydrothermal and phreatomagmatic explosions.

S01.18 Poster

Understanding and forecasting phreatic eruptions

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Phreatic eruptions are a broad class of explosive eruptions in which hydrothermal processes play a fundamental role. Here, we focus on phreatic eruptions at volcanic hydrothermal systems that are fed by magmatic input. We consider two defining characteristics of these phreatic eruptions to be (1) the dominance of hydrothermally altered or lithic components in the eruptive products and (2) the involvement of exogenous water (i.e., steam/water not immediately exsolved from melt). We synthesize data from several significant phreatic systems, including two in Costa Rica (Turrialba and Poás) which are currently highly active and hazardous. We consider two endmember types of phreatic eruptions, the first (type 1 or "phreato-vulcanian" eruptions) in which a deeper hydrothermal system fed by magmatic gases is sealed and produces overpressure sufficient to drive explosive eruptions, and the second (type 2 or "phreato-surtseyan" eruptions) where magmatic gases are supplied via open-vent degassing to a near-surface hydrothermal system, vaporizing liquid water which fuels geyser-like eruption. We examine a number of precursory signals which appear to be important in understanding and forecasting phreatic eruptions; these include very long period (VLP) events, banded tremor, and gas ratios, especially H_2S/SO_2 and CO_2/SO_2. High frequency gas monitoring in particular shows strong potential for unambiguous forecasting of phreatic eruptions, due to large compositional differences between hydrothermal and magmatic gases, and the fundamental role that the latter play in driving phreatic eruptions at many volcanoes. We propose that if multiple datasets are carefully integrated in monitoring programs, it may be possible to accurately forecast phreatic eruptions.

S01.18 Poster

Chronicles of an unexpected eruption: April 2017, Poás Volcano, Costa Rica

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Since 2016 until early 2017, Poás volcano seemed to have entered a stage of quiescence after 10 years of phreatic eruptions. Nevertheless, in April 2017 the volcano culminated into phreatomagmatic activity. On April 1, a new fumarole appeared on a tephra cliff, north of the dome. On April 7, from this spot a boiling spring geysered muddy waters up to 3 m height, releasing hundreds of cubic meters of acid water, draining into Laguna Caliente crater lake through a 400 m long stream. On April 12, the first phreatomagmatic eruption occurred beneath Laguna Caliente. This eruption launched acid mud up to the touristic mirador and fractured the dome. The same eruption triggered lahars that affected the Río Agrio and Río Desagüe rivers, west of Poás's crater. On April 14, a major eruption reached a column height of 5 km, ejecting bombs and blocks of more than 50 kg until the mirador. The dome was almost entirely destroyed, small scoria cones were formed (maximum 50 m), followed by strombolian eruptions (200-1000 m column height). During the 22 and 23 April eruptions, multiple explosions generated shock waves that were felt up to 2 km distance from the crater. The 22 April eruption was the most important of this eruption cycle, with pyroclastic flows inside the crater, and pyroclastic surges reaching the mirador (S) and "terrazas" (E) areas. The pyroclastic surge damaged the vegetation of the Botos forest (SE) and mirador (S). Bombs were found at 1.7 km distance from the vent, reaching the Visitors Centre, parking and tourist trails. Fortunately, no people were injured during this activity of Poás, the first major phreatomagmatic activity since 1953-1955. Despite the various phreatic eruptive cycles in previous decades, there were no long-term precursory signals for this April 2017 surprising culmination.

Linking 2D-and-3D ash morphometry and geochemistry to unravel the triggering and fragmentation mechanisms of proximal surges at Azufral volcano, SW Colombia

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This study presents the investigation of proximal ashes produced during one of the youngest (<4 ka) explosive eruptions of Azufral Volcano, SW-Colombia. Azufral is a stratovolcano with a summit caldera truncated by a lava-dome complex, and hosting a sulphate-dominated, acidic lake. It is one of the most dangerous volcanoes in Colombia, given the evolved composition, and the predominance of PDCs making up its <17 ka edifice.

We present new stratigraphical, compositional, and ash-morphometry data of the proximal lithic-crystalline tuffs onlapping the inner and outer crater-rim. The 3-phi and 4-phi fractions of two representative bedsets were prepared as polished thin sections for automated morpho-chemical single particle SEM/EDX analysis and complemented with 3D nano- computed tomographic reconstructions of the 2-phi fraction. The resulting componentry allowed the identification of 18-34 vol. % rhyolitic glass particles within each layer. EPMA analyses of the juvenile ash suggest that magma evolution was mainly controlled by Pl+Amp+Bt+Px+Fe-Ti oxides fractionation and magma recharge events. Pre-eruptive conditions suggest that magma mixing could have triggered magma decompression from the shallowest reservoir.

The presence of irregular, poorly vesicular glassy shards, suggest that a few gas pockets could be present in the erupting magma, and responded to decompression. However, a positive correlation between convexity and solidity clusters indicates a predominance of equant, dense, glassy/microcrystalline shards, typical of phreatomagmatic fragmentation. The subsequent vulcanian explosions resulted in the removal of a shallow, degassed plug, ejecting base surges and ballistics.

Distinguishing magmatic from phreatomagmatic pyroclastic deposits at prehistoric mafic maar volcanoes

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In a recent paper in Geosphere (v. 12, no. 5), White and Valentine (2016) review what criteria are commonly used to distinguish phreatomagmatic from magmatic explosive eruptions based on the resulting pyroclastic deposits. In summary, it's complicated! Here we restrict the problem to one magma type, basalt in a wide sense, and one volcano type, Miocene to Pleistocene maars. Examples are taken from several fields including from Argentina (Pali Aike volcanic field) and the USA (Hopi Buttes volcanic field). This produces a list of criteria that, when jointly applied to typical endmember magmatic and the much more abundant phreatomagmatic deposits, yields promising results.

The phreatomagmatic deposits typically contain more ash, are often more poorly sorted, and contain a much larger proportion of lithic (accidental) clasts. Their juvenile particles tend to be mostly sideromelane, a type of glass which rapidly alters to yellow-brown palagonite or clays, giving a distinct beige color to outcrops and a cemented porosity. Juvenile particles have varied shapes, but can be blocky. The phreatomagmatic beds in maars often include surges, which can form channels and cross-beds. Accretionary lapilli are sometimes seen.

In contrast, the magmatic layers are darker, better sorted, contain less ash in proximal outcrops, and are typically not cemented or palagonitized. These fallout deposits are very rich in scoriaceous tachylitic juvenile fragments (with less than 10% lithics) or even spatter, which can be welded or agglutinated. The vesicles are typically bigger and more abundant, and the juvenile clast shapes are controlled by vesicles.

Complexities can arise when both eruptive styles were simultaneously active from different vents, when the deposits result from eruptive styles transitional between the pure phreatomagmatic and magmatic endmembers, and due to recycling of juvenile pyroclasts and lithics in maar craters.

Basaltic phreatomagmatism in Iceland – examples of the complexities of deposit interpretation from two large explosive eruptions from Katla volcano and how to resolve them using a new particle imaging method

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Iceland is one of the most volcanically active terrestrial regions on Earth with an average of more than 20 eruptions per century. Around 80% of the eruptions are tephra generating explosive eruptions with almost 9 in 10 being phreatomagmatic. An unusually high proportion of the explosive eruptions (90%) are basaltic, which is attributed to the wet eruptive environments of glaciers, lakes, high ground water tables and also the volatile content of the erupting magma.

Katla volcano is one of the most productive volcanoes in Iceland, and it is known to produce hazardous large explosive basaltic eruptions on a regular basis. Thus Katla provides a perfect natural laboratory to study fragmentation processes of large basaltic phreatomagmatic eruptions. We have investigated the details of fragmentation mechanism and eruption dynamics for the 1755 and 1625 eruptions by combining deposit stratigraphy with detailed studies of granulometry and grain morphology analysis, componentry, granulometric modeling, and the new quantitative regularity index model that can distinguish between magmatic and phreatomagmatic fragmentation. We have also used information from historical descriptions to assess weather conditions during the eruptions and how it may influence interpretation of deposit characteristics.

The research demonstrates that magma/water interaction is important in the process of ash generation, but that eruptions of similar size, geochemistry and eruptive environment can have very different fragmentation dynamics. Our studies show that access to melt water varies significantly during subglacial eruptions at Katla up to a level of predominantly magmatic fragmentation. Finally this study shows that by integrating field observations and granulometry and applying the new regularity index we can generate a coherent model of eruption evolution.

S01.18 Talk

Topographic controls on a phreatomagmatic maar-diatreme eruption (Holocene Dotsero volcano, Colorado, USA): field and numerical results

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We analyze the eruptive products of Holocene-aged Dotsero volcano (Colorado, USA), which record evidence of a progression from effusive magmatic activity to explosive phreatomagmatic maar-forming activity to a final explosive magmatic phase. The nature of the deposits suggests that the irregular and mountainous pre-eruptive topography strongly influenced the formation of directed pyroclastic density currents during the phreatomagmatic phase, where the topographically high northern crater rim acted as a barrier and promoted transport to the south. Furthermore, the crater shape strongly controlled the grain size of the final deposits, providing further evidence that deposit grain size can be a misleading proxy for fragmentation or explosion intensity. We test these hypotheses gleaned from fieldwork using multiphase numerical modeling, extending a framework developed to model subsurface explosions in diatremes to include the surface and crater. Using a bidisperse particle population (d_1=0.0001 m and d_2=0.01 m), we confirm that a crater shape where one rim is higher than the other promotes multiple pulses of particle transport in the direction of the lower rim. The initial currents contain both coarse and fine particles, where the secondary and tertiary currents contain predominately the finer particles. This mechanism provides an alternative explanation to the formation of lapilli tuff/tuff couplets often found at maar-diatreme tephra rings. Additional modeling shows how the depth of a crater can control the grain size of the resulting pyroclastic density currents. In the case of a deep crater and relatively weak explosion, it is possible that only the fine particles escape following the collapse of the eruptive column, resulting in a fine-grained deposit. This work adds to the expanding hypotheses and models developed to describe the eruptions and dynamics of maar-diatreme volcanoes, but also highlights the limitations of our knowledge of key parameters related to their eruptions and deposits.

Synchronous volcanic activities between Shinmoedake and Ebino/Ioyama volcanoes in Kirishima volcano group: Understanding multi-volcanism

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Tajima et al. (2013) concludes the Shinmoedake volcano is characterized by active periods of 500 to 1000 years that are separated by roughly a 2000-year interval. Tajima et al. (2014) discussed the volcanic history of Ebino/Ioyama volcano determined the five craters and two lava flows which were located in Ebinokogen saddle. They discussed that three distinct eruptions from three volcanoes, Ebino, Shinmoedake, and Miike around 4.5 ka yielded similar ^{14}C ages.

After 2008 and 2010 phreatic activities, sub-plinian eruption following lava produced over 107 m^3 magma in 2011 (Nakada et al., 2013). After the 2011 Shinmoedake eruptions, many volcanogenic earthquakes occurred under Karakunidake, beginning in October 2013 (JMA, 2014). The volcanic gas from this magma may have singed from the hydrothermal system under Ebino/Ioyama from August 2014. In Ebino/Ioyama, the temperatures of the fumarolic activity on the south rim of Ioyama crater, fumarolic activity restarted on December 14, 2015 at the south rim of Ioyama crater. During this thermal anomaly event, we observed a volcanic ash deposit from a very small vent on April 26, 2017 by JMA webcam.

Shinmoedake produced fine ash that fell from October 11 to 16, 2017 and the fine ash eruption started from March 1, 2018. Lastly, the lava flow was produced at March 6 and filled in summit large crater, the magma supply stopped rapidly. The volcanic activities in Ebino/Ioyama increased after this eruption, the small eruption occurred south side of Ioyama fumaroles at April 19, 2018, lastly.

Two cases of activity, first magmatic eruptions occurred in Shinmoedake and following phreatic eruptions occurred in Ebino/Ioyama. Those results indicate that residual magma from 2011 and 2018 Shinmoedake eruptions blocked the Shinmoedake passage after the eruptions. The magma so moved toward the Ebino/Ioyama and hydrothermal system became active.

Underestimated volcanic hazards of small-volume dispersed phreatomagmatic explosive volcanism in the Central Andes Volcanic Zone, northern Chile

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Among the hydrothermal to hydromagmatic spectrum of explosive eruptions the formation of maar-diatremes is the most commonly recognized volcanism in northern Chile such as the small-volume monogenetic volcanoes of Tilocálar, Cerro Overo and Cerro Tujle volcanoes. Small volume volcanoes also commonly appear as flank volcanoes associated with central polygenetic cones such as the Alitar and Nevado Tres Cruces. Due to the variety of internal (magmatic) and external (environment) conditions control phreatomagmatic eruptions, a great variety of macro to micro textures can be recognized through various scales. Many of the studied locations indicate that their volcanic eruptions started as fissure eruptions that then quickly focused into a few vents. The influence of the ground water table and the presence of any lacustrine system, as well as the magma source, the location of structures that allow magma to rise to the surface together inferred to be responsible for the diversity of volcanic eruption and edifice types recognized in the studied region. Especially during explosive volcanic eruptions that involve interaction with water the resulting volcanic facies architecture will be diverse reflecting the potential hazards such future eruption would pose. The understanding of the tectonic and hydrologic setting of the region using traditional geophysical and volcanology field surveys should play an essential role in volcanic monitoring particularly in remote small villages (e.g. Ollague, Talabre village) located nearby active stratovolcanoes presenting permanent fumarolic activity (e.g. Ollague, Lascar volcano). This seems especially important if such volcanoes are surrounded by water saturated high altitude sedimentary basins such as salars (e.g. Carcote Salar, Lejia Lake) where even small-volume of any type of magma rise could erupt in complex eruption styles as demonstrated in such settings in northern Chilean.

Eruption dynamics at Pahvant Butte volcano, western USA, Utah: insights from ash-sheet dispersal, grain size, and geochemical data

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Shallow to emergent subaqueous basaltic explosive eruptions, here referred as Surtseyan, are a source of pyroclastic material expelled from subaqueous vents and transferred to the water column and atmosphere. They can threaten coastal communities in different ways, and one of these is through the generation of pyroclastic density currents travelling over water once the eruption becomes subaerial; these may be preceded or accompanied by eruption-fed currents moving along the sea/lake floor. One approach for studying these eruptions is through analysis of their proximal deposits, but these are commonly either inaccessible (under water) or poorly preserved by the time they are exposed subaerially. The site selected for this work, Pahvant Butte, Utah, USA, avoids these limitations. The volcano was formed by an eruption at about ~18 ky B.P. in the giant Pleistocene Lake Bonneville, initiated at a relatively shallow water depth (85 m). The water is now drained and all the deposits (proximal and distal-lake) are easily accessible and maintain a good level of preservation. This allows us to investigate the eruption dynamics of Surtseyan volcanoes, through the interpretation of geochemical and grainsize data of both proximal and relatively distal deposits at Pahvant Butte. The results suggest that distal-lake deposited ash from Pahvant Butte travelled to at least ~25 km from the vent in eruption-fed pyroclastic density currents moving along the lake floor. This transport took place even early in the eruption, apparently prior to the volcano's subaerial emergence.

How Do Giant Flooded Caldera Volcanoes Erupt? Repeated Phreatomagmatic Ignimbrite Eruptions at Taal Caldera, Philippines

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When flooded caldera volcanoes erupt, hot magma interacts with water to produce some of the most violent types of volcanic eruptions known. Despite the large hazard posed by such eruptions, they remain poorly understood. Taal Caldera in the Philippines is only 60 km south of the densely populated capital Manila and is thought to have experienced at least 5 such violent flooded caldera eruptions1. This study aims to explore giant flooded caldera eruptions by better characterising and correlating Taal's prehistoric eruption history as well as possible given the limited exposure. Initial fieldwork suggests that eruptions were more numerous and complex than previously thought, with emplacement of thick ignimbrite sheets and phases of alternating Plinian fallout with dilute phreatomagmatic density currents. Changes in abundance of ash aggregates and soft-sediment deformation structures further suggests that the involvement of water varied during individual eruptions. Several recurrent facies seem to characterise the volcanic record: (1) dark, thick ignimbrites with abundant dark scoria 'spatter' clasts, light smaller pumices, variable lithic contents and rare accretionary lapilli; (2) accretionary lapilli-rich, lithic-poor, very fine grained, light coloured ignimbrites; (3) alternating Plinian fall and dilute phreatomagmatic density current deposits with abundant soft-sediment deformation; (4) fines-poor, almost clast-supported density current deposits with varying abundances of dark scoria 'spatter' clasts and glassy-porphyritic basaltic lithics; (5) thick ignimbrites with dark and light coloured pumices of varying abundance and size with lithic concentrations at the base. These deposits will provide the basis for more in-depth analysis using ash granulometry, shape parameters, textures and vesicularity to better constrain the physical processes involved in giant flooded caldera eruptions.

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The formation of Xidadianzi maar volcano in the Longgang Volcanic Field, Northeast China: insights from topography and stratigraphy

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Hydro-volcanism in the Longgang volcanic field (LVF) of Northeast China produced a dozen maars, tuff rings and tuff cones with features of multiple craters and complex sequences.
The Xidadianzi (XDDZ)maar volcano, consisting of the South Crater and North Crater, is not well preserved. The South Crater means the traditional XDDZ maar volcano. It was considered to be a volcanic Yansai lake (Hong et al., 2000).Liu et al.(2000) proposed that it was the biggest dry maar volcano in the LVF. However, the formation of South Crater is still not well known in this area because of its modification.
This study focuses on the XDDZ maar volcano, located in Jinchuan valley, in the western region of the LVF. Based on detailed stratigraphy analysis, 14C geochronology, grain-size distribution, components and scanning electron microscopy (SEM) analysis, the eruptive sequence of XDDZ volcano(which includes the South Crater and North Crater) was constructed. The whole sequence was formed in late Pleistocene after three eruptive phases including one a wet phreatomagmatic eruption, a magma eruption, and a dry and hot phreatomagmatic eruption. In this study, the NE- trending fissure was considered by the authors as to control the formation of XDDZ maar volcano. Topographic and stratigraphic characteristics show that landforms of two craters were damaged and swamped. The authors propose that the Holocene lava flow from Jinlongdingzi (JLDZ) volcano destroyed the south tephra ring of XDDZ.

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S01.20 - Investigating eruption triggers and dynamic processes in magmas

Complex micro-textural and rheological controls on vulcanian explosion timing and magnitude at Galeras volcano, Colombia

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Understanding the degassing and crystallisation processes that modulate the magnitude and timing of cyclical vulcanian explosions is important for managing protracted volcanic crises at arc volcanoes.

We present the results of textural measurements and high-temperature rheology tests on samples of andesitic ballistics from the 2004-2010 vulcanian explosions of Galeras volcano, Colombia. We find that crystal nucleation-dominated samples with high numbers of small, more equant plagioclase microlites that experienced high ascent rates generally have a lower bulk viscosity than samples with lower numbers of larger, more prismatic microlites that experienced crystal growth dominated crystallisation under lower ascent rates. Samples with higher bulk viscosities also deformed via higher proportions of micro-cracking at the same strain rate and displayed greater shear-thinning behaviour. Texturally- characterised, time-constrained ballistics from the same period that are expected to show higher bulk viscosities were produced by small volume explosions with long repose times associated with episodes of dome-building activity, and were preceded by higher SO_2 fluxes and higher numbers of VT (volcano-tectonic) events. In contrast, counter-intuitively, time- constrained samples expected to show lower bulk viscosities were produced by larger explosions and were preceded by smaller SO_2 fluxes and numbers of VT events.
We propose that efficient densification of low viscosity, nucleation-dominated magma plugs prevents SO_2 release and produces higher volume explosions. More sluggish densification associated with higher viscosity, crystal growth-dominated magma allows porous pathways to remain open, creates more extensive micro-cracking and allows larger SO_2 fluxes out of the conduit, leading to longer repose times, smaller volume explosions and episodes of dome-building. This new conceptual model for understanding vulcanian eruption dynamics has important implications for hazard assessment during periods of low and high magma ascent rates.

S01.20 Talk

Eruptive dynamics during low-magnitude event at Campi Flegrei (Italy): the AD 1538 Monte Nuovo eruption case study

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In the last decades the high-risk Campi Flegrei Caldera (CFC) was affected by several volcanic unrests contributing to increase the scientific interest on this volcanic area.

About 70 eruptions of different Volcanic Explosivity Index (VEI) occurred inside the caldera during the last 15 ka. Probabilistic approaches allowed to estimate a probability of occurrence particularly high (i.e. 60%) for low-magnitude events respect to both medium and large-magnitude or effusive eruptions. Therefore with the aim to predict a possible future eruptive scenario it becomes relevant to explore the eruptive dynamics of small-size eruptions as wells as their temporal evolution.

The AD 1538 Monte Nuovo eruption (VEI=2) was the last CFC eruption. During this event a small 130-m-high tuff cone was formed and a deposit with a volume of about 0.05 km^3 was emplaced. The eruption started with a violent quasi-sustained phreatomagmatic activity, subsequently attenuated and then vigorously resumed in two magmatic events of less intensity and magnitude.

In this study we have reconstructed the eruptive dynamics during the Monte Nuovo eruption, from magma ascent in the volcanic conduit to tephra dispersal, by using numerical models constrained with petrological, volcanological and historical data. Our results suggest that the eruption was fed by a chemically (trachy-phonolite, H_2O~5wt.%) and thermally (~900°C) homogeneous reservoir located at depth of 4 km (~100 MPa). During the first phase of the eruption the magma rose toward the surface with a Mass Discharge Rate of about 10^6 kg/s forming a plume few km (≤5 km) high that dispersed tephra fallout in NE direction, on a wide area today densely populated. The transition toward the second phase was caused by a decrease in conduit size and an increase in magma viscosity probably due to the emplacement of a slow rising plug, in agreement with 2D-3D textural evidences in the volcanic products.

S01.20 Poster

Rapid carbonate assimilation as eruption trigger: new insights from a Somma- Vesuvius (Italy) plinian eruption

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The feeding systems of numerous explosive volcanoes (e.g. Somma-Vesuvius, Colli Albani, Merapi, Popocatepetl) are developed within carbonate bedrocks. Geochemical and petrological evidence of magma–limestone interaction has been documented in their volcanic deposits. During this reaction large amounts of crustal CO_2 can be released with possible significant consequences for the eruption explosivity and in some cases potentially acting as an eruption trigger. Consequently carbonate assimilation can be particularly crucial when eruptable magma is involved or an eruption has already started.

Therefore it is critical to estimate the timescale by which this process can occur. Although several experimental studies have shown that the decarbonation of limestone can be very rapid (minutes to days), few studies have investigated its kinetic and thermodynamic aspects.

Here we have applied a dynamic computational model for magmatic contamination to predict the timescale of isenthalpic assimilation by determining the dissolution rate of limestone. Our case study is represented by the Pomici di Base plinian eruption, the oldest and largest explosive event of Somma-Vesuvius, for which late-stage limestone contamination was previously hypothesized.

Our simulation results, together with isotopic and 3D textural evidence, suggest that the hot (between 1000 and 1050 °C) mafic (latitic-shoshonitic) portion (75 vol.%) of magma experienced fast limestone assimilation with a dissolution rate as high as ~1x10^-4 cm/s through its ascent towards the surface (at this rate a 1 cm diameter calcite sphere would totally dissolve in 5-10 minutes). The resultant rapid CO_2 liberation promoted vesiculation pulses that amplified the eruption intensity (MDR = 2-2.5E7 kg/s; column height = 16-17 km) despite the magma's low viscosity (~2 Pa s).
We conclude that late carbonate assimilation can strongly affect eruption explosivity on a short timescale with potential implications for geochemical monitoring signals.

S01.20 Poster

The pre-eruptive conditions and onset of 1902 Santa Maria eruption, Guatemala

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Volcan de Santa Maria is located in SW Guatemala (N 14°44'30'', W 91°34'00'') and is the part of Central American Volcanic Arc which was formed as a result of subduction of the Cocos plate underneath the Caribbean (Rose et al., 1977; Singer et al., 2013). Santa Maria lies in the close vicinity of 2nd largest urban centre of Guatemala – Quetzaltenango, with ~1,256,600 people living within the 30km from the volcano and ~6,197,420 within 100km radius (GVP, 2013).

The 1902 Santa Maria eruption started at 24.10.1902 and was the 2nd largest eruption in 21st century. The eruptive column reached at least 28km in height during the 18-20h long plinian phase (Williams & Self, 1983). The airfall deposit covered ~1.2 million km^2 with ~90% of material being less than 2mm (Williams & Self, 1983). The true volume of erupted material was estimated to be at least $20km^2$ (Williams & Self, 1983). Eruption ceased at the beginning of 1903 and new activity started at 1922 when an endogenous volcanic dome of Santiaquito begun to grow in the explosion crater.

The research introduces the Fourier Transformed Infrared Spectroscopy (FTIR) analysis of melt inclusions in order to determine the volatile content of magma. Basing on the ratios between CO_2 and H_2O wt% the thermodynamic framework for the pre-eruptive magma chamber will be constructed. That will lead to the estimation whether or not melt was vapour saturated prior to eruption and if retrograde boiling have occurred. This process might have been the direct trigger of the 1902 VEI6 eruption. Furthermore, the analysis will be followed by evaluation of elements partitioning between melt and the vapour phase. The evaluation of pre-eruptive conditions will improve our understanding of current eruptive activity of Santiaquito together with processes and conditions leading to large-magnitude volcanic eruptions in Latin America.

S01.20 Talk

The 1906 Vesuvius eruption: highlight on eruptive mechanisms through ashes analyses and historical evidence

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The eruption began on the 4th of April with the opening of numerous vents at the base of the Gran Cono and the flowing of conspicuous lava flows towards the south side of the volcano. This phase was followed by explosive activity (from the 8th of April) with the development of a volcanic cloud and the fall of pumice and ash on a wide territory extending eastward.

Raffaele Vittorio Matteucci (1862-1909) and Giuseppe Mercalli (1850-1914), both Director at Observatory between 1903-1909 and 1911-1914 respectively, followed the eruption and collected ash samples.

In particular, Matteucci collected systematically ash during the various eruptive stages and described step-by-step volcanic activity in daily bulletins that he sent to the authorities for risk assessment and defense of people living around volcano.

In this study the mentioned ash samples are analyzed for the first time in order to explore eruptive dynamics. Such ash samples belong to the Vesuvius Observatory Museum, where there is a rich collection of volcanic ash emitted by the Vesuvius volcano during the period of open-conduit activity that has preceded the last 1944 eruption.

Textural and geochemical analyses are in progress on the volcanic ash erupted during the whole 1906 eruption. In addition computed microtomography X-ray analysis, that offers the opportunity to visualize and quantify the internal structure of rock samples, was conducted and three-dimensional digital maps with a very high resolution of up to submicron was obtained. Preliminary results are compared with the witnesses' description of the volcanic activity at the moment of ash sampling, to identify correlation between geochemical and textural features and eruptive dynamics. Our aim is to contribute evaluating the trigger mechanisms and spatial-temporal development of this kind of eruption also comparing the results of these analyses with those previously obtained for the 1944 eruption of similar VEI.

S01.20 Poster

Analysis of petrographic patterns of Vesuvius and Campi Flegrei rocks through unsupervised neural networks

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We propose a novel approach to study and compare the possible relationships between the volcanic products of two areas: Mt. Vesuvius and Campi Flegrei. We use the Self-Organizing Map (SOM) neural network to perform a cluster analysis of the petrographic patterns of rocks from these two volcanic complexes. We have prepared a dataset including 271 petrographic analyses of products erupted by Mt. Vesuvius, Campi Flegrei and others volcanoes. Each sample is encoded by a vector of 17 features, namely major bulk components (10 features), trace elements (6 features) and Sr isotopic ratios (1 feature). The dataset is composed by four groups: Campi Flegrei products (CF) with 134 samples, Somma Vesuvio effusive eruption rocks (VF) with 24 samples, Somma Vesuvio explosive eruption products (VX) with 73 samples and a class of foreign samples (ET) with 40 samples from other Italian volcanoes, added to test the results. We chose a SOM map dimension of the 3x5 = 15 nodes and we parameterized each sample through the whole vector of 17 features. Our analysis highlighted three main clusters. The first groups the evolved products of Vesuvius and Campi Flegrei. The second primarily includes the poorly evolved products of Vesuvius and Campi Flegrei. The third cluster collects only products of the ET class. This result is consistent with a possible genetic relationship between the magmas of Mt. Vesuvius and the Campi Flegrei volcanoes that fall into the same clusters, while the foreign samples (ET) are separated in a different cluster. We have also carried out several experiments by varying the feature vectors in input to the SOM in order to investigate its sensitivity to different input parameters, i.e. major bulk components, trace elements and Sr isotopic ratios.

Pre-eruptive conditions at the Colli Albani Volcano: experimental constraints from phase equilibria studies on a leucititic magma

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The Colli Albani volcanic district is a quiescent volcano near Rome belonging to the ultrapotassic Roman Province. This volcano was characterized by high volume explosive volcanic events induced by the interaction of low SiO_2 ultrapotassic magma with carbonate rocks, representing an anomalous high explosive behaviour of SiO_2-poor magmas on planetary scale. Highly explosive eruptions are driven by the exsolution of volatile components to a separate fluid phase. The presence of crystals facilitates the nucleation of H_2O bubbles in the magmas because of a reduction of the surface tension at the bubble crystal interface. This work is focused on the determination of mineral stability fields in ultrapotassic, SiO_2-poor, H_2O- to CO_2-dominated magmas and is intended to gain knowledge needed to study the bubble nucleation in the CO_2-dominated volcanic systems.
Crystallization experiments were performed on a synthetic leucititic melt from the Colli Albani volcano at 100, 200 and 300 MPa at temperatures from 1000 to 1200°C with run durations up to 15 days. Capsules were prepared with an initial mole fraction of water of 0, 0.25, 0.50, 0.75 and 1 and run in Internally Heated Pressure Vessel at intrinsic redox conditions ($logf_{O2}$ = NNO+3). Run products were analysed by electron microprobe and spectroscopic techniques.

First results show that the liquidus for the investigated system lays between 1150 and 1200°C. In the H_2O-dominated systems, magnetite is the first crystallizing phase followed by clinopyroxene. The third crystallizing phase is phlogopite at 1000°C with a crystallization degree above 70%. In the CO_2-dominated systems (CO_2 > 70%) the first crystallizing phases are leucite and clinopyroxene. An immiscibility field leading to the formation of two silicate magmas is present at 1050-1100°C and at pressure below 300 MPa in H_2O-dominated systems.

The most common natural phenocrystal assemblage (leucite, clinopyroxene and oxides) suggests a strong precence of CO_2 in the fluid phase.

S01.20 Poster

Phase equilibria experiments on a trachyte and a trachybasalt from the Campi Phlegrei Volcanic District (Italy)

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Phase equilibria experiments were conducted on H_2O-CO_2 saturated trachytic and trachybasaltic melts from the Campi Phlegrei Volcanic District (CPVD) (Italy), representing respectively the most and the least evolved compositions of the CPVD.

Phase equilibria experiments were performed at 100, 200 and 300 MPa and at temperature between 850°C and 1050°C for trachyte and from 950°C to 1150°C for trachybasalt in the Cold Seal Pressure Vessel (CSPV) and in the IHPV under relatively oxidizing conditions (log fO_2=QFM+3.3 for IHPV; log fO_2=QFM+1 for CSPV). Run products were analyzed by electron microprobe, spectroscopic techniques and Karl-Fischer titration.

For comparison natural samples from the juvenile parts of the Solchiaro and the Campanian Ignimbrite deposits were collected around the city of Naples and on the island of Procida. The collected products were analysed with the same techniques used for the experimental ones.

A close comparison between the experimental phase assemblages and their compositions, and the phenocryst assemblages of the natural samples were found in H_2O-CO_2 saturated liquids (50%H_2O; 50%CO_2), suggesting that besides H_2O also the CO_2 was present in the fluid phase.

Experiments on the trachyte show that the most common natural phenocrysts assemblage (with phenocrysts of magnetite, clinopyroxene, feldspar, biotite and apatite) could have been formed prior to the Campanian Ignimbrite eruption at temperature between 850°C and 1000°C and equilibrated at a minimum pressure of 100-200 MPa, in liquidus with a wide range of H_2O content (appr. 2.5 - 5.5wt%).
Harker diagrams of experimental and natural samples were used to reconstruct the evolution of the CPVD melt. It is suggested that the crystal fractionation via differentiation plays a major role during the evolution of the magma prior to the Campanian Ignimbrite eruption.

The impact of large earthquakes on volcanoes

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The existence of a causal relationship between the occurrence of a large earthquake and volcanic eruptions nearby has been evidenced based on statistical data analysis. However, such a relationship is still debated, and its mechanisms are not yet fully understood. We have numerically simulated the dynamics of a magmatic system in the presence or absence of an impacting seismic wave (M7.5, with seismic waveform taken from a real case). Our 2D, transient numerical simulations account for geometrically complex magmatic system hosting compositionally different magmas with locally (time-space) defined phase distribution and properties, and most importantly for this study, for domain boundary deformation to account for seismic wave – magmatic system coupling. The numerical results show that while the internal magma dynamics are poorly affected by the passage of the seismic wave, ground shaking produces important effects on pressure evolution: i) transient pressure oscillations during and beyond seismic wave passage can be of order MPa, being larger when magma viscosity is lower; ii) after seismic wave passage a permanent overpressure of order bar remains in the magmatic system, never recovered up to the largest simulated times. Overall, the results suggest that a strong earthquake can trigger a volcanic eruption in cases which were prone to it, working therefore as a clock advance mechanism, and providing the physical framework to interpret the statistical relationships highlighted by previous authors.

Vulcanian explosion triggers at Tungurahua volcano, Ecuador: The July 14th 2013 eruption

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Tungurahua volcano has been erupting semi-periodically since 1999 and on July 14th 2013, a large vulcanian explosion occurred with almost no warning. Ballistics were ejected out to 5 km from the summit and huge infrasound signals (>5000 Pa) accompanied the explosion, testament to the immense force released during this event. Two weeks before, seismic events and their energy levels started to increased and deformation trends became more positive, indicating that a new batch of magma had possibly begun to ascend. The sudden onset of the explosion was likely triggered by the accumulation of large gas overpressures that overcame the yield strength of the magmatic plug. Experimental analysis of plug rocks ejected during vulcanian explosions provide insight into how large volumes of gas were able to accumulate and, the amount of overpressure required to rupture the magmatic plug.

Permeability tests under elevated confining pressure conditions and indirect tensile strength tests were performed on samples of plug rock from two ballistics that were expelled during the initial explosion. Both blocks are highly crystalline andesite and have connected porosities of 2-3%, dominated by micro-fractures. Permeabilities were found to be extremely low at between 10^{-17} and 10^{-18} m^2 at 5 MPa effective pressure and one of the samples became effectively impermeable above 30 MPa effective pressure. Indirect tensile strength tests revealed tensile strengths of between 9 and 12 MPa. Low permeabilities and high tensile strengths allowed for the large accumulation of gas overpressures and help to explain the high eruption energies and the release of 7000 T/day of SO_2. The input of more gas from the renewed ascent of new magma most likely contributed more pressure into an already over-pressurized conduit, thereby accelerating the sudden onset of this explosion shortly after both deformation and seismic trends had indicated a new influx of magma.

S01.20 Poster

Parametric dependence of gas flow instability onset in lava domes

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The collapse or explosive breakup of growing and degassing lava domes presents a significant hazard due to the generation of dense, mobile pyroclastic flows, as well as the wide dispersal of dense ballistic blocks. Lava dome stability is governed by the balance of transport and storage of gas within the pore space. The short-timescale flow of gas and lava in a dome is described by a set of nonlinear partial differential equations. These governing equations are shown to produce flow instabilities causing the growth of pressure perturbations that could cause the dome lava to fragment across a wide range of model parameter values. Explosive fragmentation occurs because of the significant gradients in the background pressure and porosity fields that result from steady-state conditions. However, the flow instability does not occur for sufficiently thin, permeable and viscous domes, where these gradients are less significant. For a given intrinsic permeability and viscosity, there is a critical dome height at which pressure wave growth and fluid instability will initiate. Assumptions of non-Newtonian lava rheologies modify this parameterization; however, the overall effect of fluid instability onset is shown to be independent of the choice of lava rheology.

The present analysis helps explain some features of the sudden onset of explosions in small lava domes, as well as the relative rarity of lava dome survival to large size that has been found to characterize repeated explosions at otherwise effusive lava domes. The growth of internal pressure fluctuations leads to significant periodic reductions in the stress required to fragment lava and induce sudden dome explosions. As a result, the onset of fluid instability explains how small lava domes evolve to a state of criticality before explosion or collapse.

S01.20 Talk

Behaviour of clinopyroxene phenocrysts during transport and storage of basaltic magmas: experimental study and implications for clinopyroxene barometry

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Understanding the structure of magma plumbing systems beneath volcanoes is difficult because the different approaches used to estimate depths frequently give contradictory results. In the Holuhraun 2014-15 eruption, for instance, geophysical techniques yielded shallower magma depths than clinopyroxene-liquid barometry. Part of the discrepancy may be due to the kinetics of equilibration of clinopyroxene (Cpx) with liquid during magma transport and storage. In the Holuhraun eruption, olivine tholeiite is supposed to have risen from approximately 10 km depth beneath the Bárðarbunga central volcano, before two weeks of shallow lateral transport to the eruption site. Has the Cpx composition been reset during the shallow transport or not? To answer this question, an experimental study was carried out using Holuhraun basalt as starting material. The basalt powder was first equilibrated at 1 GPa-1240°C, then decompressed to 0.5 GPa-1235°C (adiabatic case) or 0.5 GPa-1190°C (decompression and cooling), and finally maintained at these conditions from 0 to 4 days. These experiments are aimed at simulating the evolution of a Cpx-bearing magma being transported from a deep chamber to a shallower one, into which it resides for some time before being erupted and quenched.

Major textural and chemical changes occurred due to decompression. Clinopyroxene was totally dissolved at 0.5 GPa-1235°C (in less than 30 minutes), but only partially dissolved at 0.5 GPa-1190°C allowing us to follow the chemical evolution of liquid and Cpx with time. The pressures calculated with the Cpx-liquid barometer (Putirka, 2008, *Rev. Mineral. Geochem.*, 69 [1], 61-120) are close to the experimental pressures for long-duration experiments (3-4 days), while those calculated for run durations ≤ 24 hours may be highly overestimated. Our study shows that very fast magma transport to the surface is required to prevent significant chemical exchanges between crystals and liquid and to obtain reliable pressure estimates from Cpx-liquid barometry.

S01.20 Talk

Conduit gravity-inertia oscillation, a mechanism for very long period (VLP) seismicity at Kilauea volcano

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Very long period (VLP) seismicity at Kilauea volcano, Hawaii, is thought to arise from the resonance of waves in the magma plumbing system (conduits connecting the summit lava lake to cracks). VLP centroids are 1 km beneath the edge of Halemaumau crater (Chouet and Dawson, 2010), near or possibly the same as the shallow reservoir inferred by Anderson et al., (2015) from longer timescale deflation-inflation signals. Here we idealize the system as an axisymmetric conduit coupled to a tabular crack, accounting for fluid inertia, viscosity, gravity, and crack wall elasticity. The eigenmodes feature various restoring forces (fluid compressibility, gravity, and elasticity) driving oscillations in different limits. At lower frequencies, inertia balances gravity and/or crack wall elasticity. For the very long period and large crack size (2.6 km, Chouet and Dawson, 2011) inferred for Kilauea VLP events, gravity dominates the restoring force. The VLP period is sensitive to conduit length and the density contrast across the conduit. Assuming the conduit length is relatively stable, temporal changes in VLP period (15 - 40 s) over the past decade might indicate changes in density contrast from changes in gas volume fraction. The model predicts a gradual decrease in period as the lake level drops with a drastic decrease if the lake level drops into the conduit. The VLP quality factor Q is sensitive to magma viscosity and conduit radius. the observation of Q constrains dynamic viscosity. Assuming density, radius, and observed periods 15 – 40 s, Q=15 suggests a viscosity of 10 to 20 Pa s and Q=10 suggests 18 to 40 Pa s. The model also predicts shorter period modes associated with resonant crack waves, with negligible involvement of the conduit; these are possibly also evident in the seismic data.

Sill intrusion and magma eruptibility at calderas

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To understand caldera unrest, and if this may culminate into an eruption, it is crucial to analyse the eruptibility potential of the magma intruded responsible for unrest. We investigate the conditions for the eruptibility of magma intruded at shallow depth below calderas, focusing on the thermal and chemical evolution of sills. Basically, eruptibility depends on melt viscosity, crystal fraction and gas content. Therefore, we model the temporal evolution of these parameters during the intrusion and subsequent magma cooling. We assume conductive heat transfer between magma and rock and we adopt the alphaMelts code for the simulation of the thermodynamic evolution of the melt. We also consider and model the spatial distribution of the stress induced in the host-rock by the sill as an additional factor that can promote an eruption. We simulate the intrusion of a sill in two different types of calderas, namely a mafic type, with low magma viscosity and high rock Young's modulus and a felsic type, with high magma viscosity and low rock Young's modulus. Finally, we compare our results with the outcomes of a statistical analysis on a dataset of unrest at calderas. In particular, we compare the simulated evolution of the unrest in terms of eruptibility and induced stress with the distribution of the duration at real unrest episodes at calderas, distinguishing between their eruptive or non-eruptive culmination. Results highlight the importance of the stresses induced on the host-rock by the sill to determine its eruptibility.

Pre-eruptive magmatic processes associated with the 2016-2018 explosive activity of Sabancaya volcano (Perù)

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Sabancaya volcano is one of the most active Central Andes Volcanoes. Historical records reveal an eruptive activity in 1750-1784 AD and more recently in 1990-1998 AD. The most recent eruptive activity of Sabancaya started in November 2013 and is still ongoing (May 2018). This new period of activity has been divided into two stages: the first stage started in 2013 with increased fumarolic activity, and the second stage began on November 6th 2016, characterized by violent explosions of ash and juvenile lava blocks, and generated ash plumes rising up to 5-6 km. The erupted juvenile ballistic material consists of andesites (59.8-60.2 wt.% SiO_2), including plagioclase, hornblende, orthopyroxene, clinopyroxene, biotite, and Fe-Ti oxides. Detailed mineralogical studies show two different groups of plagioclase: subhedral phenocrysts with normal zoning (An_{37-30}); and subhedral phenocrysts with a sieve texture and overgrowth rims, showing oscillatory ($An_{29-60-49}$) and reverse (An_{54-57}) zoning patterns. We have also identified two different populations of amphibole: the first population corresponds to subhedral phenocrysts with low Al compositions (6-8 wt.% Al_2O_3) and the second population is composed of phenocrysts and microlites with rims of high Al concentrations (9-11 wt.% Al_2O_3), displaying increasing amounts of Mg# (72-74) toward their rims. We also observe a few orthopyroxene (En_{72} Fs_{24} Wo_4) cores surrounded by clinopyroxene (En_{42} Fs_{16} Wo_{42}) rims and rare anhedral quartz crystals. Based on thermo- barometric analyses, using the geothermometer of Ridolfi et al. (2010), the temperature is estimated at 915 ± 60 °C and the crystallization pressure at 265 ± 19 MPa, corresponding to a depth range between 9 and 11 km, where the magma reservoir would be located. These disequilibrium textures identified in the phenocrysts could suggest a mixing process due to the intrusion of a hotter magma in the reservoir, which was also suggested for the last eruption (Gerbe and Thouret, 2004).

Dynamics of volcanic ash generation within the conduit: Effects of componentry, particles size and conduit geometry

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Secondary processes of fragmentation within the conduit can alter significantly the grain size distributions (GSDs) resulting from the primary fragmentation of magma to tephra. The interaction of these processes stands until the material is expelled from the conduit to the surface. In particular, the continuous interactions between tephra particles, together with the conduit geometry, play a crucial role in these secondary processes, potentially increasing ash production. In our experiments, we used loose material collected from the fall deposit of Pomici Principali eruption (10.3 ka, Campi Flegrei) that was separated into two main groups: 1) pumices, and 2) dense clasts. Samples were slowly pressurized up to 10MPa using argon gas and then rapidly decompressed to ambient pressure. We reported the resulting GSDs and evaluated the influence of componentry and particle size of the initial sample together with conduit geometry, on size-reduction processes (i.e. gas-driven fragmentation, disruption, abrasion). Our results suggest that factors such as a reduction on the conduit diameter, larger particles and a greater amount of dense material in the initial sample enhanced the efficiency of size-reduction processes, resulting in a more efficient ash production; however the presence of crystal-rich pumice appears to have a counterproductive effect. Finally, these findings correlate well with previous studies, and they have also implications for ash dispersion models.

S01.20 Poster

X-ray microtomographic investigation to explore magma mixing as eruption trigger: the 4.1 B.P. Agnano Monte Spina (Campi Flegrei, Italy) plinian eruption case study

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Magma mixing is considered one of the main processes in triggering highly explosive volcanic eruptions. In fact, the input of fresh, higher-temperature magma intruding into a magma chamber may drive volatile transfer from one magma to another and volatile exsolution, increasing the volumetric stress in the chamber and destabilizing the magmatic system. In this way, the volume increase may accelerate magma ascent and the vesiculation upon decompression reaches, consequently, a point of no return and an eruption becomes unavoidable.

The X-ray computed microtomography (microCT) technique is a powerful tool to provide three-dimensional information on rock samples and to evaluate the textural disequilibrium due to mixing processes. Such studies can play a fundamental role in contributing to volcanic hazard assessment, particularly in densely inhabited areas. .

The 4.1 ka B.P. Agnano–Monte Spina (AMS) eruption, considered as reference event for a future large-size plinian explosive eruption at Campi Flegrei (South Italy), is mentioned in previous studies as result of a magma mixing process. Petrological data, trace elements and isotopic composition suggest that at least two magmas have interacted during the eruption.

In order to infer this hypothesis, we are analyzing the AMS products via micro-CT images. X-ray microtomographic analysis provide quantitative 3D textural features, involving vesicle and crystal distributions, filament morphology and further textural characteristics otherwise obscured in conventional 2D observations and analyses. Vesicles in volcanic rocks are
frozen records of degassing processes in magmas. For this reason, their sizes, spatial arrangements, numbers and shapes can be linked to physical processes that drive magma ascent and eruption.

These studies will shed new light on the complex interplay of processes determining bubble formation during magma mixing, ascent and eruption.

S01.20 Poster

Cryptic magma recharge controlling the intensity of basaltic eruptions during the twentieth century at Villarrica Volcano

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The Villarrica Stratovolcano is one of the most active volcanoes of the Andes (rest cycles of ~5.3 years) by erupting products of basaltic to basaltic-andesite compositions and styles from Hawaiian to Vigorous Strombolian. These features make it a remarkable place to determine the pre-eruptive parameters and processes that control the eruption dynamics in a basaltic system. We compare whole-rock geochemistry and mineral abundances, textures and compositions of the most relevant basaltic lavas of the twentieth century, which were erupted in 1921, 1948 and 1971. Using whole-rock MgO we define a primitivity trend that is positively correlated to the intensity of eruptions, in increasing order: 1921, 1971 and 1948. Two groups of plagioclase compositions are observed in all lavas: An-poor (~An60) and An- rich (~An80). An-poor compositions are the most abundant in all lavas, but the An-rich/An- poor frequency ratio varies in the same order as the primitivity trend. Both the Fo content and the chromian-spinel inclusions abundances in olivines are also positively correlated to the primitivity trend. Thermometry calculations and MELTS modelling suggest that basaltic magmas were affected by heatings of ~100 °C (from ~1090° to ~1190 °C) at ~0.5 kbar in all studied lavas . Incorporation of few volatiles and slight changes in bulk composition of magma occurred with the heating events. This could have been caused by the magmatic recharge of the Villarrica's reservoir by hotter, water-richer and slightly more primitive magmas. A longer interaction may cause a higher volatile influx from the new magma to the reservoir resulting in: 1. More primitive features; 2. Higher An-rich/An-poor abundance ratios; and 3. Higher intensity of the resulting eruption.

Experimental determinations of H_2O and CO_2 solubilities in ultrapotassic melts

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Dissolved H_2O and CO_2 in silicate magmas affect the density, viscosity and the phase equilibria of these systems influencing their evolutionary history and their eruptive behaviour. Solubility data are still missing for ultrapotassic compositions, characteristic products of some of the most dangerous active volcanic areas in the world: e.g. Mt Somma- Vesuvius and the Colli Albani volcanic district.

In this study, experiments were conducted to determine H_2O and CO_2 solubilities on end- member compositions of the Italian ultrapotassic suite: a phonolitic melt from the 79 a.D. eruption of the Vesuvius and a leucititic melt from the Pozzolane Rosse eruption of the Colli Albani Volcanoes. Synthetic analogues of the natural melts were prepared and inserted in AuPd capsules with distilled water and $Ag_2C_2O_4$ as sources for H_2O and CO_2, respectively.
Experiments were performed in an internally heated pressure vessel at 1250°C, intrinsic redox conditions ($logf_{O2}$= NNO+3) and pressures of 100-300MPa in order to bring H_2O and CO_2 in the melts in equilibrium with H_2O-$CO2_2$ fluids with varying mole fraction of water (X_{H2O}) of 0, 0.2, 0.4, 0.6, 0.8 and 1.
The composition of the fluid-phase was determined by a weight-loss method. The volatile content in the quenched glasses was obtained by FTIR spectroscopy. An accurate calibration of the absorption coefficients of the water-related and carbon-related IR bands was performed. Bulk volatile contents in pure H_2O and CO_2 samples were analysed by Thermogravimetry and Carbon-Sulfur Analyser.

First results show that the solubility of water is similar in both leucititic and phonolitic melts, increasing with pressure from 3.74 wt% and 3.62 wt% at 100 MPa to 7.29 wt% and 7.37 wt% at 300 MPa, respectively. However, a significant difference in CO_2 solubility was found between the leucititic and phonolitic melts, increasing with pressure from 2949 ppm(wt%) and 577 ppm(wt%) at 100 MPa to 8458 ppm(wt%) and 1795 ppm(wt%) respectively.

New constraints on vesiculation kinetics in rhyolitic magma degassing from 4D synchrotron microtomography and novel particle-tracking during controlled heating: Implications for eruptive style and intensity

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Volcanic eruptions' styles and intensities are largely controlled by magma's rheological and chemical properties at storage and during ascent to surface. These properties are affected by changes in temperature, pressure, and volatile content. Understanding the impact of these changes on magma degassing's kinetics constitutes a cornerstone towards comprehending how volcanoes erupt. Here, we reveal new constraints on rhyolitic (74-75 wt.%) magma degassing from time-resolved synchrotron x-ray microtomography (beamline I12, Diamond Light Source-UK) of vesiculation in water-bearing (±0.17 wt.%) melts under interrupted isothermal conditions (900-1250°C at 50°C and 100°C intervals), and during constant heating (850-1250°C) at 0.4 or 0.1°C.s^{-1}. We performed 4D (3D+time) particle- tracking analysis to measure individual bubble nucleation and growth, and estimated different textural parameters (e.g., bubble-number-density [BND]). Our results indicate that: bubble nucleation during isothermal conditions at 900°C takes 8-minutes to initiate and thereby continue. Inversely, bubble nucleation during constant heating at 0.4°C.s^{-1}occurs interruptedly, and requires only 3-minutes to start but at 930°C. In any case, bubbles were reabsorbed soon after nucleating; however, sustained bubble growth can be achieved by increasing the heating rate, melting higher crystalline/vesicular glass, or reducing the volume of glass analysed. Limited bubble growth was recorded while heating up to 1060°C at 0.1°C.s^{-1}, 35-minutes after nucleation started isothermally. Isothermally produced nucleation, and subsequent limited bubble growth during constant heating favoured the development of Plinian-type porosities (±70 vol.%) and BNDs (10^{7} cm^{-3}) at 1190-1200°C. Bubble coalescence was produced by heating to 1250°C and cooling to 1150°C immediately, reducing BND to low-explosive eruption's values. Likewise, BNDs of 10^{3}-10^{4} cm^{-3} and porosities of 20-45 vol.% resulted from different experiments that produced sustained bubble growth, indicating that diverse conditions can trigger low-explosive and/or effusive eruptions. Our results highlight the effects on magma degassing from slight changes in heating profiles, and their implications on eruptive styles and intensities.

Experimental Vesiculation and Outgassing of Crystal-Bearing Dacite

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Crystal-rich dacitic magmas may erupt effusively to form lava domes, or explosively. An eruption may switch from one style to the other, and may alternate between styles (e.g. Santiaguito, Guatemala). Volatiles play several roles in these magmas; when dissolved in the melt, they lower its viscosity. When volatiles exsolve to form bubbles (degassing), they can drive brittle failure and fragmentation. When pores connect, and volatiles can escape from the magma completely (outgassing), the explosive potential is reduced despite the high viscosity of degassed magma. We seek a better understanding of how gas exsolution and crystallinity control effusive versus explosive eruptive behavior. We previously investigated the degassing behavior of synthesized, crystal-rich (50 to 80 vol.% quartz crystals), hydrous (4.2 wt.% H_2O in the glass) dacite samples, that were heated in a parallel plate viscometer and subjected to heating and cooling cycles between the matrix glass transition (~483˚C) and ~800˚C (Pistone et al. 2017 JVGR 347:1-14). Here, we present new data on a similar suite of samples where individual cores were held at a single temperature until degassing- related expansion was complete. We heated cores (~5mm diameter, ~10mm length) at 1 atm and measured their length change on heating to 750˚C. Once above the glass transition, bubble nucleation and growth lead to rapid expansion, which halt equally rapidly after a few minutes. Crystal-free samples grew ~34%, while F50 grew ~19%, F60 grew ~15%, F70 grew 5% and F80 grew ~3%. Since quartz crystals are inert during the experiment, this means that the liquid portion of the sample reached 36±2% vesicularity for 0, 50 and 60% crystals, but at higher crystal fractions the samples began outgassing at lower vesicularity, reducing the explosive hazard. We are using X-ray microtomography to investigate whether this is achieved by cracking and/or by constraining vesicle shapes to high elongations.

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S01.21 - State of the Volcanic Hazard Map

Combining methodologies to develop the Carran-Los Venados Volcanic Hazard Map (VHM)

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The Carrán-Los Venados volcanic field (Los Rios Region, Chile) hosts at least 70 small eruptive centres (Late Pleistocene-Present). It is characterized by Strombolian and Phreatomagmatic eruptions that led mainly to scoria cones and maars with a NE-SW trend, covering an area of *ca*.160km^2. In the last century three eruptions took place in 1907, 1955 and 1979, being reawakening of older vents.

A new semi-qualitative VHM of the Carrán-Los Venados volcanic field has been published combining probabilistic and geologic field-data methodologies. To build it we considered the last 16ky where volcanic products are represented by short to large extension lava flows, ashfall, PDCs, and secondary lahars. Firstly, the most likely areas to host new eruptions were determined through a spatial probabilistic analysis using volcano-structural information. Secondly, dimensions and range of previous deposits were used to define the probable areas that could be affected by new processes, which were redefined through simulation models, and adjusted to geomorphology. The hazard maps obtained for lava flows, PDCs and lahars, were all integrated in a map considering their recurrence and magnitude, whereas those for ashfall and ballistics were considered and represented independently. This VHM integrates: (1) a local scale map (1:50,000) of the proximal volcanic hazards: lava flows, PDCs, ballistics, lahars and maximum ashfall thicknesses; and (2) a regional scale map (1:1,000,000) that shows ashfall dispersion. Hazard delineation arises in three hazard zones (high, moderate and low), characterized by different magnitude degrees.
Results show that this monogenetic field is susceptible to start a new eruptive cycle in years or decades. Future activity can severely affect closer areas, such as Nilahue and Riñinahue river valleys, Los Venados River and Muchi, Chipanco and Quirrasco estuaries. Farther regions can also be affected by ashfall during explosive eruptions. This map represents an essential tool for future volcanic crises management.

State of the Volcanic Hazard Map: Development of an open-access source- book for volcanic hazard maps. A presentation on behalf of the IAVCEI Hazard Mapping Working Group

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The Hazard Mapping Working Group of the IAVCEI Commission of Volcanic Hazard and Risk has been facilitating a number of activities to enable sharing of volcanic hazard map experiences, including discussion of hazard map development methods and their uses. An aim was to undertake a comprehensive review of current practices with a view toward defining good practices through the development of an open-access Source-book for the development of Volcanic Hazard Maps that summarizes various approaches, methods and lessons learned. The main objective of this effort is to facilitate production of maps that are effective at conveying key information and that support decision-making (from authorities through to general public as appropriate).

The workshop outcomes demonstrate that global practices used for hazard mapping are diverse and need to be volcano specific. For individuals or groups tasked with development of new volcanic hazards maps, there is little clarity or documented consensus on good practice for map development methods, map type and content, or format of display. The concept of drafting an IAVCEI source-book therefore, came about as a direct result of an identified need, especially from the new generation of practitioners working in hazard mapping.

This presentation will provide an explanation of the development of the source-book, the workshops and participants, the themes covered and the summarised outcomes of each workshop. Important outcomes have then been carried forward to construct the source-book document. A first full and illustrated draft version of the document will be made available to the IAVCEI community in August 2017. We solicit feedback from the community and stress that the aim of this work is to develop a document that reflects broad community experience and a consensus of good practice.

S01.21 Talk

Interactive web mapping and hazard communication at Campi Flegrei caldera

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Volcanic hazard maps are traditionally static in nature and do not allow user interaction or input. Maps for other hazards, such as floods and severe weather, are increasingly being presented online in an interactive and dynamic format. Once the relevant data are obtained, these web maps are easy to create, update, and allow for the clear presentation of more than one hazard. Remarkably, very few studies have investigated the usefulness of using such web-based maps for hazard communication at volcanoes.

To demonstrate the benefits of interactive mapping as a tool for communicating hazard, a new series of user centred web maps has been designed for the restless Campi Flegrei caldera in southern Italy. The preferences of 250 survey respondents and a review of twenty interactive maps from a wide variety of disciplines helped tailor maps to the needs of three user groups: local residents, decision-makers and businesses. The maps produced show unrest and eruption scenarios, as well as crisis and background hazard data.

The results highlight three key advantages of interactive maps over their static equivalents. First, they allow users to select the information most important to them. Second, they promote the collaboration of end-users in designing how information is presented. Third, they are easy to modify as new information becomes available. Such flexibility is particularly important during emergencies for conveying information on changes in evacuation procedures and levels of hazard as circumstances evolve.

S01.21 Talk

Assessing lava flow inundation and tephra fall hazards for northernmost Harrat Rahat, Kingdom of Saudi Arabia

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Harrat Rahat is a volcanic field in western Saudi Arabia extending 310 km in length and erupting basalt to trachyte. The youngest activity is concentrated in the northernmost part of the field, where new geologic mapping and geochronology reveal >300 vents with ages ranging from ~1.2 Ma to a historic eruption in 1256 CE. We calculate probabilities of future lava flow inundation and tephra fall in Harrat Rahat by combining eruptive history data with estimates of lava flow and tephra parameters, numerical lava flow and tephra dispersal models, meteorological records, and present-day topography. Vent locations, timing, and composition are integrated to produce spatiotemporal models of vent opening probability. We simulate lava and tephra eruptions using a Monte Carlo approach with parameters sampled from the eruptive history and modeled with numerical codes. Lava flow inundation is simulated over high-resolution topography using the DOWNFLOW model with flow field dimensions representing the distribution of Harrat Rahat lavas. Tephra dispersal modeling is done using Ash3d, simulating tephra fall deposits from eruptions sampling decades of wind data and the distribution of eruption parameters recorded in Harrat Rahat deposits or in analogue eruptions. These simulations are integrated with the vent opening probability to produce conditional probability maps of lava inundation and likelihood of tephra deposits exceeding a range of threshold thicknesses. Combined with the probability of an eruption over a given time interval, we produce maps representing the hazard probability over time. Hazard maps show higher probabilities of lava inundation within ephemeral stream channels and along old lava flow margins downslope of areas with high vent-opening probability. Tephra fall hazards are limited to regions of likely vent locations, with slightly higher probabilities to the east, where the predominant winds blow. Our results demonstrate an approach to probabilistic hazard mapping that is widely applicable.

Considerations for volcanic hazard mapping at small islands: an example from the open-access source-book for volcanic hazard maps

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Over the past few years, the IAVCEI Hazard Mapping Working Group has facilitated a number of activities to enable sharing of volcanic hazard map experiences, including workshops discussing volcanic hazard map development methods and map uses. One major aim of these activities is to collate collective insights and experiences and to develop a Source Book of considerations for the development of effective volcanic hazard maps. This effort is now near completion. Here, we present one of the sections in the Source Book, Small Islands, to illustrate the style of the considerations and explain their origins as workshop outcomes.

Small islands pose special cases for hazard and risk assessment and management. Tephra fall, pyroclastic flows, lava flows and debris avalanche can affect both onshore and offshore regions, including neighbouring islands. Such volcanoes can also produce phreatomagmatic eruptions, pumice rafts, and other hazards that can affect offshore regions, impacting maritime activities. On rare occasions, partial collapse of volcanoes near coasts can generate debris avalanches that trigger tsunami; primary eruption processes such as pyroclastic flows entering the sea may also generate smaller volcanic tsunami. Considerable societal challenges related to volcanic hazards are particular to islands: habitable space may be limited, and there may be no redundancy in critical infrastructure such as water, power and waste treatment. There are also challenges associated with evacuation, which is often extremely traumatic for inhabitants. For such volcanoes, the Source Book recommends that mapmakers consider including 1. Participatory approaches to hazard assessment and mapping that engage the community, in light of potential off-island evacuations; 2. Information on critical infrastructure and evacuation paths; and 3. Maritime/offshore hazard zones. Design considerations are also presented.

Development and results of a world-wide survey of official volcanic hazard maps: insights into hazard assessment input data, hazard depiction and lessons learned

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The Hazard Mapping Working Group of IAVCEI is facilitating a number of activities to enable sharing of experiences of how volcanic hazard maps are developed and used around the world. One key activity is a currently active survey that aims to collect data about official, published volcanic hazard maps and how they were developed. The survey asks questions about map content, design and input data, as well as about the map development process and key lessons learned. The responses are being used to describe and understand current practices in volcanic hazard map development.

To date the survey has captured information from over 70 volcanic hazard maps (85% long- term and 15% crisis hazard maps) from over 50 volcanoes. Results so far indicate that hazard is most commonly represented through integrated zones (e.g. high, medium and low hazard zones), with a lesser proportion of maps showing discrete hazards only, or both integrated zones and discrete hazards. Most maps provide information on four to five hazards; maps with information on just one to two hazards typically show flow hazards (lava flow, lahar, PDC). Most maps are based on scenarios (i.e., deterministic), rather than a probabilistic hazard assessment. Geological information on past activity at the volcano is the most common type of input data for hazard assessment, although modelling inputs for lahar and tephra hazard are common in more recent maps. Lessons shared by participants span a range of topics, including visual design elements to unexpected uses of hazard maps. Here, we present the philosophy behind the survey, some key results, and explain how the knowledge gained from this global map review will provide valuable input into the Source Book of Considerations for the Development of Volcanic Hazard Maps currently in preparation by the working group.

Defining uncertainty and hazard zones from numerical model accuracy assessments

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Numerical models of volcanic hazards provide deterministic or, if implemented within a probabilistic framework, probabilistic estimates of hazard footprint and intensity. These model estimates are not perfect, being affected by uncertainties in source and boundary conditions in addition to assumptions and limitations of each model. To be useful as a robust tool for mapping hazard, model accuracy needs quantification and the uncertainty represented in hazard maps. Performance metrics can be used to quantify model accuracy (e.g. Charbonnier et al., 2017), however these do not provide guidance on the location, scale or topographic influence of model error. For example, the predictive accuracy of a simulated inundation footprint is highest where the flow is deepest (i.e. in the centre of channels, or where channel sides are steep). An alternative approach to account for some degree of locational error tolerance in performance evaluation is to use fuzzy set theory. This technique replaces the discrete, binary classifications of model accuracy (e.g. Inundated/Not inundated) with a gradual 'fuzzy' classification to indicate degree of membership to each class. This approach provides a more realistic representation of model accuracy by introducing locational tolerance and presents new opportunities to create hazard maps that incorporate observed uncertainties. Using the 2012 debris flow from the Upper Te Maari crater, Tongariro Volcano as a case study, we present this new fuzzy location performance assessment methodology to quantify numerical model accuracy at different spatial scales. We demonstrate how these performance assessments can be used to identify the ideal scale for displaying simulated hazard information, and present a procedure to generate hazard zones from simulations with a defined level of uncertainty.

S01.21 Talk

Using models for hazard mapping: perspectives on user experiences and model development

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Computer models of volcanic phenomena such as tephra fall, pyroclastic density currents, and lahars are increasingly used by hazard map makers to estimate the extent of hazard zones. However, the process of choosing appropriate models and model inputs, converting model outputs into useable products, and combining model results with other geological knowledge in order to delineate hazard zones is extremely complex. Few resources exist to aid map makers in these applied aspects of model use and hazard map makers are rarely involved in model development.

Over the past several years, the Hazard Mapping Working Group of the IAVCEI Commission of Volcanic Hazard and Risk has facilitated a number of workshops around the world to enable sharing of volcanic hazard map experiences. This presentation draws upon feedback from participants in these activities in order to explore the experiences of map makers using models for hazard mapping. Challenges and successes in using models for map making are highlighted, and suggestions for model developers for improving model utility for hazard mapping purposes are discussed.

Does hazard map design matter? Effects of map content and visualisation style on volcanic risk perception and decision- making

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Maps are used to share knowledge about volcanic hazard and risk with a wide range of audiences before, during, and after a crisis. These volcanic hazard and risk maps comprise simplified representations of complex, overlapping, and uncertain geospatial phenomena that manifest on different spatial and temporal scales and with different metrics and intensities. Displaying this information so that non-specialist audiences with a range of volcanic and cartographic experience can construct meaning and make informed decisions presents a number of challenges. While there are many existing strategies for representing volcanic hazard and risk information on a map, there is little evidence for how different approaches influence the way that audiences may understand and use the map information. Here we present the results of a study investigating how choices in the way that volcanic information is communicated and visualised on hazard maps influences the way that public audiences read, draw inferences from, and make decisions with the maps. We report on the findings of a series of mixed-methods experiments in New Zealand that used eye-gaze tracking, performance-based tasks, and questionnaires to assess map reading behaviour, risk perception, and decision-making for a fictional volcanic crisis at a rural stratovolcano (Mt. Taranaki) and an urban monogenetic field (Auckland Volcanic Field). Visualisation factors are explored, such as the colour and style of hazard area representation, as well as factors related to map content, such as hazard data shown using discrete hazard footprints, integrated hazard zones, average and/or worst-case scenarios, and probabilistic forecasts.

Estimation of the vulnerability and perception of the hazards by activity of the Ceboruco Volcano, Nayarit, Mexico

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The volcano is located in the State of Nayarit, Mexico, 21,125º N and 104,508º W, it has been characterized in the past by episodes of effusive-explosive eruptions. Nelson (1986) identifies the eruptions that have occurred, called the Jala eruption, which correspond on average to an eruption every 125 years, and proposes that new eruptions are very likely. In the study by Suárez-Plascencia (1998), with geological evidence, identified hazards near Ceboruco Volcano, such as lava flows, pyroclastic surges and ash fall, based on the most recent eruption in 1870.

The vulnerable populations and facilities in the affected area and according to the hazard were identified, with the criteria of CENAPRED (2011) and CEPAL (2016) with the information generated by INEGI. The high vulnerability corresponds to communities like Ahuacatlán, Ixtlán, Jala and Jomulco, and facilities are the highways and railways. Questionnaires were applied to know the perception about hazards by the Ceboruco Volcano in the mentioned communities. The greatest frequency in the responses of people were Ceboruco volcano hazards were unlikely to occur. Ahuacatlán is the only community that identifies one evacuation route toward Amatlán de Cañas in case of occurrence volcanic activity. The misinformation generated in social networks was a major problem and one imbalance for the Civil Defense work programs in the communities near the Ceboruco Volcano.

Database of geology and geophysics studies of Mount Fuji eruptions

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Mount Fuji is the highest volcano in Japan. It has a 100,000-year eruptive history and is one of the most studied volcanoes in Japan. From 2000 to 2002, unusual numbers of low- frequency volcanic seismic activities were detected around Mount Fuji. Although the geological features of Mount Fuji were studied before, they have been studied again in detail since then. However, this work exist piecemeal in scientific literature and is not easy to exploit for further study. Because studies of the eruption histories and the physical features of Mount Fuji have progressed since the publication of the 2004 hazard map, it is necessary to update it now. We created a database of these publications and published data such as the chemical composition of ejecta, hazard maps, isopach maps and so on. To create GIS-based data is the focus of this project because the old maps in previous publications were image data and not possible to open with GIS software. If such map data can be opened with GIS software, it would be easier to analyze map-based data and overlay information. 90 isopach maps and 20 hazard maps have been converted into GIS-based data. This data is expected to be used in the study of past eruptions and predictions and assessments of future eruptions of Mount Fuji.

S01.21 Poster

Probabilistic volcano evacuation maps

Gordon Woo

Risk Management Solutions , UK

At any given time during a volcanic crisis, there will be some probability of a major life- threatening eruption. Depending on the current level of this hazard probability, decisions can be made over which groups of the population at risk might be evacuated. Every evacuation decision involves a complex trade-off between economic disruption and public safety. A methodical basis for deciding such trade-offs is to use cost-benefit analysis. This differs from standard deterministic decision criteria which have fixed mapped evacuation zones, corresponding to an extreme eruption scenario. It also differs from imposing acceptable societal risk limits in accounting explicitly for the evacuation cost and time, as well as the likelihood of people becoming casualties in an eruption. Both of these factors routinely enter into the judgements made by populations at risk as to whether to evacuate or not.

Cost-benefit criteria define probability-dependent evacuation zones. For the full range of probability of a significant eruption, these evacuation zones can be mapped. Such maps can be further differentiated according to population segments which differ according to their risk aversion, and special needs for evacuation.

With its large local population, Vesuvius is recognized as one of the most challenging cities on volcanoes to evacuate during a volcanic crisis when the evidence for an imminent major eruption is sparse and highly ambiguous. The application of cost-benefit criteria to Vesuvius was developed by W. Marzocchi and G. Woo (J. Geophys Res., Vol.114, 2009), but no mapping was included in the analysis. Vesuvius is used here as an important test case for the production of probabilistic volcano evacuation maps. Such maps should be instructive as supplementary graphical aids to those responsible for making volcano evacuation decisions under great uncertainty.

Considerations for volcanic hazard mapping – community input through international hazard mapping workshops

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Since 2011, the Hazard Mapping Working Group of the IAVCEI Commission of Volcanic Hazard and Risk has facilitated and participated in several workshops to enable sharing of volcanic hazard map experiences. These workshops include State of the Hazard Map workshops in 2014, 2016, and 2017 (in Indonesia, Chile, and USA, respectively); Hazards Assessment workshops in 2016 and 2018 (in Indonesia and Peru); Volcano Observatory Best Practice workshops in 2011, 2013, and 2016 (in Italy and USA); and a Communication of Hazard Maps in Central America workshop in 2017 (in Guatemala). Geologists from 29 countries around the world, including a large number of hazard map authors and designers, have participated in this series of workshops.

In these workshops, participants discussed the variety of inputs for geologic map and hazard assessment generation, including geologic field mapping and reconstruction of eruptive histories; methods of data integration; use of models to complement field observations; incorporation of stakeholder needs; elements of hazard map design; the wide variety of products that are associated with maps in the suite of hazards assessment; and communication of hazards information.

An open-access source-book for the Development of Volcanic Hazard Maps is being assembled to summarize the issues discussed in these workshops. This document will include a faithful representation of the content discussed by workshop participants. Reports from each workshop will feed directly into the source-book, which is being organized to help the user find relevant information for future hazard map design.

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S01.22 - Mapping volcanoes for hazard assessment, resource-management, and building cultural value of the territory

Mapping primary lahars at Cotopaxi volcano with NIR and visible imagery obtained with a UAV: preliminary results

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During the last centuries, Cotopaxi volcano has produced several primary lahars which flowed its northern, south-western and eastern drainages. The detailed cartography of those deposits is only possible in the proximal zone at the foot of the volcanic edifice. However, it has not been performed mainly due to the lack of adequate imagery and the highly complicated contact patterns observed in the field. This has lead to inaccurate cartography of the most recent lahars and generalizations in the interpretation of the deposits.
We have used an unmanned aerial vehicle (UAV) to obtain detailed imagery of the primary- lahar deposits in two proximal zones located in the N and NE flank of Cotopaxi volcano. The imagery includes near infra-red (NIR) and visible-light bands. Additionally, high-resolution (25 cm-pixel) DEM's have been created from that imagery. The combination of those bands has revealed to be a useful tool for the individualization and cartography of the lahar deposits. Notably the NIR band, which is sensitive to vegetation, has provided higher contrast in the resulting images, given that different lahar deposits have also developed different type and amount of vegetation in their surface. Also, the detailed DEMs have allowed the identification of subtle morphologies that are otherwise impossible to map in the field. At least three different lahar deposits, belonging to the eruptions of 1744, 1768 and 1877, have been identified with these images.
The detailed cartography of these deposits will provide enhanced insights into the size (e.g. volume, discharge rate) of the lahars. These informations together with the improved cartography can be used to test numerical models of lahar flow and to better assess the hazard associated to primary lahars at Cotopaxi volcano.

Thematic maps contribution to the flooding phenomena hazard assessment in a very active volcanic area: The case study of the eastern flank of Mt. Etna, Italy

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During the two last decades, very violent and unexpected flooding phenomena affected the eastern flank of Mt. Etna volcano causing not only heavy damages to the territory but also loss of human lives. Data reported in the daily chronicles (newspapers and local reports) indicate that areas more frequently hit by these disastrous events are Giarre and Acireale, two municipalities located near of the eastern coast of Sicily. The most disastrous and fatal event is dated 13 March 1995 and affected the Giarre and Acireale municipalities, causing the tragic death of 12 people. The most recent events are dated October 2014 and 2015, and generated huge damages to properties and infrastructures in some areas around Acireale and once again in Giarre municipality. In order to provide a useful contribution for the identification of the areas more subjected to potential flooding phenomena in the eastern flank of Mt. Etna, we present a multidisciplinary study based on geo-lithological and morphometric mapping of the Etnean eastern flank, combined with land cover, hydrological elements and rainfalls data. The study, developed on GIS platform, allowed to obtain the first results on the flooding hazard assessment in the eastern flank of Mt. Etna. These results provide interesting elements of discussion that, probably, should be taken into account for the correct management of a territory often subjected to morpho-lithological changes due to the frequent volcanic activity.

S01.22 Poster

Atlas of Volcanic Seamounts in Italy

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A comprehensive review of publications, maps, conference presentations and cruises reports concerning submerged volcanic structures in Italian Seas, including islands, has been performed with the aim of providing products for the EMODnet Geology Project. The Project, funded by the European Commission, aims at the collection and harmonization in European Seas of as many existing marine data as possible, to be represented on digital maps and made freely available through a dedicated portal (http://www.emodnet.eu/). The Geological Survey of Italy is Partner of the Project and Leader of Work Package 6 "Geological events and probabilities", which includes earthquakes, volcanoes, landslides, tsunamis, fluid emissions and Quaternary faults.

In order to collect and harmonize existing data on submerged volcanoes, the Geological Survey of Italy cooperates with the Science Department of RomaTRE University. The results obtained go well beyond what was foreseen for the EMODnet Geology Project: the amount of data recorded, interpreted and harmonized has led to the development of an original and complete database, which will be published in a volume of a Geological Survey of Italy collection.

Significant effort has been dedicated to identify the extent of each volcanic edifice (so far very poorly defined) on the most detailed available bathymetric maps. Data collected allowed a classification of different edifices, based on morphology, chemistry, ages and main structural lineaments. Where possible, the age and style of the most recent eruptions, as well as the presence of active fluid emissions, have been listed in order to support future possible evaluation of volcanic hazard.

Mapping of long dormant volcanoes for hazard and environmental management, risk mitigation, landcare, geo-cultural heritage, and sustainable development: the Colli Albani case study

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Università Roma Tre, Italy

Long-dormant volcanoes are poorly defined in terms of time lag from their last eruption. Several examples exist of reawakening of volcanoes previously considered extinct with documented eruptions only in the pre-Holocene rock record. The Colli Albani caldera is one of such volcanoes, for which the known age of the youngest preserved primary deposit is debated at 36 ka or < 23 ka. However, recent studies have illustrated the extent to which the preserved volcanic stratigraphy severely under-represents the full eruptive history especially of long dormant volcanoes where inter-eruptive periods are long enough to allow erosion and removal of significant parts of the primary deposits, especially for small events. In this presentation I will summarize almost 20 years of studies of the post-23 ka stratigraphic record at Colli Albani and its mapping, involving the multidisciplinary cooperation with archeologists in order to unravel the potential hazards of this volcano and its impacts on human communities up to historical times. The Colli Albani case study not only illustrates the fundamental role of interdisciplinary field-studies in long-dormant volcanoes, but shows that these volcanoes need as much attention to the volcano- sedimentary record as to the primary volcanic stratigraphy.

S01.22 Talk

Volcano Geology Commission: geological maps and their applications. A short overview

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At present, the IAVCEI Commission on Volcano Geology has more than 180 members and its main aim is to promote postgraduate research in geological aspects of volcano studies, provide a forum for discussion among researchers on new developments in geological studies in volcanology, and encourage multidisciplinary research across the wide range of geological fields involved in volcanology. A special attention is given to the geological fieldwork and mapping in volcanic areas as the basis for detailed volcanological, magmatic studies, computational modelling and for understanding the behaviour of volcanoes and their future activity in terms of volcanic hazards (for active or recent volcanoes). We present a summary of the achieved results and the perspectives for the future of the Volcano Geology Commission.

Land-sea geological mapping of the active volcanic island of Vulcano (Aeolian Islands, Italy)

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Geological mapping in volcanic islands is a fundamental tool to improve the understanding of their evolution and eruptive history and provide valuable information for decision-making processes in territorial management and volcanic risk evaluation. So far, most of the geological studies rely on subaerial fieldwork, overlooking the near-shore sectors mainly due to the difficulties associated to surveying submarine areas. On the other hand, the eruptive history and volcano-tectonic evolution of subaerial and near-shore areas is often intrinsically correlated, as well as the associated hazard. Starting from a fruitful collaboration between volcanologists and marine geologists, here we attempt to provide an integrated land-to-sea geological mapping of the island of Vulcano, with particular attention to the coastal areas. A special focus is given to the evolution of the north-eastern sector of the island, where the multistage La Fossa Caldera and the active cone of La Fossa have developed. We have combined all the stratigraphic and geological data derived from subaerial field studies with a detailed analysis of high-resolution multibeam bathymetry collected all around the island. Despite some limitations derived from the lack of samples and in-situ observations for the near-shore sectors, we are able to confidently map the offshore extent (at least down to -120 m and in several sectors down to -800 m) of the main subaerial volcanic units recognized onland. This provides information on i) the localization of submerged volcanic centres, ii) the distribution of the main lava flows and pyroclastic successions from the land into the sea, particularly for the Holocene activity, and iii) the continuation of caldera borders in shallow water. More generally, this study highlights the utility of integrated subaerial and offshore geological studies to better understand the main volcanic, volcano-tectonic and mass-wasting processes affecting the volcanic islands and the implications for a first geohazard assessment.

S01.22 Poster

Under the radar:
New activity beneath the "Roof of Patagonia", Domuyo volcano, Argentina

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Volcanoes dormant for thousands of years ago are challenging, both for hazard assessment and for understanding their physical processes. Nevertheless, the monitoring of dormant volcanoes has experienced a revolution over the past 25 years thanks to the advent of satellite-based remote-sensing methods. In this study, we present geodetic observations (interferometric synthetic aperture radar - InSAR - time series and interferograms from the SAR sensors onboard the ALOS, ALOS-2, Radarsat-2, and Sentinel-1 satellites) and thermal observations (radiance time series retrieved from the moderate resolution imaging spectroradiometers -MODIS - onboard the Terra and Aqua satellites) of a new center of unrest discovered in the southern Andes, beneath Domuyo volcano. Domuyo is a little studied 4700m elevation volcano that is considered a dacitic dome rising out of a caldera; it features an active hydrothermal system, but most recent eruptions are Pleistocene to possibly Holocene. Our geodetic analysis reveals that Domuyo was the location of gentle to null subsidence from 2008 to 2014, which abruptly started inflating in 2014, continuing to present. This surprising inflation has been roughly linear (~11 cm/year), and is consistent with a sub-horizontal flattened ellipsoidal source between 5.5-6 km depth that coincides with the width of the caldera. In contrast, our thermal analysis, based on a new algorithm that captures the diffuse emissions of heat through volcanic edifices, reveals that the thermal output of Domuyo was relatively steady from 2008 to 2013. Then, it abruptly started to decline at a roughly steady rate (~ -20mW/m^2/sr/micron/yr) through 2017, with an increase of thermal emissions over the past year. Our results beg the question: what are the physical mechanisms that can account for simultaneous inflation and reduced thermal output while also accounting for a time lag between both observables? We present some of the competing mechanisms in this presentation.

Our landmark: Introducing the Pirongia Volcano as a significant geoheritage site of New Zealand Pleistocene volcanism

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The production of detailed, informative volcanological maps is important for the recognition of volcanoes as landforms of high geoheritage value. The eroded volcanic edifice of Mt Pirongia is a prominent topographic and indigenous cultural landmark within the Waikato region of North Island, New Zealand. The expansive (120 km^2) mountain was the site of voluminous (c. 50 km^3) basaltic eruptions associated with the Alexandra Volcanic Group in Pleistocene times. These eruptions produced one of the largest basaltic volcanoes in the North Island. Pirongia Volcano has attracted the attention of historically influential geologists such as Ferdinand von Hochstetter (1859) due to its isolated regional setting and rare varieties of highly-porphyritic ankaramite basalt. However, because of its dense forestation and limited rock outcrops, geological mapping was never performed at a detailed scale. Consequently, Pirongia Volcano has remained largely forgotten in the North Island volcanic narrative. In this study, we present the results of our field mapping which include: (1) the first volcanological map of Mt Pirongia, and (2) geomorphic reconstructions of its original volcanic edifice. The map reveals the post-erosional distribution of lava fields, volcaniclastic breccias, dikes and pyroclastic deposits from which the volcano was constructed over its c.1 million year eruptive lifespan. Projection of erosional topographic features (i.e. radial valleys, ridges and their medial planezes) indicates that eruptions at Pirongia were associated with at least three major, overlapping phases of cone-building. The proposed vent locations correlate with mapped vent proximal deposits (dike swarms and vent-proximal andesitic PDCs and scorias) and imply erosion of 200-300 m from above the present summit (959 m a.s.l). The new map enhances the geoheritage status of Pirongia as a unique, regionally significant stratovolcanic complex. Its publication will include a companion map for hikers of the Te Araroa trail, New Zealand's premier walking track that traverses Mt Pirongia.

S01.22 Talk

Mapping the deep ravines and bush-clad peaks of a region's landmark: the first geological map of Pirongia Volcano, New Zealand

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Maps of active and extinct volcanoes are a fundamental starting point for the interpretation of volcanic terrain and its processes of formation. Volcanic edifices are dynamic structures affected by rapid growth and degradation, so the approach to mapping of their deposits (i.e. lava flows, domes, dikes, pyroclastic flows and lahars) is highly dependent on the degree of surface preservation of the edifice. Ancient volcanoes present a unique challenge for mapping because of their highly eroded state, where only remnants of their original morphology are preserved. Pirongia Volcano (959 m a.s.l.) of western North Island, New Zealand is a Pleistocene (c. 2.49-1.60 Ma) composite volcano with a complex but poorly understood eruptive history and heavily eroded, bush-clad edifice. In this study, we present the first volcanological map (1: 10,000) of Pirongia Volcano, based on the results of our extensive field campaign between 2016 and 2018. The map uncovers previously unknown volcanic deposits including extensive lava flow fields, radial dike swarms and andesitic pyroclastic deposits related to at least three (long since) eroded pyroclastic cones. It provides a first-order framework for the identification of major cone-building phases, based on geographic, topographic and petrographic correlation criteria. Our map updates the previous interpretation of Pirongia as a shield-type volcano, to a composite cone complex with multiple overlapping eruptive centres. The map shows the dissection of the edifice by severe fluvial erosion, which has formed radial valleys (up to 350 m deep), inverse topography and dike-controlled ridgelines with only a few planeze surfaces remaining on the lower flanks. Significantly, the mapped deposits suggest that Pirongia's eruptive history was more explosive than previously recognised, and characterised at certain stages by vulcanian explosions and multiple cone-building episodes – similar to other active North Island volcanoes such as Mt Taranaki.

The geological land-sea cartography of Ischia Island: knowledge at the basis of geo- environmental diversity

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In December 1999 the Campania Region, has formalized its participation in the National CARG Project (Geological Cartography) co-financing the geological mapping of the emerged areas and marine areas (up to the isobath of -200 m), also proposing geological survey to the scale 1:10,000 of the coastal geological sheets of the territory which have allowed the land/sea connection. A further significant feature for the study of submerged coastal marine areas (up to isobath of -30 m), was the underwater geological survey and adoption of homogeneous criteria of geological detection between emerged and submerged coastal areas. As part of the activities carried out for the COV10, the General Government of the Territory and Civil Protection Department of the Campania Region in close collaboration with the INGV-OV and availability of the Center of Villa Dohrn in Ischia part of the Stazione Zoologica of Naples, identified and proposed an initiative in the field of civil protection with educational purposes in the primary and secondary schools of the island of Ischia focused on the geological, geo-environmental, geo-cultural aspects of the island of Ischia for the purposes of perception, awareness, prevention and mitigation of risk. The main geological aspects of Isle of Ischia and their implications for the ecology of the coastal marine communities, are represented in the evolutionary volcanic framework of the complex land- sea system, in the awareness of the perception of all the elements connected to the natural hazard and to the study and enhancement of the resources and environment.

S01.22 Poster

New geological mapping (scale 1:10 000) and revised eruptive history of Ustica Island (southern Italy)

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A new geological mapping of Ustica Island (southern Italy) at 1:10.000 scale is here presented as the result of geological and structural fieldwork and remote sensing analysis, combined with literature radiometric ages and a large set of original petrochemical data. Fieldwork and stratigraphy are based on lithostratigraphic units as the basic units for mapping, combined with lithosomes (=eruptive centres) and unconformity-bounded units providing correlations. Five synthems (Passo della Madonna, Timpone Basile, Via dell'Arso, Cala Giacone), and the informal Paleo-Ustica unit are subdivided by primary marine erosive unconformities. Accordingly, the eruptive, structural and magmatic history of Ustica is described as a result of four major growth stages (Eruptive Epochs 1-4), interrupted by prolonged periods of quiescence and marine erosion and deposition. The oldest hyaloclastites and pillow lavas (Epoch 1, ~737 ka) are related to ENE-WSW oriented fissural submarine activity. The emergence of the island corresponds with the emission of the mildly subalkaline basalt and andesite lavas and pyroclastic products relative to Mt. Guardia dei Turchi and Mt. Costa del Fallo stratovolcanoes (Epoch 2, 519-476 ka), forming the main WNW-ESE elongated volcanic relief in the middle of the island. Along the western coast of Ustica are present the coeval minor eruptive centers of Spalmatore and Punta di Megna, together with the offshore pyroclastic vent of Casa Zacami. The subsequent activities of Mt. Costa del Fallo (Epoch 3, 424-412 ka) is characterized by the Grotta del Lapillo trachytic pyroclastic products and a laccolite body, passing to mugearitic lava flows. A prolonged period of quiescence is recorded in different marine terraces raised at elevations of ~100 m asl due to regional tectonic uplift. Renewed activity produced the sightly differentiated Na- alkaline pyroclastic products of the Capo Falconiera tuff cone, formed during the Last Interglacial (~120 ka) during a period of prevailing marine erosion and deposition.

Assessment of connectivity and hydrological efficiency at Volcán de Colima, Mexico: spatiotemporal changes related to the July 2015 eruption

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Connectivity is a hydrological concept whose theoretical and methodological framework has grown recently; the application of this concept permit to characterize the spaces based on the combination of the landscape elements and how this combination promotes or not the transport of sediments. This concept has been applied to different environments, however, its application in active volcanic environments is incipient.

The 10-11 july 2015 dome collapse activity at Volcán de Colima (México) emplaced pyroclastic flow (PF) deposits along the Montegrande ravine, up to 10 km and over an area of more than 4 km2. The PF destroyed the vegetation on the southern slope of the cone, overfilled the ravine and left an important amount ash fall deposits on lateral terraces. The application of the Connectivity Index (IC) and the Lateral Hydrological Efficiency Index (LHEI) was calculated for the Montegrande ravine prior and after the 2015 eruption to understand changes in sediment availability and transport. Prior to the eruption, the IC index had the highest value only on the upper slope (> 30°) of the volcano and along some section of the ravine in correspondence of the steepest terraces.

The emplacement of the 2015 PF change completely this scenario; all the ravine now has the highest value of IC and LHEI with important implications in lahars generation. Since the eruption of 2015, the frequency of the lahars increased significantly and has modifying the landscape along the ravine; the analysis of the IC and LHEI has allowed the identification those spaces that, in addition to the volcano, have an important capacity to contribute and transport sediments into the ravine, material that can be assimilated in the processes of lahar increasing its volume and danger. Identifying these spaces coud contributes in the efficient application of intervention actions aimed at reducing risk

Geological map of the volcanically active western Zacapu lacustrine basin area (Michoacán, México) and its usefulness for archaeology and hazard assessment

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The Zacapu lacustrine basin (1980 m asl) is located in the northern-central part of the Michoacán-Guanajuato Volcanic Field (MGVF), which constitutes the western-central segment of the Trans-Mexican Volcanic Belt. Detailed geological mapping of a ~400 km^2 quadrangle encompassing the western margin of the basin together with $^{40}Ar/^{39}Ar$, ^{14}C, and palaeomagnetic dating of volcanic products allowed to establish a stratigraphic framework (Reyes-Guzmán et al. 2018; Mahgoub et al., 2018) for this archaeologically and volcanically important area. Several of the Late Holocene lava flows were densely inhabited (urban-sized settlements) in Pre-Hispanic time and suddenly abandoned around AD 900, when the Malpaís Prieto lava flow erupted covering an area of 5.5 km^2. About 300 years later, during the Post-Classic period of Mesoamerican archaeology, the area became repopulated again, including the Malpaís Prieto lava flow, which hosts one of the sites where the Tarascan Empire (AD 1250-1521) has its roots. Whole-rock chemical and petrographic analyses of the different rock types in this area have also helped to identify/corroborate some of the sources of raw materials for buildings and stone tools (e.g. Darras et al., 2017). Future collaboration with archaeologists will not only help addressing further questions related to past population movements and the provenance of lithic materials, but maybe also provide clues in regard to the origin of legends and religious traditions that might have their roots in close connection to past volcanic eruptions. The collected data is also of paramount importance in addressing volcanic hazards in the area. In particular it shows that Holocene activity in the MGVF has not been restricted to the trench-ward margin where the historic Paricutin and Jorullo eruptions occurred, but that new volcanoes may form up to 100 km further inland in the future, having greater socioeconomic impacts on Central Mexico.

S01.22 Talk

The hazard map for Ceboruco volcano – modeling based on the eruptive history and final products

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Ceboruco is an active stratovolcano in the western Trans-Mexican Volcanic Belt and considered one of the 11 potentially most hazardous volcanoes in Mexico by the National Center for Disaster Prevention (CENAPRED, 2014). Ceboruco is quite young (<100,000 yrs) and its eruptive history is characterized by abrupt changes in eruptive style and variable duration of individual eruptive phases, which complicates hazard assessment in comparison to other Mexican volcanoes.

During its eruptive history, effusive activity has been prevalent, however, the major AD 1000 Plinian Jala eruption (VEI=5) produced a great diversity of pyroclastic deposits, including tephra fallout, ballistic ejecta, pyroclastic flows and surges, as well as extensive lahars.

Three individual eruptive scenarios of different magnitude were identified and served as a starting point for constructing an integrated and simplified (easy to read) hazard map for Ceboruco volcano. The map depicts main hazard zones to be impacted to different degrees by different volcanic phenomena and allows identifying population centers and important infrastructure within the area of Ceboruco's influence. The latter should enable local authorities to undertake vulnerability and risk analyses and to subsequently implement hazard mitigation measures (tracing evacuation routes, establishment of shelters, etc.), and optimize decisions in regard to future economic development and territorial use planning.

S01.22 Poster

The areal, thickness and densities distributions of Campanian Ignimbrite, Campi Flegrei, Italy

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The 39 ka Campanian Ignimbrite (CI) is the largest caldera-forming eruption of the Campi Flegrei (Giaccio et al., 2017). The main CI is interpreted as emplaced by a PDC that travelled more than 80 km, over an area of > 30.000 km^2, and surmounted ridges more than 1000 m high (Fisher et al. 1993). Despite the large number of works regarding volume estimation of the eruption, the calculation of DRE volume ranges from 23 to 300 km^3 (Scarpati et al. 2014).

Field work in strategic locations around the Campanian plain east of the caldera reveals the topographic control over the deposit distribution. Sampling during field work focused on the thickness of the deposits, the dimensions of lithic clasts and bulk samples for density measurements. We have produced a new density, mass and welding map of CI. Deposit density and porosity decrease with distance and increase with altitude.

A detailed isopach map for the flow units of CI shows the dispersion of pyroclastic deposits, as well as the thickness of deposits and dispersal area in relation to paleotopogrAPY. Bibliographic data were collected both in proximal and distal areas. All data have been geo- referenced in Quantum GIS (QGIS) with the geological map of Italy. Isopach lines were traced on a topographic slope map derived from a Digital Elevation Model.

We can now delimit the distribution of the PDC and define the extent of the flow. The map will be also used to evaluate a new detailed estimate of the volume of CI flow.

Contribution of Geological Survey of Italy to Cartography of Volcanic Areas

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The Geological Survey of Italy (GSI) has promoted to adopt a national rule for the geological field survey and the volcanic areas representation in the new Geological Map of Italy at 1:50,000 scale (CARG Project - Console et al., 2017 and References therein).

For this reason, new stratigraphic methods to carry out the Official Geological Sheets of main Italian volcanic areas have been experimented.

This methodology has been based on the integration of different kinds of stratigraphic units and multidisciplinary data, mutually useful to accurately describe the different Italian volcanic contexts. Therefore, detailed geological field surveys (until at 1:5.000 scale or minus) have been carried out by different Research Teams charged with the geological Sheets realization on behalf of the GSI and some Regional Administrations. The on land surveys of the coastal volcanoes or the volcanic islands have been completed for the first time using direct/indirect underwater campaigns. The legends, schemes and database of the Sheets managed to summarize a large number of different information that has been nationally agreed upon. Such a collection is certainly a valuable prompt for a serious consideration representing a data source for this session's goals.

Indeed, over thirty new official geological Sheets at 1:50,000 and 1:25,000 scale that adopt this methodological approach have been produced by the GSI. They cover Quaternary volcanic areas, some of which are active.

Moreover, several updated geological maps for some of the main Italian volcanic Districts have recently been published by prestigious Authors. These maps are the product of processing and updating the data that has been collected by these authors for the CARG Project.

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Volcanic Hazard Map for Lahar and Pyroclastic Density Current by Lava Dome Collapse at Jeju Island, Korea

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This study can be used to minimize damages caused by lahar and pyroclastic density currents occurred on Jeju island. First, in order to determine the runout range of pyroclastic density currents on Jeju island, lava dome collapse on 8 locations of outer rim of Baekrokdam crater were simulated by TITAN2D numerical simulation program. We set parameters as internal friction angle as 30° and bed friction angle as 20° to control velocity of currents occurred by lava dome collapse. Then we set the height and radius of lava dome, initial speed of collapse and simulation times. And we carried out numerical simulations for a total of 96 scenarios. The result shows that the maximum runout distance was 13.4 km in case of lava dome collapse. Second, it was performed schematic prediction on the impact area of lahar hazards at the Mt. Halla volcano, Jeju island using Laharz_py program. In order to comprehensively address the impact of lahar for the Mt. Halla, two distinct parameters, H/L ratio and lahar volume, were selected to influence variable for Laharz_py simulation. It was carried out on the basis of numerical simulation by estimating a possible lahar volumes of 30,000, 50,000, 70,000, 100,000, 300,000, 500,000 m^3 according to H/L ratios (0.20, 0.22 and 0.25) was applied. The number of streams which affected by lahar tended to decrease with increasing H/L ratio. The results of this study will be used as basic data to create a risk map for the direct damage that can be caused due to volcanic hazards arising from Mt. Halla, Jeju Island, Korea.

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S01.23 - Volcanic-hydrothermal systems structure, dynamics, monitoring and hazards

The September 7, 2018 M8.2 Chiapas, Mexico earthquake, and its possible influence on the El Chichón crater lake

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On September 7, 2017, at 04:49:17 UTM, a magnitude 8.2 earthquake, with epicenter in the Gulf of Tehuantepec at 14.761° N, 94.103° W and at a depth of 45 km, seriously affected most of southern Mexico. In a recent visit to El Chichón volcano crater, located about 270 km north of the epicenter, several new landslides reaching the crater lake were observed on the internal crater walls. The landslides were probably caused by the earthquake since some inhabitants of the El Guayabal and Colonia del Volcán communities, located about 7 km east of the volcano reported rumbling from the volcano during the earthquake. To determine the effects of the earthquakes and the landslides on the crater lake, we discuss here the hydrogeochemistry of water samples collected in March 2018, and compare the data with chemical analyses of previous years. Measurements of pH at 10 shallow sampling sites at El Chichón crater lake in March 2018 were similar to those measured in March 2017; temperature also showed similar ranges. Major ions (Na, K, Ca, Mg, SO4, Cl), and boron, lithium, and silica concentrations showed a moderate decrease respect to 2017. However, H_2S (as sulfide in ZnS precipitate in the water sample), which was below detection levels in 2017 in all but one of the 10 sites, was detected in all but one site in 2018. Since disturbances from landslides may cause the ascent of deep seated gases to the surface, we propose that the observed increase in sulfide may have resulted from the upwelling of H_2S from the bottom of the lake triggered by the September 2017 earthquake and landslides.

The effect of barometric pumping on the soil CO_2 emission and associated hazard: a case study in the Island of Volcano

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In volcanic areas a huge amount of volcanic gases, especially CO_2, is also emitted in areas far from main vents, forming fumarolized zones or diffusing through the soils producing anomalous areas of degassing. Long exposure to high levels of CO_2 represents a risk for human health, hence the spatial distribution of high degassing zones must be taken into account in risk assessments. In addition, for a more accurate definition of the risk also the processes affecting the variability of soil CO_2flux must be investigate, indeed under specific conditions low degassing zones can reach high levels of emissions in response to specific processes. One process able to strong influence the emission of CO_2 from the soil is the so called "barometric pumping", according to which: the drop in atmospheric pressure induces the migration of gas from deep soil layers toward the surface, as result a fast drop in barometric pressure determines a sharp increase of the soil CO_2 flux.
Herein we report the results of investigations on this process conducted on the Island of Volcano by comparing continuous temporal data series of soil CO_2 flux and barometric pressure acquired in different zones of the island. The results showed as the relative highest rise of CO_2emissions (up to 3 orders of magnitude) were found nearby the highest degassing area, whereas lower relative increases were found in areas both with higher or lower fluxes. To investigate on the factors mainly ruling the amplitude variations, we modelled this process. The model results shows as the relative flux increase mainly depends on advective flux components: lower is this component higher is the relative variations, this implies that in sites with low flux value we can have huge flux increases, able to generate potentially dangerous situations.

S01.23 Poster

Gas hazard induced by blowouts of shallow boreholes in the urbanized Roman area (Italy)

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The eastern part of the capital city of Rome is located on the flanks of Alban Hills, a quiescent volcano that produced lahars until the IV Century b.C., by water overflows from the Albano crater lake. High CO_2 and H_2S fluxes occur in zones located above structural highs of the buried carbonate basement, where the surficial impervious layers have been removed by quarrys or mining excavations (e.g. Cava dei Selci and Solforata). In absence of wind, the gas denser than air accumulates in morphological depressions, where it may reach lethal concentrations. In the last 15 years several accidental by gas blowouts occurred from shallow wells drilled in the SE periphery of Rome and at Fiumicino, on the Tyrrhenian coast, near the Tiber river mouth. These accidents reveal the presence, at shallow depths (10-200m), within the surficial volcanic pile or the underlying Plio-Pleistocene sedimentary sequence, of confined pressurized aquifers into which gas rising from depth dissolves. Any time the impervious cover confining the pressurized aquifer is crossed by a well, a gas blowout occurs creating a serious hazard if the well is not equipped with a suitable preventer. The Fiumicino accidents, occurred in 2005 and 2013, indicate that shallow pressurized aquifers exist also at relevant distance from the nearby volcanic complexes (ca. 35 km) and in zones where the carbonate basement is over 2 km deep. Carbon dioxide soil flux surveys revealed that in some cases the gas was diffused from the wells within surficial permeable terrains, creating a health hazard in nearby houses whose occupants had to be evacuated (e.g. Cava dei Selci in 2010 and 2018; Rome in 2008 and 2016). To remove the hazard costly cement squeezes had to be carried out, to restore the deep impervious confining cap. However, these problems create delicate health and socio-economic problems.

Monitoring volcano-hydrothermal systems by continuous magnetotelluric data: a synthetic study on the Campi Flegrei area (Southern Italy)

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Monitoring hydrothermal systems is of crucial interest for different applications, such as volcanic hazard assessment and geothermal energy exploitation. In this work, the feasibility of using continuous magnetotelluric (MT) measurements for monitoring hydrothermal systems developing within active volcanoes is investigated. The MT method is indeed a good candidate for characterizing the dynamics of a volcano-hydrothermal system as it is suitable for deep exploration of the subsoil (from one hundred meters to hundreds of kilometers) in terms of electrical resistivity values, which are strongly sensitive to variations in temperature and underground fluids distributions. To test the proposed methodology, a reliable model of the Campi Flegrei (Southern Italy) volcanic complex based on geochemical and geophysical data is built and a sensitivity study is carried out by changing the fluid flow rate of the hydrothermal source and the permeability distribution of the system. In particular, for each evolution scenario the MT sensitivity has been studied by evaluating the time intervals needed for observing significant resistivity variations. The simulations have shown that the MT monitoring is much more sensitive to changes in rock permeability rather than in the fluid flow rate emitted by the source. In general, time intervals not useful for volcano monitoring purposes (i.e., longer than 10 years) are found if only changes in fluid flow rate are assumed to govern the hydrothermal system dynamics. Conversely, by increasing the permeability of the hosting rocks up to about one order of magnitude, consistent resistivity variations are observed over a period ranging from one year and a half to three months. Such findings are promising and encourage the use of the continuous MT measurements in active volcano-hydrothermal areas.

Analysis of the seismic and hydrothermal activity of the La Malinche volcano, Mexico

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The La Malinche volcano is located in the eastern sector of the trans-Mexican neovolcanic axis, it is a Quaternary volcano whose age is approximately 49,000 years. Studies based on geology and radiocarbon dating rule that this volcano is in an inactive state, however, there is still uncertainty about its activity. To obtain a diagnosis of its activity, seismic monitoring and self-potential studies have been proposed.
Since 2012, seismicity has been identified in the volcano, earthquakes with magnitudes between 1.0 and 2.7, with depths ranging from 4 to 12 kilometers. The observed focal mechanisms indicate, on the one hand, a normal fault associated with deep earthquakes that are the product of a tectonic process, whose focal mechanism is parallel to the fault system of the Puebla graben, on the other hand, shallow earthquakes show different mechanisms to local tectonics.
It has been proposed to use the self-potential (SP) method, with the objective of identifying a hydrothermal system that implies that La Malinche is in an active state, in the sense that it has enough energy to generate water steam. From the measurements of SP made in profiles from the summit to the lower flanks, two main areas have been determined: (1) The upper part of the volcanic building where a hydrothermal system has been identified, whose lateral extension comprises between 1.5 and 2.5 km with respect to the summit of the volcano; (2) a hydrogeological system, identified in the lower area of the volcanic building and (3) Structural features such as faults around the volcano and the boundary of the old caldera. The observed seismicity and the anomalies of the self-potential indicate that the volcano is active.

Potentially harmfull elements accumulation in fumarolic alteration products at three hydrothermal systems of Greece

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Samples of efflorescences and encrustations of hydrothermal origin have been collected at three fumarolic areas in Greece. The three sites are Sousaki, Thiafi (Methana) and Kokkino Nero (Kos) and all belong to the South Aegean Active Volcanic Arc. Samples were analysed for their mineralogical (XRD and SEM-EDS) and chemical composition. Solutions obtained from both mineralization with HNO_3 and leaching with distilled water, were analysed for major (ICP-OES), minor and trace metals (ICP-MS) and for sulfate contents (IC). Results show that their composition is mainly controlled by the petrological composition of the substrate (ultramafic rocks at Sousaki, felsic volcanic rocks at Methana and low-grade metamorphic rocks at Kos). The microenvironmental conditions (humidity, oxidizing or anoxic, exposed or sheltered from meteoric agents) as well as the rainfall regime of the area play also an important role. The presence of highly soluble sulfate minerals with elevated contents of many metals further underscores the significant influence of hydrothermal activity on elements' mobility. The sometimes very high concentrations in toxic elements like Al, As, Co, Cr, Ni evidence also a potential environmental impact.

S01.23 Poster

The CO_2 output from the Sperchios Basin area (central Greece): the role of hidden degassing from streams

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The Sperchios Basin is an actively spreading rift area with deeply rooted extensional faults and also a site of quaternary volcanic activity. Such geologic conditions favoured the formation of many hydrothermal systems, whose surface expressions are among the biggest thermal springs of the whole Greece. Degassing of deeply derived geogenic CO_2 is highlighted by strong bubbling within the main pools of the springs. Flux measurements were made in the Thermopyles spring with the floating chamber method and results showed that bubbling gases in the spring release about 1 ton/day of CO_2. The outgoing stream has a flow of more than 250 l/s of water rich in CO_2 (about 16 mmol/l). Although no bubbling is visible along the stream, after 300 m, the CO_2content decreases to 2 mmol/l, indicating an intense CO_2 degassing. This was quantified in more than 10 tons/day, suggesting that most of the degassing is not visible. Output estimations at the close by thermal springs of Psoroneria and Ypatis have not been made yet, but considering that the bubbling in their pools and the water outflow rates are similar, the CO_2 emitted will be of the same order of magnitude. Further contributions from the Sperchios area may come from the Kamena Vourla springs and from diffuse soil degassing. To sum up, the best estimate of the total CO_2 output of the studied area is in the order of many tens of tons/day. Such output is comparable to that of the single active volcanic systems along the South Aegean Volcanic Arc (Sousaki, Methana, Milos, Santorini, Kos and Nisyros) and it highlights the importance of hidden degassing along CO_2-oversaturated streams.

S01.23 Poster

Multidisciplinary study (CO_2 flux, ERT and self-potential surveys) in Fondi di Baia, Astroni and Agnano volcanoes: insights for the structural architecture of the Campi Flegrei Caldera (southern Italy)

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In the period 2016-2018 we analyzed through soil gas, self-potential (SP) and Electrical Resistivity Tomography (ERT) investigations some poorly-studied sectors of the Campi Flegrei caldera. We selected the Fondi di Baia craters located in the western side of the CF caldera, the Astroni crater and the minor caldera of Agnano both located in the central sector. The distribution of soil CO_2 flux anomalies, highlights a main degassing structure NNE-SSW oriented likely corresponding to the major eruptive fissure joining the three craters of Fondi di Baia and Baia. SP measurements indicate lower values (down to -75 mV) for the northern crater, where higher values indicate upflow of hydrothermal fluids. This different feature between the two craters is also marked by the N-S ERT profile that highlights a deeper structure for the southern crater. Also for the Astroni crater the CO_2 flux anomalies mark a main NW-SE structure characterized by low values because either a self-sealing by hydrothermal deposits or a high permeability diluting the gas flux by air. The comparison with the SP map highlights the main features permeated by fluids circulating into the subsoil, which well corresponds with the formations detected through a geoelectrical imaging of the shallower part of the crater. Within the Agnano caldera, the distribution of soil CO_2 flux anomalies highlights that main degassing occurs along E-W and possibly also along NW-SE structural discontinuities corresponding to those highlighted in the structural map and as also suggested by measures of SP. This study adds new information for the reconstruction of the volcano-tectonic buried structures in Campi Flegrei caldera, and their link with the circulation of hydrothermal fluid. It also suggests a multidisciplinary approach to better understand the active degassing structures in areas of the Campi Flegrei caldera without clear superficial signs of fumarolic and/or hydrothermal activity.

S01.23 Poster

Self-Potential, Surface Temperature, CO_2 measurements and related structural discontinuities on Mount Hasan, Turkey

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Mount Hasan (3253 m a.s.l.), a double peak stratovolcano is a member of Central Anatolian Volcanism and rises ~2250 meters above the basement. Today's stratovolcano, the neo- volcano Hasandağ, rises up on older paleo- and meso- volcanoes. Nearly 300,000 people are living in the vicinity of Mount Hasan. Therefore, risk related analytical investigation is essential on the volcano to determine the potential hazard.

Self-Potential (SP), surface temperature and CO_2 measurements have been carried out to reveal out the hydrothermal fluid circulation. Measurements have been conducted on five radial profiles descending from the summit and a long circumferential profile surrounding the base of the volcano; with a total length of ~93 km. Self-potential and surface temperature measurement were obtained at 25 and 50 meter intervals and CO_2 measurements were taken at 1 and 2 km intervals. Additionally, ASTER thermal infrared satellite imagery is used for a temporal investigation of surface temperature, surface temperature anomaly and relative radiative heat flux.

We have been able to observe hydrological and hydrothermal zones on the volcano and the typical "W" shaped volcano-electric signal has been well observed with a maximum of 3.8 V potential difference. The elevation / SP gradient (Ce-gradient) have been calculated to enhance the SP anomalies and to reveal out the structural control on the hydrothermal activity. Along with the hydrothermally active summit zone, Ce-gradient showed us that the buried caldera structures have control on the hydrogeological nature too. Hydrothermal zone starts above 2250 meters and above 3000 meters, fumaroles, hot-grounds and water vapour have been observed and measured. The highest temperature and CO_2value measured in the fumarole vents is 68.7 °C and ~10000 ppm respectively.

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Research on Mud Volcanoes in Xinjiang and Taiwan, China Based on Geochemistry Causes

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Mud volcano is a kind of structural geology phenomena under certain hydrogeology environment. The mud volcano is always related to the oil-gas belt. Gas and groundwater close to surface in some region, under pressure from underground, bring sediment to surface alone crack. There are different kinds of mud volcanoes, such as mud cone, mud shield, mud basin, mud pool and mud hole according to different mud consistence.

Mud volcanoes in China are mainly located in Xinjiang and Taiwan. Those in Xinjiang are located in the midwest region of Northern Tianshan, and five of them were representative, including Horgus, Dushanzi, Wenquan, Poplar vally and Sailetike. Poplar vally and Sailetike mud volcanos are the largest mud volcanic cluster in Asia. There are more than twenty mud volcanoes in Taiwan, mainly located in Gaoxiong and Hengchun, and seventeen of these are in activating stage. The geological feature of these mud volcanoes are very typical.

The author tested gas, fluid and solid components of mud volcanoes in the midwest region of Northern Tianshan from 2006 to 2012, and found geochemistry features of these mud volcanoes as followed:

1. Mud volcanoes in Horgus, Dushanzi, Poplar vally and Sailetike have similar geochemistry features, while it shows some significant differences in Dushanzi.
2. The gas component of mud volcano mainly is alkane gas with about 35.6%-72.0% except mud volcano in Wenquan.
3. The gas of mud volcanoes showed typical crust-derived helium with low $^3He/^4He$ and R/Ra value about 0.09~0.049.
4. The δ13C2 value of mud volcano is above 28‰, and both C1/C1-4 and δ13C1 value showed origin of gas is from lower-middle Jurassic coal measures rock.
5. The concentration of liquid ions in mud volcanoes near Mount Wushan in Taiwan is close to that of seawater.

Interaction of geothermal, tectonic, and magmatic processes in the Hengill area, SW Iceland: uplift and subsidence episodes at the roots of geothermal systems

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High-temperature geothermal fields owe their existence to magmatic supply (i.e. intrusions) and faults that provide high-permeability fluid flowpaths necessary for geothermal energy production. The Hengill area experiences crustal deformation from several interacting sources. Hengill is at a triple junction of the Eurasian-North American-Hreppar plate boundary, where the total plate spreading and shear is about 1.8 cm/yr. On top of the steady strain build-up due to plate motion, an intrusive episode between 1994 and 1998, sourced at

~7 km depth (near the brittle-ductile transition in the area), caused 2 cm/yr of uplift and tens of thousands of earthquakes - including several M>5 events. In 2008 two M6.1 earhquakes occurred at the eastern margin of the Hengill area. Geothermal production was greatly increased in 2006. The combined production is now 420 MW electricity and 430 MW hot water at Nesjavellir and Hellisheiði power plants in western Hengill, causing localized subsidence of up to ~2.5 cm/yr in areas of maximum extraction. Injection of residual fluids from the geothermal production cause localized seismicity, some accompanied with shallow transient deformation. In 2006, a much wider subsidence started in eastern Hengill, with total subsidence of about 12 cm between 2006 and 2018. This regional subsidence has been interpreted to be sourced at a similar depth as the 1994-1998 intrusion (~7 km), but in a slightly different location. There are signs of cessation of this wider subsidence in the end of 2017. Other high-temperature magmatic-hydrothermal systems in Iceland, such as Krísuvík (no geothermal production) and Þeistareykir, have shown somewhat comparable behavior of inflation-deflation episodes, while other systems have not during the last few decades. We focus here on the deformation history of Hengill and how it eventually relates to fueling of the geothermal systems, which generally require quite shallow (~2-4 km) intrusions for economic energy production.

S01.23 Talk

The shallow water submarine hydrothermal field off Zannone Island (central Tyrrhenian Sea, Italy): the impact of venting activity on seafloor morphology and benthic community

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The Zannone Hydrothermal Field (ZHF), located in the shallow-waters (<150 m wd) of the western Pontine Islands (Tyrrhenian Sea), represents a natural laboratory to study the mpacts of venting activity (mainly CO_2) at the seabottom and to evaluate their effects. The ZHF is located on the Ponza Zannone morpho-structural high and was studied using a multi- disciplinary approach (integrated analysis of video observations, high resolution multibeam bathymetry and seismic profiles, water, gas, sediment and rock samples).
Active venting was recognized in several locations by the observation of bubbles and gas plumes. The main seabed structures due to venting activity are five giant depressions located between -105 and -140 m that formed during the Holocene.
Other morphologies related to vent activity are small pockmarks, authigenic mounds and sulphur crusts. Active vents are diffusely colonized by bacterial mats, whereas areas influenced by fluid emissions are characterized by specific foraminiferal assemblages and peculiar agglutinated species able to cope with acidic condition (i.e. Spiculosiphon oceana). The geochemical signature shows active, CO_2-dominated degassing with a significant contribution of mantle volatiles ($^3He/^4He$ values >3.0 Ra), similar to those recorded in other shallow water areas of the Tyrrhenian Sea (Stromboli and Panarea islands). Geochemical analyses suggest that the vented hydrothermal volatiles are probably associated with residual magma batches, chemically similar to the Pleistocene trachytes cropping out at Ponza Island, that still provide thermal energy to the submarine geothermal system.
The vent activity at the ZHF seems to be controlled by the tectonic structures of the Ponza- Zannone structural high and fed by hot volatiles of magmatic origin. At present it is characterized by slow and diffuse degassing but in recent times it encompassed more explosive events. Finally, diffuse episodes of such activity have to be considered in terms of possible triggering mechanisms of shallow instability phenomena.

Systematic soil gas studies for volcano-tectonic analyses of the Los Humeros Geothermal Field, Mexico

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Mexico is known for its excellent geothermal resources. The Trans-Mexican Volcanic Belt (TMVB), is hosting two of the four geothermal production fields in Mexico used for power generation. One of them is the Los Humeros Volcanic Complex (LHVC), situated 180 km E of Mexico City in the eastern portion of the TMVB.
Experiences from the operation of the Los Humeros geothermal field indicate the existence of a superhot geothermal reservoir with temperatures > 380°C, however, geothermal fluids at such high temperatures could only be used to some extent for energy production, due to their aggressive physicochemical characteristics.

The focus of the study is on the structural control on migration pathways of hydrothermal fluids to identify and assess hydraulically active (permeable) fault segments or buried discontinuities along major fault zones. Especially in low permeable reservoirs, fault zone architecture and its permeable structures form primary controls of fluid flow.

Techniques for soil gas measurements provide important tools for the qualification and quantification of volcanic gases. During the first field campaign in 2017, 2600 CO_2 flux measurements were taken in an area of 3x6 km based on a regular sampling grid within the caldera. At selected sites d13C isotope samples were collected to distinguish between biogenic and geogenic origin of CO_2 flux anomalies.
Based on these results a large-scale sampling grid was developed for Micro Gas Chromatography (CO_2, N_2, O_2, CH_4, H_2, etc.) and alpha-particle spectroscopy ($_{222}$Rn, $_{220}$Rn). Furthermore, samples have been taken for isotopic analyses of $_3$He/$_4$He ratios for the identification of possible mantle signatures.
The goal of our systematic and area-wide approach is to put surface gas emissions and soil gas concentrations in the spatial context to the geothermal-volcanic system for a comprehensive understanding of fluid migration in the subsurface.

S01.23 Poster

Mass and stress balance continuous monitoring in volcanic geothermal fields: integrated observational approach for exploration drilling

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In volcanic and hydrothermal geosystems, the observation of mass and stress changes provide us with better volcanic hazard assessment to mitigate the risk and a better estimation of geothermal resources to sustain our energy needs. The estimation of such processes on active volcanic systems is challenging; the exploitation of geothermal volcanic systems address similar processes with less danger and with better constrained boundary conditions.

With combined continuous gravity and ground motion recording, we address mass and stress changes within geothermal reservoirs in relation with external solicitations (reservoir exploitation) and natural forcing (local and regional earthquake activity and earth tides). This contributes in knowing the reservoir properties, structure and long-term behaviour. The expected gravity amplitudes are small (e.g., <1 to 100s microgal, 1 _gal=10e-8 m.s-2). We therefore use high performance instrumentation such as broadband seismometers and superconducting gravity meters; all other parameters that may affect the records (deformation, hydrological parameters, pressure, temperature, snow height...) are also monitored. We deployed in December 2017 a network of gravimeters (3 iGrav superconducting gravimeters and 2 gPhone spring-meters), supplemented with tilt-meters, GNSS receivers (complemented with InSAR analysis), hydro-meteorological stations, snow height observation instruments, piezometers in shallow boreholes, ... Additionally, we performed absolute gravity measurements (FG5), and a repetition gravity network was set-up and measured several times since the summer 2017.

Theistareykir (Northeast Iceland) geothermal system is at early stage of exploitation. After being used for power production (90 MW), all extracted fluids are re-injected. We present here the site, the infrastructure, the instruments deployed and preliminary results. Our goal is to demonstrate that we can monitor and interpret integrated high quality data for a better understanding of magmatic and hydrothermal reservoirs in order to prepare and optimize future highly challenging exploration aiming at drilling into magma.

S01.23 Talk

A geochemical aspect of the recent activity of Mt. Iwo-Yama, Kirishima volcanoes, Japan

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Mt. Iwo-Yama belonging to the Kirishima volcanoes has erupted for the first time in 250 years in April 2018, and its activity is likely to continue at least for next few years. Ebino Highland adjacent to Mt. Iwo-Yama is a famous tourist destination in a southern part of the Kyushu Island. The recent activity of the volcano strongly affects the regional economy including tourism.

The recent activity of Mt. Iwo-Yama started with the opening of fumaroles on the crater area in December 2015. After that, an expansion of fumarolic area toward adjacent highland area has been observed accompanied with increasing of the activity. Meanwhile, several thermal springs have emerged in the highland area. The changes in the water chemistry, especially in the concentration ratio of chloride to sulfate, of those thermal springs seem to be in good accordance with the seismic and tectonic activities around Mt. Iwo-Yama.

With the phreatic eruption in April 2018, muddy high-temperature water spouted out from the newly opened crater resulting pollution in the downstream river. The muddy water is extremely high in acidity and concentrations of chloride and sulfate with a remarkable amount of arsenic. Also, it contains fluoride, boron and several heavy metals in relatively high concentration. The mud from the crater is mainly composed of grayish argillaceous particles suggesting that it is originated from highly-altered zone contacted with geothermal fluids beneath the volcano. Physicochemical characteristics of the muddy water help us to understand the shallow geothermal system of the volcano.

Coupled field-experimental approach to establish trigger factors and dynamics of large hydrothermal eruptions at the Rotokawa Geothermal Field, New Zealand

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Hydrothermal eruptions triggered by explosive vaporization of water are a common phenomenon occurring within geothermal fields. Sudden blasts are caused by complex, yet poorly discernible changes in field dynamics due to: human operations, weather, slope movements, tectonic events, fluid circulation, rock fracturing, and alteration. In New Zealand, where many geothermal fields are exploited for renewable power generation, the risks from hydrothermal eruptions are huge. At Rotokawa Geothermal Field a stable base-load power (174 MW) is generated 24/7, making it a critical national facility supporting New Zealander communities and industry. Recognizable hydrothermal breccia deposits indicate at least thirteen large eruptions at this site over the last ~20,000 years, representing a likely ten-fold frequency of smaller events that could disrupt operations and threaten lives.

A combined field-experimental approach is here used to test actual triggers and dynamics of the largest eruptive event known at Rotokawa (~6060 years ago), which erupted a breccia over an area of ~12 sq km, reaching up to ~11 m-thick. Erupted lithologies within the breccia, representative of the exploded host rocks were analyzed for their petrophysical, textural and petrological properties in relation to alteration type/intensity, and served for reconstruction of the dynamic properties and eruption depth(s). Breccia samples were then rapidly decompressed from elevated pressure-temperature conditions using the fragmentation bomb at LMU, mimicking a Rotokawa-like eruption triggered by sudden perturbation of the hydrothermal system (e.g. seismic induced fracturing of shallow/cap rocks). Experiments allowed to further explore eruption-controlling parameters as geological variation, rock alteration, fracture types and water/steam pressure. Moreover, fragmented particles were recovered for analysis and comparison to field settings.

By using a range of differently altered and pre-fractured lithology, as well as varying decompression rates, we attempt to estimate the conditions fueling this massive ~6060 years-old eruption.

S01.23 Talk

The 2018 February-April unrest phase at La Soufrière of Guadeloupe (French West Indies) andesitic volcano: deep magmatic fluid transfer into the hydrothermal system and dome-structure modulation

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After 25 years of gradual increase, unrest at La Soufrière of Guadeloupe reached its highest seismic energy level on 27 April 2018, with the largest felt volcano-tectonic (VT) earthquake (M4.1) recorded since the 1976 phreatic eruption. This event marked the onset of a third seismic swarm (180 events, 2 felt) following a swarm on February 1st (30 events, 1 felt) and April 16-17 (140 events, 1 felt). Many events were hybrid VTs with long-period codas, located 2-4km below and clustered within 2km of the volcano along a regional NW-SE fault cross-cutting La Soufrière. Swarm Elastic energy release increased with each swarm whereas inter-event time shortened. During this period, summit fractures continued to open and thermal anomalies extended. Fumarole fluxes increased significantly until 20th April reaching a maximum of 80m/s and 111°C, before declining slowly after 22nd April to ~95°C and ~30m/s. Gas compositions revealed increased, high C/S and CO_2/CH_4 ratios and track hydrothermal P-T conditions that reached the critical point of pure water several times. High-frequency MultiGAS data revealed increased CO_2/H_2S ratios and SO_2 contents. Portable MultiGAS data identified the reactivation of degassing fractures (T=93°C, $H_2S/SO_2 \approx 1$). Although there is no evidence of upward magma migration, we infer that a major injection of magmatic fluid heated and pressurized the hydrothermal system, compatible with GNSS horizontal displacement of 5-7 mm/y (1995-2015) within 1km from the dome. This triggered seismogenic hydrofracturing, basal spreading of the dome's SW flank, and likely induced changes in deep hydraulic properties (permeability) and drainage pathways, ultimately lowering fumarolic pressure. Although this injection was modulated by the hydrothermal system during unrest, the unprecedented seismic energy release and recurrent critical point conditions of hydrothermal fluids suggest that non-magmatic explosive activity could occur in the future should similar unrest phases reoccur. An evolution towards magmatic conditions cannot be excluded.

A geochemical reappraisal of the hydrothermal system of La Soufrière of Guadeloupe (French West Indies) with implications for unrest

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We have re-assessed the main physicochemical features of the hydrothermal system of La Soufrière of Guadeloupe (FWI) andesitic volcano. We applied gas geothermobarometry and tested different hypotheses, particularly for redox conditions. The investigation on recent fumarolic samples benefited of independent analyses of the ^{13}C exchange between CH_4-CO_2 and isotopic geothermometery. A careful analysis of different techniques adopted historically for gas sampling and analysis by OVSG has allowed us to extend the use of our thermodynamic modeling back to the last 20 years. We then tracked the evolution of P-T conditions of the gas equilibrium zone within the hydrothermal system, often reaching or slightly exceeding critical point conditions. Our results show that long-term P-T fluctuations characterize the behaviour of the hydrothermal system in relation to injections of more magmatic deeper-sourced fluid into the hydrothermal system. This is also corroborated by concomitant fluctuations of halogen species recently determined in alkaline samples as well as condensates. Whether such long-term P-T increases reflect pulsatory behaviour of the deep source injecting fluids upward, or are due to the modulation determined by the dome's structure via the many structures dissecting the dome and relaxing the accumulated tensions, is matter of the ongoing investigations. Given the ongoing deformation recorded on these structures, recurrent strong seismic unrest, and the possibility of outside forcings (regional strong earthquake, extreme rainfall) on the overheated and pressurized hydrothermal system, scenarios that could lead to sudden decompression of critical fluid must be considered in monitoring strategies and risk analysis.

S01.23 Poster

Hazards from endogenous gas emissions at horizontal drillings for water exploitation in Tenerife, Canary Islands

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Groundwater, the most important water resource in the high islands of the Canaries, is intensively developed through horizontal and vertical works. To extract the water, traditional perforation methods consisted on: (i) Galleries or horizontal drillings, more developed in Tenerife, and (ii) wells. Water galleries are sub-horizontal tunnels, some excavations reach up to 6 km long. Tenerife is riddled with 1051 galleries, totalling ~1700 km, and 393 wells. These provide an exemplary resource for subsurface science, yet entering water galleries is difficult and not without serious risk. Hazards include the often small section, possibility of wall/roof collapse, high temperatures at close to water saturation air humidity, and in many cases the presence of high amounts of volcanic gases, mainly CO_2. In this study we show that volcanic rifts and dykes play an important role in the hydrodynamics of the island. Dikes and fractures are usually parallel to the volcanic rifts, facilitating longitudinal flow, and considerably reduce transversal flow. At the same time they facilitate the rising of magmatic gases, representing an important hazard when magmatic gases accumulate in the galleries. Since exploitation of groundwater resources in Tenerife started, more than 20 people have died due to exposure to high concentrations of volcanic gases. In February 10, 2007, a fatal incident occurred inside "Piedra de los Cochinos" gallery, when six walkers asphyxiated. Due to this accident, and since 2011, the Mining Service of the Canary Islands Government has permanently closed 117 water galleries and wells in the Canary Islands, most of them in Tenerife. By understanding the hydrogeology, lithology and the architecture which the galleries themselves facilitate detailed study of better hazard mapping and monitoring can be achieved.

S01.23 Poster

Influence of regional and volcano- tectonic features on Las Tres Vírgenes hydrothermal system, Baja California Sur, Mexico

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The Tres Vírgenes geothermal field, located in the Santa Rosalía basin, Baja California Sur (Mexico), is the fourth largest producing geothermal field in Mexico (Gutiérrez-Negrín 2015). The Tres Vírgenes region comprises three volcanic centres (from oldest to youngest): La Reforma caldera (1.38 Ma), Sierra Aguajito (1.17 Ma) and Las Tres Vírgenes (Middle Pleistocene-Holocene, Schmitt et al. 2006). Field surveys conducted during 2015-17 in the area resulted in mapping of hydrothermal alteration, mostly occurring along faults and more pervasive in the Sierra Aguajito area. Several fault-rock samples were collected along major regional lineaments, on minor faults and volcano-tectonic features in order to quantify the influence of regional and local features on the volcanic hydrothermal system. Distinct ignimbrites were sampled to characterize the overall permeability of the volcanic area (Vignaroli et al, 2015). Ongoing work includes micro-structural analysis, image analysis, diffractometer analysis and permeability tests on whole rock samples. Analysis of fault-rock samples confirmed the general transtensive regime characterizing the Santa Rosalía basin, characterized by shear planes offsetting crystals/lithics with a strike-slip kinematics, fractures and veins at constant angles with respect to the shear zone (0°, 30°, 45° and 60°) and local rhomboidal, pull-apart or en-echelon geometries developed by veins or fractures. Hydrothermal alteration occurs either as veins or as mineral patches (amygdale, possibly laumontite). In some cases, hydrothermal alteration develops argillitic alteration bands, where quartz and plagioclase phenocrysts are usually crosscut by veins and fractures but still maintain sharp borders (no reabsorption), while pumice and lithics appear pervasively altered and hardly recognizable, suggesting low temperatures (100°C) for hydrothermal alteration, that usually proceeds parallel to the overall shear direction of the fault. The largest abundance of 'big-sized crystals' calcite veins was found along major regional faults, indicating the key role of regional structures in promoting the interference between magma and sediments.

Mineralogical, geochemical and isotopic characterization of the hydrothermal sites at Ischia island (southern Italy)

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The island of Ischia, lying north-west in the Bay of Naples, along with the Phlegrean Fields and Vesuvius, forms a quiescent volcanic area belonging to the alkali-potassic Quarternary Roman Province, Italy.

The geological features of Ischia derive by ca. 900 m of intra-caldera resurgence in the last 33 ka, volcanic episodes (the last of which at 1302 AD), and hydrogeological and flank instability. The setting also characterizes for thermal springs, endogenous degassing and a high heat flux, at the basis of the local resource. Hydrothermal activity appears correlated with tectonic elements. They occur particularly in the northern, western and southern slopes of the Mt Epomeo resurgent block, just along its marginal faults driving the rapid uplift. The endogenous supply is a shallow magmatic system and the associated seawater-dominated high temperature geothermal system.

This contribution concerns with sulfur-bearing minerals, efflorescences and hosting terrains from selected hydrothermal sites. Neo-mineralizations are useful tools to define type and evolution of hydrothermalism, also providing keys to understand the volcano dynamics.

Mineral assemblage, texture and chemistry were determined by X-ray diffraction, electron microscope, and bulk and in- situ geochemistry. ^{34}S compositions were determined on separated sulfur-minerals. Alunite is the main phase, followed by alunogen, sulfur and K- alum. Other minor sulphates are gypsum, pickeringite, halotrichite, coquimbite, tamarugite and voltaite. Kaolinite and illite/montmorillonite constituted the clay components.
The neogenesis can be related to a leaching alteration action of the substrate rocks, with residual enrichments in Al, Cr, Fe consistent with the observed mineralogy. Our results when compared with literature data provide interesting ideas useful in a variety of disciplines such as: i) geological, i.e., the understanding of physico-chemical properties of rocks and their behavior, ii) archeological, i.e., alum production and marketing in the medieval times, iii) volcanological, i.e., the setting of the volcano and its possible behaviour.

CO_2 and radon distribution in the groundwater of Rome (central Italy); evaluation of Natural Gas Hazard in a densely populated area

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The city of Rome is located in the Roman Comagmatic Province (central Italy), where large sectors are affected by a huge CO_2 degassing from both soils and aquifers. CO_2 is produced at depth (mantle and/or decarbonation processes) and upraise towards surface through fault and fracture systems; it partly dissolves in shallow aquifers depicting wide CO_2 -rich water areas. When aquifer is gas-saturated CO_2 can reach surface, permeating soils. Furthrmore, U and Ra-rich volcanites outcrop, being important radon-sources; as a consequence, both high levels of radon in soils and ground waters can be found. Gases exhaled from soils and aquifers can enter houses, potentially reaching harmful indoor levels, creating a big concern for the local population. Accordingly, an evaluation of the level of Natural Gas Hazard (NGH) in densely populated areas, must be done.

We assessed the NGH level in the urban area of Rome, where about 2500000 people habitually live, through an extensive geochemical study in groundwater (around 240 samples). Dissolved CO_2 and radon distribution in groundwater, along with isotopic characterization of total carbon (i.e. carbon dioxide) to determine its origin, were assessed. High pCO_2 waters emphasised the presence of five sectors actively degassing in Rome. CO_2 isotopic characterisation of these waters point out a deep provenance of carbon dioxide, as recognised in the natural gas manifestations of Central Italy. Conversely, CO_2 -poor waters have an isotopic signature highlighting an organic (i.e. shallow) provenance of CO_2.
Radon-rich waters mainly reflect the outcrops of U and Ra-rich volcanites; they were recognised in the southern sectors of Rome where thick Alban Hills volcanic products largely outcrop.

In the identified NGH-prone areas, both CO_2 and radon indoor level surveys must be promoted by local authorities, mainly in the most populated sectors, where the presence of these gases in dwellings could represent a very big concern for people’s health.

S01.23 Poster

Ash time series from the 2017 eruption of Mount Agung, Bali

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After more than 50 years of repose, Mount Agung in Bali erupted explosively on November 21st 2017. The subsequent explosive eruptions on 25-27 November 2017 had increase intensity. Ash deposits on the southeast flank and northeast sides of the volcano were sampled respectively on 21, 25 and 27 November 2017. We analyzed two grams of each sample by using SEM (FEI Quanta series FEG-650) in order to classify particles into lithologic and textural categories (components). We find differences in compisitions and morphological characteristic of the ash particles. The ash sample from the initial eruption on November 21st was dominated by hydrothermal altered rock (>90%) with a smaller portion of juvenile material (<5%) suggesting a phreatomagmatic explosive mechanism i.e. rising magma came in contact with hydrothermal altered rock. The November 25th and 27th volcanic ash samples showed larger portions of juvenile (< 40%) and lithic (<55%). Ash samples contain glass with a few primary crystals covered by a lot of secondary minerals. Widely varying clast vesicularities reflect complex variations in the relative timing of vesiculation and water-induced fragmentation and become more uniformly in the range of 70% regardless of magma viscosity. We also analyzed the ash composition using the WDXRF PANalytical Axiosmax PW4400. The silica content varies during the 21-29 November 2017 eruption period from 55.43% (basaltic-andesite) to 59.56% (andesite), consistent with a change in erupted componentry. Our analysis indicates that the componentry of ash evolved as the eruption progressed, with increasing amounts of juvenile material and a decrease in hydrothermally altered material.

Keywords: Agung volcano, eruption, volcanic ash, phreatomagmatic, juvenile, lithic, bubble wall.

Outgassing of mantle fluids across an tectonically active crustal segment in between two volcanic systems (Etna and Aeolian arc): the Nebrodi-Peloritani case

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Mantle-degassing occurs primarily through active volcanic systems and young oceanic lithosphere. Mantle-volatiles are also released by tectonically active continental regions, but the magnitude of this phenomenon is far less characterised. Helium (He) is a powerful tracer to track deep volatile degassing, because the mantle contains more ^{3}He than the crust/atmosphere systems, which are dominated by radiogenic ^{4}He produced in the crust.

Here, we studied the volatiles in thermal manifestations discharged along the Nebrodi- Peloritani chain in north-eastern Sicily, with the aim of investigating the origin of thermalism and the related fluids. Thisseismically active region connects the African- SicilianMaghrebides to the SouthernApennines, and its geological evolution has been controlled by the convergence between the European and African plates, as well as by the subduction of the Ionian slab beneath the Tyrrhenian crust

Water and gas samples,collected throughout the study area, exhibit a ^{3}He excess that is evidence for an active outgassing of mantle-derived volatiles. The computed mantle-derived He fluxes are up to 3 orders of magnitude higher than those typical of stable continental areas.We argue that these high fluxescannot be sustained by diffusion through the crust, but rather require deep fluid transport via advection through the regional tectonic discontinuities. The area, despite being a chain, is located between two most active volcanic systems, Mt.Etna to the south and the Aeolian arc to the north. Geophysical observations and models support the existence of toroidal flows in the mantle that bypass the subduction plate and produce a mantle rise below the studied area, and are thus consistent with the presence of magma accumulation at the mantle-crust interface, or even in the crust. Our study suggests a) the possible presence of magmatic intrusions below this sector of the Maghrebian-Apenninic chain, and b) the active role played by regional discontinuities in transferring mantle fluids towards the surface.

Impact of volcanic degassing on groundwater quality at El Hierro Island (Canary Islands, Spain)

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El Hierro is the youngest volcanic system of the Canary Islands archipelago. The island is made up mainly of basaltic lavas and is currently active. The last eruption in 2011-2012 was submarine about 1.5 km off its southern coast. In this work we report on a hydrogeochemical study of the aquifers of El Hierro. Dissolved gas compositions clearly indicate a magmatic input. While CO_2 contents are not particularly elevated (pCO_2 < 0.11 atm), He shows high concentrations and isotopic values (R/Ra 2.59-7.99). The chemical composition (mostly bicarbonate-alkaline and bicarbonate-earth alkaline) and pH (7.05 – 10.67) of the groundwater is mainly controlled by the volcanic gas flux and the degree of water-rock interaction. Secondary contributions to the water chemistry derive from mixing with sea water (generally from sea spray) and anthropogenic contamination (primarily from fertilizers application). The intense water-rock interaction allows the release of many trace elements (Fe, As, Mn, Li, Se, Cd, U, Zn, Ba, Rb, Cu and V). Particular attention is given to the high concentrations (up to 258 µg/l) of Vanadium dissolved in water of El Hierro. Such high concentrations derive from the high Vanadium contents of the aquifers rocks and the chemico-physical conditions (slightly alkaline and oxidizing) that favours the solubility of this element in the groundwaters of El Hierro.

S01.23 Talk

Subsoil-complexity and its implication for degassing processes and ground surface variations at Rotokawa geothermal field, New Zealand

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Surface expressions of hydrothermal systems (e.g. mud-pools, fumaroles, collapse or explosions craters) are manifold, highly complex and do vary significantly over space and time. Often such features represent major tourist attractions as for instance in Yellowstone (USA), Solfarata (Italy), or Wai-o-Tapu (NZ). Similar landscape also dominate areas exploited for geothermal energy as e.g. at Rotokawa Geothermal Field in New Zealand. For this valuable power resource (174 MWe capacity), the presence or formation of geothermal features may represent a significant threat to both safety and operability.

Here, we report results from a field campaign designed to characterize the properties of the subsoils at the Rotowaka steamfield. The main surficial lithologies correspond to the 1800 years-old Taupo pyroclastic deposits covering most of the geothermal field. The steamfield is characterized by a complex pattern of surficial alteration, and its surficial manifestations results from an interplay of natural hydrothermal degassing features, and effects of mining activity occurred in the past decades. The survey included in situ physical (temperature, humidity) and mechanical (permeability, strength, stiffness) measurements of subsoil levels, as well as mapping of the surficial hydrothermal features and their distributions. The subsoils are locally dominated by levels showing an alternation between very high and low permeabilities, which seems to affect both the temperature distribution and surficial degassing. A large range of surface temperatures (18-95°C) has been measured across the upper 1-2m, steepest gradients can be linked to the formation of impermeable layers, often (sinter or sulfur) crusts.

Rotokawa, with its large variability of geothermal feature, and its complex relation between natural and anthropogenic effects, is an ideal exemplar to investigate how alteration processes may affect the permeability and strength of the near-surface environment, which may result in sinkhole-collapse craters, or in worst cases, can produce pore pressure augmentation that may trigger explosive events.

S01.23 Poster

Contrasting SP Anomalies at Fumarole Zero, White Island, New Zealand

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White Island, in the Bay of Plenty, NZ is the emergent summit of a submarine stratovolcano that lies on the offshore north-eastern tip of the Taupo Volcanic Zone. The island hosts a well-developed hydrothermal system, including a hyper-acidic crater lake, acid springs, and energetic fumaroles. It is the most frequently active volcano in New Zealand with multiple phreatic and phreatomagmatic eruptions occurring in recent decades. Constraining subsurface flow dynamics within the hydrothermal system is critical for understanding volcanic processes to improve monitoring and eruption forecasting.

In July 2017, we undertook an electrical self-potential (SP) survey at White Island. The survey focused around the vigorously degassing Fumarole 0, which is thought to represent a direct degassing conduit from the magma reservoir. We measured four linear arrays, approximately 100 meters in length, arranged in a spoke-like pattern centred around the fumarole. Preliminary results show a positive SP anomaly near the fumarole with progressively negative values moving radially outward. The low positive values (<10 mV) imply some hot upflow of fluid near Fumarole Zero. However, negative values (>-125mV) suggest some interplay of cooler downflow and changes in salinity and gas saturation in the subsurface.

A similar radial survey was taken in September 2015, just months before the last eruptive episode. Interestingly, those results show the opposite pattern with negative anomalies adjacent to Fumarole Zero and progressively more positive values moving away. Considering recent advancements by Christenson *et al*. (2017) modelling the evolution of the hydrothermal system at White Island based on geochemistry, this work explores the implications of these opposing results for interpreting SP anomalies in active, high temperature, volcano-hydrothermal systems.

S01.23 Poster

Seismic and electrical signals are correlated during rise of magma in the Ubinas volcano, Perù

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The Ubinas volcano, considered the most active in Peru, is permanently monitored using various geophysical methods. The seismic monitoring corresponding to the March- December 2016 period reveals a pattern in the evolution of seismic activity; we identify four main stages: Stage A is presumed to indicate the end of the previous eruptive process (2015). Stage B is characterized by the presence of "tornillo" events that would indicate pressure and fluid passage in a resonant cavity. During stage C, there was an increase in proximal volcano-tectonic and hybrid earthquakes, the latter indicating that the rise of magma is almost at the end of its path to the surface. Finally, in stage D, five explosions occurred. On the other hand, between September and November 2016, a continuous record of Self-Potential (SP) was also obtained on a site located on the upper part of the northwestern flank. The recording highlights a positive SP anomaly that occurred between September 9 and 14, which correlates with the increase in the number and energy of the Hybrid earthquakes in those days. Both SP and seismic signals of hybrids and their correlation is interpreted as a result of the rise of magma, i.e. the hot material that rises not only generates hybrid events, but also causes temperature rises in the environment of the hydrothermal zone, thus being the cause of the anomaly observed at SP recording.

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S01.24 - Volcanic Islands from hazard assessment to risk mitigation

Hazard and risk assessment at Reykjanes, vulnerability of infrastructure

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Volcanism in Iceland is affected by the North Atlantic plate boundary and the hot spot underneath the island. The Reykjanes peninsula, in SW Iceland, has five volcanic systems with SW-NE orientation, where volcanic activity occurs in episodes, with roughly 600-750 years between periods of activity. The last volcanic period started in the east part of the peninsula around AD 700 and propagated westward, ending in the Reykjanes fires 1210-1240. Historical records exist on the last volcanic episode. The peninsula has been mapped in details and indicates at least some 16 historic lava flows. The eruptive activity of Reykjanes peninsula is characterised by fissure eruptions on land. In one case the fissures extend into the sea generating phreatomagmatic eruptions. The main hazard associated with fissure eruptions are lava flows, gases, and tephra fall (in case of phreatomagmatic activity). The Reykjanes peninsula is highly populated with over 70% of the Icelandic population (total population in Iceland being 348450). The main international airport for Iceland is on the edge of the westernmost volcanic system, where over 98% of all tourists come through. Further the towns of Reykjanesbær, Grindavík, Garður, Hafnir, Sandgerði and Vogar are located on the edge of this volcanic system. To analyse the volcanic hazards in the area we use probability density function and susceptibility analysis. The area with highest probability of a vent opening was analysed in relatation to the location of the urban areas along with the critical infrastructure such as power lines, telecommunication, and transportation system, as those play a crucial part during volcanic crises. The result of this work shows that the westernmost part of the peninsula can be divided to hazard zones that help for future mitigation and land planning.

S01.24 Poster

The GPS network of INVOLCAN for the volcanic surveillance of Canary Islands

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Since 2004, Instituto Tecnológico y de Energías Renovables (ITER), in collaboration with the University of Nagoya and GRAFCAN, is monitoring Canary Islands with a network of differential GPS stations. Since its creation in 2011, Instituto Volcanológico de Canarias (INVOLCAN), started coordinating the collection and the processing of the data of the INVOLCAN's GPS Network.

Currently the network consists of a total of 35 stations distributed over the Canarian Archipelago: 5 on La Palma, 6 on El Hierro, 1 on La Gomera, 12 on Tenerife, 4 on Gran Canaria, 4 on Fuerteventura and 3 on Lanzarote. The network is composed both of Leica and Ashtech stations. Data of ITER and Nagoya Univ. stations are collected daily through UMTS connection.

All the data are processed to retrieve daily solutions, using Bernese 5.2 processing environment. The processing is performed weekly, using preliminary IGS orbit data, with the purpose of redacting an informative summary of the volcanic activity: GUAYOTA (www.involcan.org/guayota). Once final orbit data are available at IGS, data are reprocessed, inserted into a MySQL database and published on monthly bulletins (www.involcan.org/boletinmensual).

INVOLCAN GPS Network was used during the eruption of El Hierro, 2011-2012, to monitor the deformation due to magma movements before, during and after the eruption. Furthermore the long term time series provides useful information about the geodynamics of the Canarian Archipelago.

S01.24 Poster

Development of the Red Sísmica Canaria (C7) or the volcanic surveillance of Canary Islands

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Since November 2016, Instituto Volcanológico de Canarias (INVOLCAN) started the deployment of a broadband seismic network on Canary Islands: Red Sísmica Canaria (RSC) (FDSN code C7; http://doi.org/doi:10.7914/SN/C7) with both scientific research and volcano monitoring purposes.

The network started with the installation of 15 broadband stations acquired throught the MAKAVOL project (MAC/3/C161) in Tenerife and Gran Canaria islands. Data are sent in real-time through UMTS connection to an acquisition center located at ITER where they are processed, stored and managed through a SeisComPro installation. Real-time seismograms and hypocenters are shown at the INVOLCAN monitoring center.

This first nucleus of the network was devoted to the monitoring of volcanic seismicity of Tenerife Island. It was able to record the increase of the seismicity in 2017, because of a pressurization of the hydrothermal system of the island, testified by the 5-fold increase in the diffuse CO2 emission from the crater of Mt. Teide volcano (Tenerife).

Another improvement of the network was the acquisition of 15 more broadband stations in the framework of the VOLRISKMAC project (MAC3.5b/124; http://volriskmac.com). These new stations were deployed on Tenerife, El Hierro and La Palma islands and will be deployed on Gran Canaria and La Gomera islands as well. The first 5 stations on La Palma were deployed during the October 2017 seismic crisis, related to a sub-crustal magmatic intrusion beneath the magmatic system of Cumbre Vieja volcano.

We show the temporal variation in the network performances, both in terms of minimum magnitude of detection and uncertainty in the hypocentral location.

Improving the understanding on the origin, evolution and potential hazards of the Chilean Volcanic Oceanic Islands and Seamounts

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Volcanic Oceanic Islands and Seamounts (VOIS) related to hotspots are one of the best settings to study mantle-surface interactions. Their geological and geomorphological evolution is closely linked to competing processes during alternating and/or coeval periods of construction and destruction that results from the balance among volcanism, intrusions, tectonics, subsidence/uplift, mass wasting, sedimentation, and subaerial and wave erosion.

VOIS are relevant because they host especially vulnerable ecosystems when face volcanic eruptions and other geological hazards. For those populated, volcanic eruptions may have a significant impact on local populations, infrastructure, economy and biota. Emissions from VOIS could have even an impact on the global climate and the ocean geochemistry. Related geological hazards extend beyond the eruptive activity (e.g.: catastrophic landslides). It is therefore fundamental to know how these VOIS form, evolve and are dismantled, in order to know what potential processes can be expected in the near future.

We present a new project focused on the main VOIS of Chile: Easter Island and Juan Fernandez Archipelago, where little is known in detail about their geomorphological evolution and controlling factors such as (1) the history of island emergence and subsidence, (2) the magnitude of the vertical movements involved, (3) rates of growth (due to intrusions and eruptions), and (4) erosion rates.

This project aims to better understand the interplay between the more relevant processes that influence their evolution, and to propose a unified model for oceanic island evolution. The main effort of this project will be to understand what are the main controlling factors involved in the geomorphological evolution of the Chilean VOIS, and in particular to test the hypothesis of that vertical displacement is mostly controlled by high growing rates during the shield stage and by enhanced erosion rates during the subsequent quiescence period in more mature islands.

Monitoring a volcanic island: the case of the August 21th 2017 Md=4 Ischia earthquake

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The Ischia island, in the Gulf of Naples, has an eruptive history characterized by the occurrence of explosive and effusive eruptions, as well as by caldera collapses phenomena and resurgence processes. Its last eruption, a lava flow one, occurred on 1302. A caldera resurgence phenomenon generated the Mt. Epomeo horst, settled in the centre of the island.

The first instrumentally recorded damaging earthquake located in the island occurred on August 21st 2017 and had Md=4 (Mw=3.9).

The event caused 2 casualties, 42 injuries and extensive damage to the Casamicciola Terme town and its surroundings, along the northern structural rim of Mt. Epomeo; it was followed by a seismic sequence of almost 20 earthquakes with significantly lower magnitude.

The Md=4 earthquake features were studied through a multiparametric geophysical approach that allowed to retrieve the seismogenic scenario in agreement with the rheological stratification of the crust in this zone.

Even though this earthquake represents a positive scientific example in term of geophysical, geological and volcanological studies inspired by this event, at the same time may also represent the classical example of the technical difficulties in monitoring an island.

Since the installation of the seismic network (roughly 20 years ago), approximately less than 20 micro-earthquakes (Mdmax=2.4) were been recorded and located in the area before the Md=4 occurrence. The lack of instrumental records significant from a statistical point of view as well as some technical problems related to the transmission of part of the signals caused the uncertainties related to the first locations of the Md=4 event.

However, with a prompt reaction, our Institute organized a lot of geological, volcanological, geophysical and geochemical on-field studies that allowed us to collect a huge volume of data that greatly help in the improvement of the monitoring of the area.

S01.24 Talk

Seismicity, volcanic history and flooding of Ischia Island (Southern Italy) for the assessment of geological risk

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The Ischia island may be a laboratory for volcanic, seismic and hydrogeological risks assessment, from which to draw lessons for integrated planning in risk areas. In fact, the Island is a volcanic field, formed by the succession of eruptions with different mechanisms, powers and risks; the seismicity, dated back since Greek colonization (VIII century B.C.), has been characterized by the occurrence of shallow depth and high intensity earthquakes; and finally, the succession of rock layers with different permeability, promotes, during heavy rainfall, flows with high kinetic energy and devastating landslides.
The geological risks at Ischia are significant, due to a remarkable development of settlements and to unsuitableness of planning that bring attention to the vulnerability of the area.
Eruptions: The Island is formed by volcanic rocks deriving from eruptive centres largely destroyed or covered by subsequent activity and resurgent phenomena; the most recent eruption occurred in 1302. A zoning for future events is proposed.
Earthquakes: Historical seismic activity (1228-1883) and the last earthquake occurred on 21st August 2017 after a secular seismic silence show the low magnitude and high intensity of the events. The comparison between the distribution of the damage produced by the 1883 catastrophic earthquake, the epicentre distribution of historical seismicity, the tectonics and the present urban development provide the level of risk and its zoning.
Floodings: Historical informations about floodings arise from the XVI century. A well known disastrous event occurred in 1910; it was generated by an elevated atmospheric instability due to the presence of cold air at high altitude. The last more meaningful landslides were recorded in the 2006 and 2009 in south-eastern and northern sector of the Island respectively. The map of flood zoning points out that the main mud-flow sources are located in the Mt. Epomeo massif.

Problems in seismological monitoring of volcanic islands

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The seismic monitoring of volcanoes poses specific issues because of the network geometry which, often, does not allow high quality locations of the off-shore seismicity. In the case of seismic networks distributed on archipelagos, a further problem arises from the uneven distribution of the seismic stations, which can bias the hypocenter locations.

We propose different strategies to improve the quality of earthquake location on volcanic islands and archipelagos. The first is to include the amplitude information within the location algorithm. Although being not a new idea, we propose a novel non-linear approach, designed to operate also in low signal/noise ratio conditions. Furthermore, applying a singular value decomposition approach, similar to that proposed by Bondar and McLaughlin (2009) but extended to a non-linear location procedure.

We applied this method to both synthetic data in realistic conditions as well as to actual data recorded by Red Sísmica Canaria, managed since 2016 by INVOLCAN, for the location of earthquake in the surroundings of the island of Tenerife (Canary Islands).

Numerical simulations of landslide- induced tsunami at Stromboli island: a modelling comparison

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Volcanic islands are prone to massive flank collapses that are able to trigger tsunamis affecting the near- and far-field. Tsunami hazard assessment is crucial for keeping the coastal communities safe and for managing catastrophic events. The occurrence of Stromboli 2002 tsunamis lighted out the necessity of taking adequate countermeasures to protect coastal areas from this menace. This work is aimed at identifying the most suitable modelling approach for landslide-triggered tsunami hazard assessment at Stromboli by comparing several models, at different levels of approximation and accuracy. The maximum wave run-up, the invasion maps at Stromboli, and the waveform sampled at four proximal sites was obtained using NHWAVE three-dimensional non-hydrostatic model in sigma- coordinates (Ma and Kirby, 2012) and the HySEA family of geophysical codes (e.g., Macías et al., 2015) based on either single layer, two-layer (landslide and sea) stratified systems or multilayer shallow water models (https://edanya.uma.es/hysea) and compared. Both rigid and deformable (granular) submarine landslide models, with volumes ranging from 6 to 20 millions of cubic meters, have been used to trigger the tsunami waves. Results show that the invasion maps at the Stromboli village are quite comparable between hydrostatic and non-hydrostatic models, the differences being likely associated with the need of accounting for wave-breaking effects in non-hydrostatic models. Nevertheless, as expected, strong differences between the waveforms produced by models considered are present. This study shows that the use of non-hydrostatic, second-order accurate models, coupled with a multilayer approach, allows a better description of the waveforms, and thus a comparison with those recorded at the proximal gauges installed at Stromboli. Finally, the non- hydrostatic models such as Multilayer-HySEA, solved on accelerated GPU architectures, display the optimal trade-off between accuracy and computational requirements, at least for what concerns the proximal wave field of landslide-generated tsunamis.

Seismic emergency for Ischia island following the Mw 3.9 earthquake of 21 of August 2017: the actions of SISMIKO group

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On August 21, 2017, at 18:57 UTC, an earthquake of M_D 4.0 (M_w 3.9) occurred in Ischia, a volcanic island located in southern Italy. The earthquake caused two victims, several buildings collapsed and most of the damages were circumscribed to the areas of uptown of Casamicciola, a district of the island. In the past, 12 earthquakes with magnitude between ~3 and 4.3 occurred on the island, all of them were concentrated in the north-western sector in the area between Casamicciola and Lacco Ameno. After the earthquake of August 21 2017, SISMIKO, the coordinating group of the emergency seismic network at Istituto Nazionale di Geofisica e Vulcanologia (INGV), was activated and four seismic mobile stations were installed. At the beginning, all the mobile stations (coded as T13?? and with network code ZM), acquired locally and were equipped with short period sensors (only one was equipped with both velocimeter and accelerometer). In the following months, the seismic signals for some of these stations were telemetered in real time to the INGV monitoring acquisition room for surveillance purposes. Nowadays, the mobile seismic network on the island is composed by six stations equipped with short period and broad band sensors, and accelerometers. Real time data acquired from SISMIKO stations are available in the European Integrated Data Archive (EIDA). Although the seismicity followed the M_w 3.9 mainshock lasted only a few days, the addition of mobile stations T13?? improved the performance of the seismic network in Ischia for the localization analysis and for the detection of very low magnitude earthquakes.

S01.24 Poster

The Panarea-Stromboli linkage: evidences from acoustic signals and isotopic features

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Stromboli and Panarea, both belonging to the Aeolian arc, are known for their volcanic features that makes them a laboratory for multidisciplinary studies. At the end of 2002 both Stromboli and Panarea have been theatre of unusual volcanic activity characterized by a huge gas blast occurred at the main hydrothermal field of Panarea (Caracausi et al., 2005),followed by an intense eruptive phase at Stromboli.

Despite is widely accepted that the N40° fault represents the tectonic link between the Panarea and Stromboli edifices (Heinicke et al., 2009), is still debated if this linkage involves the magmatic roots of the two volcanoes, or it is just a tectonic connection between two different feeding systems with different magmatic reservoirs.

In order to investigate this question, a multidisciplinary observatory, connected to a buoy, has been deployed over the submarine hydrothermal vents, operating and transmitting data in near-real-time. Collected data show as the submarine vents are affected by seasonal trends and changes due to tides,thus the raw data were filtered before any analysis.

The acoustic data were analysed with the aim of investigating bubbling variations related to gas flow rate. Several anomalies have been documented in the bubbling activity, physical- chemical parameters as well as in very low band frequencies likely related to dynamic of the fluids along cracks (Alparone et al., 2010). An astonishing correlation between soil CO_2 flux emissions from craters of Stromboli and the acoustic signals in the 2-25Hz range has been identified, suggesting how this linkage (Heinicke et al., 2009) could act as escape route for fluids characterized by a common source.

Those acoustic observations, paired with the comparable behaviour of the He isotope marker in the fluids coming from both volcanoes, suggest that the “Panarea-Stromboli linkage” could concern the deep magmatic system of the two apparatus.

Population dynamics: the changing spatial pattern of hazard vulnerability and resilience on São Miguel, Azores (Portugal)

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This project examines risk mitigation from a physical and a human perspective on the Island of São Miguel, Azores. It aims to investigate population exposure to volcano, volcano-related and earthquake hazards and community resilience both in the past and at the present. The study identifies the ways in which population growth, migration, and settlement have exposed people to hazards over time, and seeks to improve knowledge of vulnerability and resilience. H*azard, vulnerability* and *resilience analyses are reported*. Hazard-analysis is based on already existing geological and historical data on earthquake, volcanic and volcano-related events. Vulnerability-analysis involves the use of demographic and other official data sets to provide insights into population change over time and spatially. Issues of evacuation are also considered. Resilience analysis is carried out using archival data sets. These data enable the evolution of communities and their practices with respect to geophysical threats to be considered through time and over space. Finally, the preliminary results of a new survey, that has aims better to understand how the communities perceive hazards today is reported. Initial results from the project indicate that the inhabitants of the island are generally unaware of the existence of volcano and volcano-related events; but are far more conscious of the risks posed by earthquakes. These results differ from those of an earlier study carried out more than two decades ago. It is contended that researching at the interface between the social and earth sciences will: improve hazard mitigation by promoting community knowledge and, boost resilience and so allow suggestions to be made to the authorities about the mitigation of risk.

Keywords: hazard, vulnerability, resilience, human mobility.

The 1909 Chinyero eruption on Tenerife (Canary Islands): insights from historical accounts, and tephrostratigraphic and geochemical data

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Tenerife is the largest and most populated island of the seven Canary Islands accounting for ca. 900.000 inhabitants and receiving about 5 million tourists each year. Tenerife is one of the most active among the seven Canary Islands accounting, in historical times, 6 eruptions. The last one took place on 18 November 1909 from the El Chinyero vent on the northwestern Santiago rift. This fissural eruption was well documented by scientists and eyewitnesses, but there is a lack of data on the high-energy phase that produced the most significant emissions of ash and lapilli at the onset of the eruption. Here, we review historical documents (e.g. newspapers, dispatches, telegrams); eyewitness accounts and scientific reports were reviewed from a volcanological perspective and integrated with data from the analysis of deposit features, allowing an accurate reconstruction of the eruption and its dynamics.

The eruption was fed by a compositionally discrete magma batch that ascended rapidly within the crust, producing rather violent pulsating Strombolian explosive activity in the early phases of the eruption. This activity produced a ca. 80 m high scoria cone and heavy fallout of lapilli and ash over the entire northern sector of the island of Tenerife. The energy of explosive activity waned after 3 days, giving way to the weak Strombolian explosive activity that contributed to a lesser extent to the buildup of the pyroclastic pile. Eruptions such as those from the Chinyero vent in 1909 are representative of rift activity on Tenerife and constitute a volcanic hazard for present-day inhabitants.

S01.24 Poster

Slope Maps of Mountainous Volcanic Islands, Coupled With Ground Observations, Reveal Volcanic And Non- Volcanic Risks

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Volcanic islands, especially when mountainous and densely vegetated, are places in which access for fieldwork can be difficult. This problem is compounded when the islands are Small Island Developing States with limited resources. There is, therefore, a need for efficient ways to combine freely available remote sensing data with focussed ground observations at accessible sites. In this contribution, we show how slope maps, derived from remotely sensed digital elevation models (ALOS PALSAR 12.5m pixel DEM), can be used to define areas of high hazard from a variety of high mobility flows, the nature of which can then be identified by ground observations.

These high mobility flows can be produced by a variety of primary volcanic, secondary volcanic and non-volcanic processes. Their common feature is that they tend to produce extensive areas with low slope angles, for example, valley-filling pyroclastic flow deposits, lahars and coastal alluvial fan deltas. In mountainous islands, such areas are highly attractive for urban development and associated infrastructure. This may lead to a strong spatial correlation between severe hazard and high density of exposed population and assets, producing zones of severe risk. In order to mitigate this situation, we propose that the combination of slope maps and ground observations provides an effective low-cost basis for maps to assist the preparedness, mitigation, response and recovery stages of emergency management.

We illustrate this with examples from the volcanic island of Dominica (Lesser Antilles, Caribbean) of low-slope areas formed by a variety of high mobility flows, the nature of which is evident from ground observations. These examples include cases where the flows have occurred in historic time (most recently as a result of Hurricane Maria in 2017), and cases where pre-historic volcanic activity and other events have left clear geomorphological effects.

Optimising the focal mechanism solution uncertainties from volcano-tectonic earthquakes recorded on small-aperture seismic networks: A case study from the Soufrière Hills volcano, Montserrat

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Volcanic islands present an interesting challenge for scientists working to model and monitor volcanic systems. Seismic monitoring is often the backbone of any volcano observatory; however, complexities due to highly heterogeneous crustal properties of volcanoes become amplified on small islands due to restricted seismic network configurations. Focal Mechanism Solutions (FMS) are commonly calculated to identify the structural features and to characterise the stress regimes of the volcanic system. Credible FMS rely on accurate first-motion data, including polarities, take-off angles, and good azimuthal coverage, which are dependent on the earthquake locations and seismic velocity model. One particular challenge is the interpretation of faulting geometry differences associated with tight spatiotemporal earthquake clusters. Whilst the implications of a tight cluster with diverse faulting geometries are intriguing, they require a thorough investigation to ensure the diversity is not due to poor FMS estimations.

We analyse FMS from Soufrière Hills volcano, Montserrat, employing multiple velocity models and seismic station configurations, to gain a better understanding of the range of uncertainties in these solutions. We examine the nature of volcano-tectonic (VT) earthquakes recorded during the SEA-CALIPSO seismic experiment. Whilst the earthquakes occur in a tight spatiotemporal volume, the FMS suggest diverse faulting geometries. The data include a temporary deployment of 29 three-component, 2 Hz seismographs and 204 single-component 'Texan' seismometers, in combination with the nine broadband stations of the Montserrat Volcano Observatory seismic network. Our analysis highlights that P-wave take-off angles can vary dramatically (up to 70° in certain instances) at short recording distances (4-6 km), yielding calculated FMS with large uncertainties. These results indicate that the seismic station configuration and velocity model resolution both play key roles in FMS calculation, highlighting the importance of carefully designing seismic station configurations for short-term research deployments and long-term monitoring campaigns in complex volcanic island settings.

S01.24 Poster

Primary surface faulting triggered by the 21 August 2017 M 4.0, Casamicciola earthquake (Ischia island, Southern Italy)

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On August 21, 2017 at 20:57, an earthquake with Md 4.0 (Lat. 40.74°, Long 13.90°, hypocentral depth at about 1.2 km) hit the Ischia island. The main shock heavily damaged the hilly sector of Casamicciola Terme village, reaching a maximum intensity of VIII in MCS/EMS scale, and causing two fatalities. Widespread damages also occurred in the Fango district (Lacco Ameno village) where the intensity reached VII-VIII MCS.
Although the Casamicciola earthquake is a small size volcano-tectonic event, it produced several ground coseismic effects as recognized for shallow earthquakes occurring in other volcanic areas.
Soon after the mainshock, a reconnaissance survey of the geological and environmental effects was conducted by a joint team from the EMERGEO Working Group and CNR/IAMC. The group collected data on both primary and secondary effects, recording more than 100 geological field observations. In detail we have surveyed coseismic fractures and ruptures, some modest gravitational phenomena such as small size collapses of some m3, small landslides in volcanoclastic deposits and widespread coseismic effects related to the shaking e.g., collapse of drywalls.
According to the pattern of coseismic effects, the area of ground deformation was identified along the fault systems E-W and WSW-ENE oriented in the northern sector of the Mt. Epomeo, already mapped in literature as active structures.
We found significant evidence for coseismic surface faulting, testified by a main alignment of ruptures for a 2 km end-to-end length and normal dip-slip displacement of 1-3 cm, with E- W predominant strike. The length of ruptures, geometric pattern, movement direction, offset, relationship with the topography, comparison with structural setting and historical siesmicity, strongly suggest a primary tectonic origin for the mapped ruptures of the 21 August 2017 volcano-tectonic event. Moreover the primary and secondary coseismic geological data allowed us to assess the preliminary intensity of VII ESI scale.

Seismic and geochemical signatures of a recent magmatic intrusion at Cumbre Vieja volcano, La Palma, Canary Islands

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Cumbre Vieja is the most active volcano of the Canaries; 7 of the last 16 historical eruptions have occurred there. Seismic swarms beneath Cumbre Vieja have been recently recorded after 30 years of quiescence. The Gutenberg Richter b-value reached values >1.9 for these seismic swarms. Furthermore, the high stress drop values retrieved for some of the strongest earthquakes, together with the depth of the hypocenters (15-25 km), seems to indicate that the seismicity was related to a magmatic intrusive episode. Monitoring of diffuse gas emission has been regularly performed at Cumbre Vieja over the last 17 years. The He emission survey performed in June before the first seismic swarm on October 7-9, 2017, recorded the highest value of He emission since 2002 and was estimated at 43 kg d^{-1}. During the second seismic swarm on September 13-14, 2017, a much higher He emission value was observed, reaching 198 kg d^{-1}. The He emission value decreased steadily until reaching a minimum value (6 kg d^{-1}) within a 2 month period. Diffuse CO_2 emission behavior has been opposite to that of He, increasing from 788 t d^{-1} in early October 2017, up to 2,303 t d^{-1} in January 2018. Seismic and geochemical data are consistent, and fit with previous models of the magmatic system proposed on the basis of petrological data. We hypothesize that the recent seismic swarms at Cumbre Vieja were caused by an upward magma migration from an ephemeral magmatic reservoir, located in the upper mantle (about 25 km depth), towards another reservoir located close to the Moho beneath Cumbre Vieja (12-15 km). The consequent depressurization of the magma batch was the source of the volatiles observed at the surface, which matches the expected geochemical behaviour of both gases.

The seismicity of Tenerife and its surroundings

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Tenerife is an active volcanic island which experienced several eruptions of moderate intensity in historical times, and a few explosive eruptions in the Holocene. The increasing population density and the consistent number of tourists are constantly raising the volcanic risk of the island. Since 2016 the island has shown evidence of ongoing unrest, with increased volcano-tectonic seismicity, occurrence of long-period events and marked changes in the diffuse gas emissions. On 02/10/2016 the occurrence of a remarkable swarm of long-period events was interpreted as the effect of a transient massive fluid injection episode into the deep hydrothermal system of Teide volcano. Actually, since Oct. 2016, the hydrothermal system of the volcano underwent a progressive pressurization, testified by the marked variation of different geochemical parameters. The most striking observation is the increase in the diffuse CO_2 emission from the summit crater of Teide volcano which started increasing from a background value of about 20 tons/day and reaching a peak of 175 tons/day in Feb. 2017. The pressurization process has been accompanied by an increase in the volcano-tectonic seismicity of Teide volcano, recorded by the Red Sísmica Canaria, managed by INVOLCAN. Since November 2016 the network detected more than 1000 small magnitude earthquakes, located beneath Teide volcano at depths usually ranging between 5 and 15 km. On January 6th 2017 a M=2.5 earthquake was recorded in the area, being one of the strongest ever recorded in decades. Most of the events show typical features of the microseismicity of hydrothermal systems: high spatial and temporal clustering and similar waveforms of individual events which are often overlapped. We present the spatial and temporal distribution of the seismicity of Tenerife. Furthermore we analyze the statistical properties of the numerous swarms recorded until now and the spatial and temporal variations of the Gutenberg-Richter b-value.

S01.24 Poster

Volume-time distribution and rheological behavior of lava flows and domes from Ischia Island (Campania, Italy)

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Ischia island is a densely inhabited active volcano, hosting a permanent population of about 50'000 people which increases during summer. Nonetheless, the risk associated with lava flows in case of renewal of activity is relatively understudied. We present the first analysis of the distribution of lava units volumes during the last 10 ky.

We also present a textural analysis and a rheological study of natural and partially- crystallized magma from the Arso Lavas (1302 A.D) and Zaro Lava domes and flows (6 ± 2.2 ka). The present work aims at investigating the role of the high crystal cargo (up to 75% for Arso and 87% for Zaro) in the rheological behavior of these lava flows. Three gaussian- shaped peaks observed in both CSDs can be interpreted as the magma chamber crystallization phase with rise of magma to surface in at least two stages. The emplacement temperature can be established by removing the microcrystal population in a temperature- controlled furnace. The rheological properties are determined by a uniaxial press.

One of the important targets for this work is the relationship between the velocity of the lava flows and the ground slope. All the data necessary to apply the Jeffreys equation, relative to the environment and to the area of emplacement, like position, geometry and slope of the channel, have been evaluated by a GIS analysis. The rheological model will be improved with analogue experiments, aimed to mimic lava flow dynamics, performed on reconstructed paleomorphology by 3D printing. The eruption duration of Arso Lavas is known because it is the last eruption at Ischia, which occurred in 1302 A.D. This information makes it possible to constrain a rheological model that can be extended to estimate the impact parameters of other similar lava flows on the island.

Planning investigations to define volcanic hazard at densely populated volcanic islands. The case of active volcanic island of Ischia (Italy)

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Ischia is a densely populated active resurgent caldera home to c. 50,000 inhabitants and located few tens of kilometres from Napoli city (Italy), therefore the volcanic hazard assessment is a primary objective. The knowledge of the volcanic past behaviour and the definition of its present state are essential to define the hazard assessment at this active volcano. In addition, a prescient knowledge of potential eruptive scenarios, based on past activity, is critical to the accuracy of the forecasting. These kind of studies at Ischia encounter notable difficulties as volcanic islands typically only preserve portions of the erupted deposit, as they are the subaerial portion of usually much larger and complex edifices. Thereby only the deposits and the eruption vents of a limited fraction of their history are easily accessible. Consequently, the real areal distribution of both effusive and explosive eruption deposits could not be mapped and isopachs and isopleths for pyroclastic deposits can be only partially reconstructed. In addiction the intense urbanization hides year by year the available natural outcrops and morphology. Therefore, the collection of all the physical parameters necessary to the definition of eruptive and deformational history and present state of the magmatic feeding system of Ischia is not simple and in some cases it seem to be very hard to accomplish. These evidences have changed the way we used to plan the field work and to process the collected data as frequently they are incomplete with missing significant items.

Nevertheless, the current volcanological and structural understanding suggests that the eastern sector of the island, particularly active during the past 2.9 ka, and the margins of the resurgent block are the sites with the highest probability of vent opening. All the eastern sector can be affected by pyroclastic currents and pyroclastic fallout, in case of renewal of volcanism.

Geochemical evidences of increasing magmatic gas input during the 2011-12 volcanic unrest of Santorini, Greece

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On January 2011 an anomalous seismicity (ML<= 3.2) began inside the Santorini caldera on the active volcano-seismic Kameni line, and continued up to April 2012. In the same time GPS, InSAR and SqueeSAR observed a rapidly expanding radial deformation from a point located within the caldera to the north of Nea Kameni (NK), the volcanic islet where six eruptions have occurred from 1570 to 1950. Concurrently, fumaroles and gas discharges showed important geochemical variations indicating an increasing input of magmatic gas. This crisis did not lead to a volcanic reactivation but it was interpreted as related to the inflation of a magmatic source.

In order to contribute to the evaluation of the unrest crisis, on behalf of Greek scientists, we carried out from early January 2012 to June 2013 an extensive geochemical study on the Kameni islets and on Thera Island. We repeated six surveys of soil diffuse CO_2 degassing and in-soil gas concentration on established grids of measurement points, together with samplings of the main fumaroles and thermal springs to be analyzed both for chemical and isotopic composition.

Our data show that an increasing gas output occurred both from Nea Kameni (CO_2, H_2) and Thera (CO_2) soils, and an increase of the magmatic components was observed at Palea and Nea Kameni fumaroles and thermal springs. Our data show that some geochemical changes precede, by a few weeks, the highest seismic rate episode of January 23-24, 2012.

This contribution proposes a new geochemical approach to face a volcanic unrest like the 2011 Santorini one. The research collected a sound dataset on fluid geochemistry that might be very useful as a reference background for a future volcanic unrest of Santorini.

S01.24 Poster

Impacts of an extreme hurricane upon easily-eroded volcanic rocks: the example of Hurricane Maria in Dominica, West Indies, September 2017

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Many of the rocks that make up volcanic islands, especially in the tropics where weathering is intense, have low resistances to erosion and are prone to mass transport during and after intense rainfall. Our field investigations in Dominica, after extreme Hurricane Maria on 18/19 September 2017, have shown how the consequent natural hazards multiplied the effects of the hurricane.

Large numbers of landslides occurred in a variety of volcanic lithologies: where the rocks were relatively fresh, the landslides evolved into debris flows laden with large boulders (some with dimensions up to ca. 2m x 3m) that demolished buildings and caused many deaths. Where the rocks were intensely altered, mud-rich debris flows evolved into lahar- like mudflows. Inputs of sediment from these landslides into the flooding rivers, along with abundant tree debris, caused rapid sediment aggradation and overbank floods especially where low bridges developed tree debris dams.

Conversely, where river flow accelerated through bridges, scouring of the weak volcanic rocks on which many of these were built led to bridge abutment collapses: a mode of failure that is rare in non-volcanic settings but also occurs in other volcanic landscapes, notably New Zealand. Since the hurricane, landslides have continued, especially in steep riverbanks cut into old debris flow deposits rich in altered volcanic material. The ongoing consequences include continued sediment aggradation and flooding, and disruption of riverbank infrastructures such as water pipelines.
Building codes and infrastructure planning need to reflect these consequent hazards of non- volcanic events in volcanic areas. Furthermore, the potential for the locally catastrophic landslide and flood damage was not well represented in warnings prior to the hurricane. We emphasize the need for integrated hazard maps and warning systems in volcanic islands where disasters can be triggered by both volcanic events and the interactions of non- volcanic events with volcanic rocks.

S01.24 Poster

Risks management planning on a volcanic island: fear and loathing in Ischia

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The small volcanic island of Ischia is gigantic challenge as far as risks analysis and risks management planning.

On a mere 46 sq.kms. surface all imaginable natural hazards are present, hence management of risks and civil protection are logistic nightmares in themselves; this peculiarity combined with the insularity of the area makes all possible line of approach and/or operation further complicated since all transport and logistics must be performed by air and sea only.

Emergency plans have been prepared singularly by each of the six municipalities of the island; no global plan nor specific guidelines issued by Regional and/or National authorties exist. Furthermore, the six single emergency plan are far from being ineherently coherent. To top it all, the six emergency plans are at the time purely formal documents, since they have never been tested with neither small-scale nor full-scale exercitation and even publicity and diffusion of the plans amongst the residents is less than minimal, as the crash test of 2017 Casamicciola earthquake dramatically showed up.

A drastic improvement can hence be achieved only by:

A) devising an effective plan for the entire island.
B) materially and effectively promote the plans’ diffusion and knowledge in order to achieve a minimum level of systemic resilience.

Seismological and geophysical studies for site effect characterization following the 2017 Mw 3.9 Ischia earthquake

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A Mw 3.9 earthquake, occurred on August 21 2017 in Casamicciola Terme (Ischia Island, Southern Italy) caused two casualties, dozens injured and extremely large damage concentrated in the northern part of the volcanic island where it was recorded a PGA of 0.27 g and macroseimic intensity up to 8 EMC. To investigate the possible relation between damage and site effects, the Emersito++ INGV task force worked in the framework of the preparatory surveys to seismic microzonation of the villages of Casamicciola Terme and Lacco Ameno. The working group carried out several seismological (sixty single station seismic noise measurements and three seismic arrays) and electromagnetic (twelve Time Domain Electro-Magnetic TDEM and five capacitive-coupled resistivity profiles) investigations in the most damaged areas to study the local site effects associated to geological and volcanological settings. The H/V spectral analysis performed on seismic noise acquired in the most damaged areas does not show important peaks related to local amplification effects. The noise polarization analysis, however, shows peculiar directional trends that could be reasonably related to the geological and volcanological setting of the investigated areas. The 1D shear-wave velocity (Vs) models obtained by the different arrays inversions are characterized by Vs velocity values approximately ranging from 0.4-0.7 km/s in the first 150 m depth up to 2 km/s at 500 m depth. Electromagnetic inversion results show shallow layer with resistivity between 10-100 Ωm with variable thicknesses up to a maximum of 20-30 m which overlay a more conductive layer (resistivity of less than 10 Ωm) with up to a depth of approximately 60 m. The analysis of earthquakes, recorded at the stations of National Seismic Network and of temporary network currently operating in the area, are used to retrieve information on local amplifications effects and to integrate the results obtained from seismic noise analysis.

S01.24 Poster

Long-term eruption forecasting at Ischia volcano

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The island of Ischia, located in the Gulf of Naples (Italy) is a densely inhabited and highly touristic active volcano. Its geological history is characterized by both effusive and explosive eruptions alternating with quiescent periods. It undergoes a mechanism of resurgence, which influences the volcanic activity, determining the conditions for magma ascent along the eastern edge of the resurgent block or along regional fault systems. In this study we reappraise the geological knowledge based on the volcano's past activity and observed deposits trying to (i) constrain the probability of next eruption in a given time interval, and
(ii) set up a spatial probability map for vent opening. For all the above points, we pay a particular attention in keeping account of the uncertainty associated to our estimates, both of aleatoric and epistemic origins. Being a small island, a substantial source of epistemic uncertainty arises from the impossibility of constraining vent location and erupted volume from distal deposits (which are under the sea), while proximal ones are often buried by more recent lava flows, tephra layers, or landslide deposits. In this respect, we take into account the uncertainties on the eruption catalog completeness and on the inferred vent locations. We build up a refined catalog of eruptions for the last 10 ky of activity at Ischia, then we analyse the statistical distributions of the time and time-type occurrence of eruptions, and finally we design a map for the probability of vent opening. These results are then merged to set up a Bayesian Event Tree for a long-term eruption forecasting, which represents a quantitative probabilistic basis for a full Probabilistic Volcanic Hazard Assessment.

S01.24 Talk

Study of propagation pattern of landslide-tsunamis generated in Ischia Island

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Ischia Island has been repeatedly affected by mass collapses, some of which with tsunamigenic potential, due to a number of factors. The most important of these are the steep slope of Mt. Epomeo flanks, the submarine escarpments at the end of the shelf, and the seismic shaking caused by the volcanic activity.

The most relevant cases of mass failure studied in the literature and postulated to be tsunamigenic are 1) the collapse of the southern sector of the Mt. Epomeo edifice, associated with a huge submarine deposit reaching more than 50 km run-out; 2) a number of small-size scars and small-volume underwater deposits found along the northern and western coasts of the island; 3) the hypothesized failure of Monte Nuovo, on the western flank of Mt. Epomeo, with tremendous destructive potential on the island itself and, through the associated tsunami, also at large distances.

Tsunamis generated by landslides in Ischia may affect the coast of Campania and in particular the Gulf of Naples, that is an area with a very high population density and a high value of industrial, port and touristic infrastructures.

The focus of this work is the evaluation of the pattern of the maximum tsunami energy. To this purpose we perform a number of numerical simulations by moving the same landslide source in different hypothetical positions around the island. The landslide dynamics is computed through the code UBO-BLOCK, and the tsunami propagation by means of the code UBO-TSUFD, both in-house developed. The final goal is to characterize the coastal areas most prone to tsunami inundation and most exposed to tsunami risk from Ischia sources.

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S01.26 - Volcanic ash from monitoring to impacts

The Vespa-system: Real-time estimation of eruption source parameters

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We describe attempts to automatically estimate time series of plume height and mass eruption rate during explosive eruptions in Iceland. The Icelandic Meteorological Office (IMO) is responsible for monitoring over 30 active volcanic systems, and operates two fixed position C-band weather radars and two mobile X-band radars, which are crucial in monitoring plume height, due to their independence of daylight, weather and visibility. These data are available in real-time to the natural hazards specialists and meteorologists on duty in the IMO's 24/7 monitoring room. In case of an eruption the data are also communicated to London VAAC to support their ash transport simulations for aviation safety purposes. The newly developed VESPA software uses automatically derived plume height estimates from the radar data to calculate the eruptive source parameters (mass flow rate, vertical velocity and vent radius) through an inversion algorithm using PlumeMoM, which solves the 1D plume model equations, and atmospheric profiles from the ECMWF numerical weather prediction model. Furthermore, the estimate of mass eruption rate calculated by VESPA are used to initialize the VOL-CALPUFF dispersion model to forecast the local impact on the ground due to tephra fallout. In this study we describe the VESPA-system and discuss estimated eruption source parameters for the eruptions of Grímsvötn 2004, Eyjafjallajökull 2010 and Grímsvötn 2011.

S01.26 Talk

Geochemical, Textural, and Morphological Study on Volcanic Ash of Merapi May 11th, 2018 Phreatic Eruption

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A phreatic eruption occurred at Merapi Volcano, Central Java on May 11th, 2018. Since its VEI 4 magmatic eruption on October 2010, there were at least six to seven reports of phreatic event, the latest even created eruption column as high as 5.5 km above summit. VONA (Volcano Observatory Notice for Aviation) alert was raised to red level as the ash cloud drifted downwind to south direction, causing the airport to shut down its operation for a couple of hours.

To have a better understanding of the event, samples were collected from field and were analyzed using WD-XRF Spectrometry to obtain geochemistry information, and also combining binoculars and Scanning Electron Microscope (SEM) to obtain textural and morphological information. The geochemistry result from whole rock analysis shows that the composition of the ash samples falls into basaltic-trachyandesite category (54.5% SiO_2, 3.9% Na_2O and 1.9% K_2O) and this result corresponds to the composition of volcanic ash produced on April 2014 phreatic eruption. Meanwhile, observation of 50 selected grains under binoculars and SEM, resulting in at least three categories of particles: unaltered lithics, free crystals, and altered particles (lithics and crystals). The geochemical, textural, and morphological analysis of volcanic ash give good evidence of phreatic eruption.

S01.26 Poster

A story in a grain: what ash fragments can tell us

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Volcanic ash is produced by multiple processes and dispersed under different conditions at nearly all volcanoes worldwide. The recent direct observations of many eruptions dominated by ash emission activity has contributed to make volcanologists well aware of the importance (in terms of frequency, impact and eruption dynamics) of these eruptions, whose deposits have been probably overlooked in the past for many volcanoes worldwide. Despite the inherent small grain size, volcanic ash still brings inside first order information, that can be extracted and interpreted in order to understand volcanic processes. This is particularly important especially for those eruptions dominated by ash deposition, where information on eruption dynamics and magma history can only be derived from ash grains.

The combined use of different techniques to extract information on size, shape, texture and composition on single ash grains has revealed a very powerful method for the study of these eruptions. Studies on different products of ash-dominated eruptions from volcanoes in Italy or elsewhere are here compared, and the different types of derived information discussed in terms of fragmentation dynamics, eruptive and syn-eruptive processes.

Modelling the resuspension threshold of volcanic ash in dry and wet environments by wind-tunnel experiments at controlled humidity

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The resuspension of volcanic ash by wind is a hazardous phenomenon threatening health, society and environment during and after eruptions at scales local to regional. Ash resuspension can be modelled, given that appropriate model input parameters are provided. So far, hazard-oriented resuspension models used literature parameters derived for non- volcanic particles, with limited data on the effect of environmental humidity. In this manuscript, we describe novel experimental results on the resuspension of volcanic ash particles, providing the first systematic parameterization of volcanic ash resuspension ever performed under controlled humidity conditions. We achieved this goal by using a unique environmental wind tunnel facility and volcanic ash from two different eruptions from the Eyjafjallajökull and Campi Flegrei volcanic areas in Iceland and Italy, respectively.

In humid environmental conditions, volcanic ash features, such as size-dependent shape, density and porosity, produce ash-specific resuspension behaviour. In general, the hindering effect of humidity on resuspension decreases with increasing particle size, but ash from the two investigated eruptions display a factor of two difference in this trend, with fine ash from the Eyjafjallajökull being five times more difficult to resuspend than that from Campi Flegrei.

Physical modelling of the experimental results is in reasonable agreement with an up to a factor of 6 increase in cohesion forces with increasing environmental humidity, and contribute to a better understanding of how ash textural and morphological differences can control the water retention potential of volcanic ash (and thus its resupension behaviour) in humid environments. Operatively, we propose that previous, literature parameters are only to be used for modelling the resuspension of volcanic ash in dry environments, whereas in wet environments, the new, ash-specific parameters we present may be more suitable.

Wind-remobilization of volcanic particles: field observations and physical processes

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Several studies during the last couple of decades have provided new insights into our understanding of primary tephra fallout dynamics. Physical characterization of the deposits as well as important advances in analytical and numerical modelling have contributed to better understand tephra dispersal and sedimentation processes and develop accurate probabilistic hazard assessment strategies. However, less attention has been dedicated to the characterization of wind-remobilization as a secondary but often syn-eruptive volcanic hazard. Better understanding of this phenomenon is crucial to the mitigation of the associated impacts. In fact, public health and critical infrastructure functionality are often disrupted for long periods of time as a result of ash wind-remobilization exacerbating the consequences of primary hazards and local pre-existing conditions (e.g. droughts). In addition, wind-remobilization of volcanic particles is a global concern since it is not only confined to the source area (i.e. primary tephra deposit) but it can affect large areas up to several hundreds of kilometres far from the source. We present here a detailed physical characterization of wind-remobilized ash particles associated with the deposits of the 2011 Cordón Caulle eruption (Chile). This eruption produced plumes of 3-14 km a.s.l that were dispersed towards the East-Southeast, sedimenting about 1 km^3 of tephra, covering vast areas of the Argentinian Andes and Patagonia. The finest and upper layer of the associated deposit has been remobilized since shortly after its deposition and it continues to be remobilized even up to today. We combine field observations, grain size and shape analysis with atmospheric parameters (e.g. wind velocity, precipitations) and surface conditions (e.g. roughness) to investigate wind-remobilization processes as well as their correlation with wind friction velocities and mass flux of remobilized volcanic ash in arid and semiarid regions (Patagonian steppe).

S01.26 Talk

The ash mass load of volcanic plumes: retrievals from a new millimeter-wave radar at Stromboli and Sabancaya volcanoes

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In the framework of the French Government Laboratory of Excellence ClerVolc initiative, two experiments using a new millimeter-wave radar were carried out to retrieve various physical properties of the ash plumes, especially the mass loading parameters which are critical for the modelling of ash dispersal, as well as to study the internal dynamics of the plumes and their fallout. First measurements at Stromboli in 2015 using a 95 GHz cloud radar prototype with a fixed beam pointing above the crater characterized the distribution of plume internal reflectivities, plume widths and durations at unprecedented space-time resolutions. Combining radar in situ measurements with data modelling from a disdrometer and ash sampling on the ground further allowed the retrieval of ash concentration and gradients inside the plumes, and sometimes proximal fallout. Plume maximum ash concentration range from 1 mg/m3 to about 1 g/m3. Structuration of ash concentration with variations by a factor of 3 was also found to occur inside the falling ash in correlation with variations in the sedimentation rate measured on the ground by the disdrometer. New results from radar measurements inside stronger plumes and fallout at Sabancaya volcano (Peru, May 2018) using volume scans will also be presented.

S01.26 Talk

In situ terminal settling velocity measurements at Stromboli volcano: Input from physical characterization of ash

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Ash terminal settling velocity is an important parameter to measure in order to constrain the internal dynamics and dispersion of ash plumes and clouds and their relationships with fallout deposits from which eruption conditions are often inferred. Many studies have empirically highlighted the need to consider shape parameters to better constrain ash settling velocity as a function of size. During a radar measurement campaign of volcanic plumes at Stromboli volcano in 2015, an optical disdrometer was used to measure falling ash particle sizes and their settling velocities, and six fallout ash samples were collected. Particle sizes, shapes and densities were calculated using a morpho-grainsizer and by water pycnometry. We focus here on the characterization of ash and on implications for settling velocities.

Sieved ash samples show sorted and coarse Particle Size Distributions (PSDs) ranging between less than 63 µm to at least 2000 µm with modal values between 125-180 µm and 250-355 µm. Every PSD is offset compared to the indicated sieve limits, 26.2 % up to 96.2 % of the distributions being higher than the sieve limits. The diagonal of the upper mesh size is therefore used as the upper sieve limit. Morphologically, particles show decreasing average shape parameters with increasing circle-equivalent diameter, the latter being equal to 0.8 times the particle longest axis in average. Particle densities increase from 2645 kg m^{-3} to 2811 kg m^{-3} with decreasing particle size. Ash terminal settling velocities were determined using tests in laboratory and using the best empirical model (Ganser, 1993). If used in adequate conditions in the field, disdrometers have the capability to monitor ash sizes and settling velocities in real-time, providing sedimentation rates and first-order ash concentrations. Detailed particle size distribution and shape parameters may further be used to constrain radar-derived mass loading parameters of the ash plumes.

S01.26 Poster

Mass Eruption Rates of fountain-fed tephra plumes during the 2011-2015 paroxysms at Mt. Etna from Doppler radar retrievals

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Estimating eruptive source parameters during explosive eruptions is a major challenge in terms of hazard and risk assessment. These inputs are essential to initialize tephra dispersal models forecasting the impact of ash plumes and tephra deposits. Between 2011 and 2015, Etna volcano has produced 49 paroxysmal episodes of fountain-fed tephra plumes that reached up to 15km (a.s.l.). These paroxysms were analyzed using the 23.5cm wavelength Doppler radar (VOLDORAD 2B) signals along with visible camera images of the monitoring network of the Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo. Range gating of the radar beam allows the identification of the active summit craters in real-time, no matter the meteorological conditions. The radar echoes help to mark the onset of the paroxysm, the transition to stable fountains (climax), and the end of the climax, therefore providing paroxysm durations. A methodology is developed to retrieve in real-time a Mass Eruption Rate (MER) proxy from the radar echo power and maximum Doppler velocity measured near the emission source. The increase in MER proxies precedes by several minutes the time variations of plume heights inferred from visible and X-Band radar imagery. A calibration of the MER proxy against ascent models based on observed plume heights leads to radar-derived climax MER from 2.96×10^4 to 3.26×10^6 kg s^{-1}. We inferred Total Erupted Masses (TEMs) of tephra, allowing quantitative comparisons of the relative amounts of emitted materials among all paroxysms. When the climax is identified, it is found to release 76% of the TEM. Our calibrated TEMs are larger than those retrieved by satellite and X-band radar observations, deposit analyses, ground-based infrared imagery or dispersion modeling. The radar-derived mass load parameters therefore represent a very powerful all-weather tool for the quantitative monitoring and real-time hazard assessment of tephra plumes at Etna.

S01.26 Talk

Fragmentation mechanisms revealed trough the ash morphology and texture at Sakurajima volcano (Japan)

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Volcanic ash represents a fundamental source of information on eruptive processes occurring both prior and after explosive eruptions. In particular, many studies evidenced how volcanic ash can be used to extract unique information about the style of volcanic activity and the relative fragmentation processes. We present a detailed study of ash collected during classical vulcanian activity at Sakurajima volcano (Japan), aimed at investigating the relationships between eruption dynamics and the key features of the resulting volcanic ash (e.g. shape and texture). Information about fragmentation mechanism is revealed by a comprehensive investigation over a complete sequence of activity observed in summer 2013 and October 2014. Based on SEM imaging of the ash samples, 4 main categories (Blocky Irregular, Blocky Regular, Rough-Vesicular, and Rough) have been defined. These characterize all the different phases observed in the eruptive activity, without showing important changes in concentration or morphology. The ash morphology has been then quantitatively defined trough a set of shape parameters, and compared with textural features (ground mass crystallinity, vesicularity) in order to outline the relations with different styles of activity observed during the whole sequence. An exhaustive quantitative dataset on the shape and textural variability of Sakurajima ash provide important insights into magma fragmentation mechanisms and their relations with the evolution of eruptive dynamics.

Understanding the frequency and style of past explosive eruptions in the Mexico City region from a 400 m lacustrine core

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Mexico City is one of the most densely populated regions on Earth, lying on the axis of the Trans-Mexican Volcanic Belt, a continental arc resulting from subduction at the Meso- American trench, ~300 km south-west of the city. Large (>4,000 m AOD) evolved polygenetic volcanoes, such as Popocatépetl and Nevado de Toluca, lie within 100 km, and the basin that houses the city hosts numerous small monogenetic scoria and tuff cones of the ~6000 km^2 Sierra-Chichinautzin Volcanic Field. Both types of volcanism present diverse eruption styles and pose a hazard to Mexico City inhabitants.

A ~400 m long sediment core drilled by ICDP in 2016 was recovered from Lago Chalco, an endorheic lake on the southeastern edge of Mexico City. It is a rare volcanic archive, preserving an extensive tephra (~150 falls) and volcaniclastic record of past eruptions over
~350 ka. Using ^{40}Ar/^{39}Ar geochronology we will establish an age model for the core, and thereby determine eruption frequencies and repose times for the region. The record will allow us to identify variation in volcanic output over timescales comparable to the lifetime of local volcanoes, and provide important context to understand present-day hazards. It will also help evaluate systematic variations in output through time. Geochemical analysis permits correlation of tephras in the core with those in other cores, and field exposures around Mexico City, to identify the source volcanoes. Ash particle morphologies, petrology and physical assessment of the volcanic deposits, (through logging, description and interpretation), will help determine the eruption styles, ultimately to assess what scenarios may affect the Mexico City region, and inform future hazard assessments. Distal fine ash deposits will aid studies on the extents and effects of larger caldera-forming eruptions further afield in Mexico and Central America, and will help correlate the Chalco core with other regional core datasets.

S01.26 Poster

Integrated monitoring of volcanic ash and forecasting at Sakurajima volcano, Japan

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Eruption of Sakurajima volcano is characterized by frequent vulcanian eruptions at Minamidake or Showa crater in the summit area. We install an integrated monitoring system of volcanic ash, and it is composed of remote sensing sensors; X-band radars, LIDAR and GNSS to detect volcanic ash cloud with different wave lengths, and 12 optical disdrometers on the ground covering all the direction from the crater to measure drop-size distribution and falling velocity. Campaign sampling of volcanic ash supports to convert particle counts measured by the disdrometer to weight of volcanic ash. Seismometers and tilt/strain sensors are available to estimate discharge rate of volcanic ash from the vents. Radar can detect volcanic ash cloud even under invisible state due to fog covering the volcanoes. Aneruption on November 13 was the largest event at Sakurajima volcano in 2017, however volcanic cloud was not visible due to cloud covering the summit. The radars reveal height of ash cloud reaching an elevation of 4.2-6.2 km. PPR of GNSS analysis (Ohta and Iguchi, 2015) suddenly increased after the eruption, and large-PPR paths from the satellites to ground-based receivers were intersected to each other at the elevation of 4.1 km. Height of volcanic cloud is also estimated to be 4.5 km from discharge rate of volcanic ash, which is empirically related to seismic energy and deflation volume from ground deformation monitoring (Iguchi, 2016). By using the discharge rate and height of the volcanic cloud, we forecast weight of ash-fall deposit by using PUFF model. The forecasted ash weight is verified by ground-based disdrometers. We also obtain distribution of ash-fall deposit by using an empirical relationship of total amounts of reflectivity of the radar with and ash-fall deposit on the ground. LIDAR is useful to detect volcanic ash, when low-density volcanic ash is emitted from the craters.

In situ observation of falling ash by using PARSIVEL disdrometer during the 2018 eruptions at Shinmoe-dake volcano, Japan

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Real-time observation of properties of falling ash from an explosive eruption is needed for rapid prediction of possible hazard caused by volcanic ash particles on human health, critical infrastructure and agriculture. However, such an observation has been insufficient, and evaluation of volcanic ash largely depends on geological survey after the end of eruptive event. Here, we apply PARSIVEL disdrometer for in situ observation of falling ash from the 2018 eruptions at Shinmoe-dake volcano, Japan, to develop a method of the real-time observation. The PASIVEL is an optical disdrometer which can measure the number of falling particles with a size and velocity, and has been used for rain fall observation in the field of meteorology. The PARSIVEL was installed in 11.9 km ENE from the Shinmoe-dake vent since October 20, 2017. We set the interval of sampling every 5 minutes. The comparison with eruption records to data sampled by the PARSIVEL shows that we succeeded to observe falling ash from a small continuous eruption in March 2 and Vulcanian eruptions in March 12, 14, and April 5. Results of the observation show that temporal change of size d, velocity v, and precipitation of falling ash, which is defined by the PARSIVEL apparatus observing the volumetric flux of rain drops, r within the range of $d < 1.25$ mm, $v < 4.8$ m/s, and $r < 0.74$ mm/h. We found that the largest size particle do not always have the highest falling velocity, suggesting that a density variation in the particles. The density variation can be caused by difference in vesicularity of individual particles or effect of aggregation which is formed by smaller particles.

S01.26 Poster

Volcanic Ash Data Assimilation for Atmospheric Transport Models

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The Japan Meteorological Agency (JMA) has two operations for volcanic ash forecasts: the Volcanic Ash Fall Forecast and the Volcanic Ash Advisory. In these operations, the forecasts are calculated by atmospheric transport models. The initial distribution of volcanic ash in the models is the most important but also the most uncertain factor.

For improvement of the initial distribution, we are developing a volcanic ash data assimilation system based on the three-dimensional variational data assimilation method (3D-Var) using weather radar and meteorological satellite observations.

The radar observation is expected to provide three-dimensional parameters such as ash concentration and parameters of ash particle size distribution. The satellite observation is anticipated to provide two-dimensional parameters of ash clouds such as mass loading, top height and particle effective radius. In this study, we estimate the thickness of ash clouds using vertical wind shear of the JMA numerical weather prediction.

In addition, we are developing a data assimilation system based on the four-dimensional variational data assimilation method (4D-Var) for reconstruction of the ash distribution in both eruption columns and volcanic-ash clouds after advection. For 4D-Var, it is necessary to develop a Tangent Linear model (TL) and Adjoint model (AD) from the original Non- Linear model, and by doing so we can use various observations in the data assimilation window. Analysis from 4D-Var is under constraints of model dynamics such as wind advection and gravity settling. As a result, 4D-Var can extract much information from observations.

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S01.26 Poster

The 1918 Eruption of Katla Volcano, Iceland

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Iceland is one of the most volcanologically active regions in the world, with at least 217 eruptions, of which 161 were explosive, in historic time (i.e., since ~AD 870). Katla volcano, located below the Mýrdalsjökull ice cap in the East Volcanic Zone, is the second most active volcano with 23 explosive eruptions in historical time with magnitudes (tephra volumes) ranging from 0.02 to >2 km^3. On average, there has been one eruption per 50-year interval, and the repose time ranges between 13 to ≥100 years. The historic eruptions have all been of basaltic magma, and phreatomagmatic in nature due to interaction of the erupted magma with meltwater from the overlying ice cap. However, Katla volcano has also featured moderate to large Holocene silicic phreatoplinian and Plinian eruptions. Eruptions from Katla pose significant hazards both locally (e.g., widespread tephra fall and large jökulhlaups) and globally (e.g., high abundances of fine ash affecting aviation) due to the highly explosive nature of the eruptions, the proximity to inhabited areas and, and the generally long duration (weeks to months). We present a case study of the most recent eruption that broke through the ice cap. It began about 100 years ago, on 12 October 1918 and lasted for 24 days. It produced a tephra fall with a volume of about 0.7 km^3 and with a >14-km high plume. We will present an evaluation of key eruption source parameters for the 1918 event at Katla via field data and assessments using the TEPHRA2 model in inversion mode.

S01.26 Poster

Volcanic eruption clouds detected by weather radar under moist environment

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The optical measurements, such as ground-based instrument, camera, and satellite, have some limitations to detect volcanic eruptions in cloudy or precipitation conditions. The weather radar is one of the key instruments for studying and monitoring volcano eruptions. The purpose of this study is to understand the inner structure of the volcanic eruption columns and ash clouds under precipitation conditions using weather radar.

The volcanic eruption occurred under rainfall conditions at Sakurajima on 29 August 2013 is analyzed. The data from the Tarumizu X-band polarimetric radar, which is located approximately 10.7 km from the Showa crater, is investigated by the Analytical Tools for Three-Dimensional Weather Radar Data (ANT3D) which was developed by Kagoshima University.

The results show the three-dimensional development of volcanic ash columns and precipitation. We estimated the eruption column to be 4000 m high. The volcanic ash clouds merged with the precipitation system 10 min after the eruption. When the volcanic eruption occurs, the specific differential phase (KDP) of ash couldn't be detected, while the KDP of ash under moisture environment increased to detectable values. We found that the polarimetric radar parameters, especially KDP, are good for discriminating ash clouds from precipitation echoes.

Observations of Sakurajima Volcanic Eruption Columns with Three Different Types of Weather Radars

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The present paper describes the results of observational studies of volcanic ash columns using three different types of weather radars: X-band marine radar, bi-static Ku-band radar, and operational X-band polarimetric radar. The X-band marine radar, which is used for ship navigational safety, was set up at the Kurokami observatory which is located about 4km from the vent of Sakurajima volcano. The marine radar has a slot antenna scanning speed of 48rpm, with a vertical beam width of 22° and a horizontal beam width of 1.2°, and a range resolution of 8m. We carried out observations by physically changing the rotational axis of the slot antenna from vertical to horizontal so as to achieve an elevation angle resolution of 1.2°. The Ku-band radar located at the same site as the marine radar has a Luneberg antenna with a horizontal and vertical beam width of 3°. The antenna rotates spirally from an elevation angle of 0° to 90° to obtain hemispherical volume data in one minute. The X- band polarimetric radar located approximately 11km from the vent of the Sakurajima volcano can measure volcanic ash columns three-dimensionally every 5 minutes, even though it is an operational radar and its antenna scanning strategy is adjusted to suit heavy rainfall observations.

Utilizing these different types of radar data, we performed detailed analysis of eruption columns. The marine radar succeeded in detecting falling pyroclastic particles at the beginning of the explosive eruption. The radar also reveals the fine structure of upward motion in the eruption column every 1.5 seconds. The following temporal change of the eruption column structure such as the size sorting process was detected three dimensionally by the Ku-band radar. Then wide-area distributions of ash falls were obtained by the operational X-band radar data.

Ku-band Rapid Scanning Doppler Radar for Volcanic Eruption Monitoring

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Recent studies have found that meteorological radars are effective for the quantitative evaluation of pyroclastic material. Based on such findings, Kagoshima University began outfitting a rapid scanning Doppler radar (KuRAD for short) for use in volcanic observations as a part of a research project entitled 'Creating a Community Resilient to Large Volcanic Eruptions' (2016 – 2021). When a large-scale eruption occurs, the ash fall distribution will be measured by dynamic radar observation and the information gathered will be provided to the national and local government officials in charge of disaster prevention so as to increase the safety of local evacuees and the rescue and reconstruction crews working in the affected areas.

KuRAD is intended to dynamically observe and analyze the multiple dangers that accompany volcanic eruptions: i.e. eruption columns, pyroclastic flows and ash clouds. KuRAD is also used to observe heavy rainfalls, which themselves may cause multiple disasters. The main KuRAD characteristics are 1) high speed antenna scan capable of observing the three- dimensional development of rapidly changing eruption columns at 1 minute intervals, 2) high spatial resolution data at 2 m range intervals revealing the detailed structures of volcanic plume and pyroclastic flows, 3) transportable and authorized to operate at the locations of seven active volcanoes in Kyusyu, Japan, and 4) can be operated remotely from Kagoshima University.

KuRAD trial observations of Sakurajima volcanic eruptions were carried out over 2 months commencing April 2017. A total of 80 eruptions, including 13 explosive eruptions, 10 of them had ash column heights higher than 3000 m. KuRAD was able to detect the development of the volcanic ash column three-dimensionally. After examining KuRAD performance we set up the radar in Miyazaki prefecture on May 2018 to monitor Shinmoedake volcano eruptions and to provide ash fall information to local authorities on a real-time base.

S01.26 Poster

Contribution of Popocatepetl Ash to air pollution in Mexico City during 2017

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Ash emission from Popocatepetl Volcano in central Mexico has been frequent since 1994, but previous attempts to recognize its effect on nearby Mexico City's air quality have been camouflaged by several factors including changing winds and reworked older tephra and lake deposits, as well as pollutants from factories and vehicles. A correlated detailed analyses of the samples from our UNAM-SECITI ash sampling network and the particle data from the RAMA (atmospheric monitoring network) and their timing show that PM 10 and PM2.5 increased after the ash emissions in June through August and in November and December when fine ash was carried toward Mexico City. Many small ash emissions occurred during June and July when the dominant winds blow toward Mexico City producing an increase in PM 10 and PM2.5 in fourteen occasions of about 20% reaching 93-103 (PM10) and 63 (PM2.5), all well above the limit of 75 $\mu g/m^3$ for PM10 and 45$\mu g/m^3$ for PM2.5. On August 15, both PM 10 and 2.5 concentrations doubled in all southwestern stations where fine ash was deposited. The November 4 ash emissions produced an increase of 10 to 20% in PM10 and PM2.5 but doubled with the November 9 and 19 emissions in the stations in southwestern Mexico City. Already high PM2.5 and PM10concentrations in December increased sharply with the ash emissions, reaching PM2.5 concentrations of 106-142 and PM10 of 93-168. Samples (ground stations) taken during and immediately after the emissions also contain fine particles of plagioclase and crystalline silica with some magnetite and glass.

S01.26 Poster

Retrieving near-source volcanic plumes: exploitation of ground- based microwave radar measurements during Etna 2013 explosive eruption

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An explosive volcanic eruption can cause a variety of severe and widespread threats to human well-being and the environment. The detection and quantitative retrieval of tephra clouds is of significant interest due to the environmental, climatic, and socio-economic effects of ash fallout, which might cause hardship and damages in areas surrounding volcanoes. Real-time monitoring of such phenomena is crucial for initializing ash dispersion models. The most distinctive characters of Mt. Etna, located on the east coast of Sicily (Italy), are the lava fountains, relevant for the large amount of tephra discharge rate. Tephra dispersal from an explosive eruption is a function of multiple factors, including magma discharge, degree of magma fragmentation, vent geometry, plume height, particle size distribution and wind velocity (Sparks 1986; Mereu et al, 2015). Within the experimental site near the Mt. Etna volcano, a large set of instrumentation is installed, including seismic sensors, an optical lidar, a microwave radar, an infrasound array, a video camera. In the morning of 23 November 2013 an explosive lava fountain erupted from the New Southeast Crater (NSEC) of Mt. Etna, one of the most active volcanoes in Europe. The lava fountain was clearly observed from two ground-based radars, an X-band polarimetric microwave weather radar (Marzano et al., 2013) and an L-band Doppler radar named Voldorad (Donnadieu, 2012) as well as from a video thermal-infrared camera. Taking advantage of the capability of the ground-based radars to probe the lava fountain and extending the VARR methodology, we can estimate the Mass Eruption Rate (MER) from 3 main techniques: 1) the surface-flux approach (SFA); 2) top-plume approach (TPA) and 3) mass continuity approach (MCA). The analysis of this case study indicates that ground- based polarimetric and Doppler microwave weather radars can be exploited to provide a self-consistent monitoring of the explosive volcanic eruptions activity.

VOLCAT (Visual Observation Laboratory for Capturing Ash Transition) for automatic remote imaging of volcanic ash particle

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Rapid characterization of volcanic ash particles is important to evaluate the activity of ongoing eruption. However, the characterization tends to behind the transition of ongoing eruption because of the time loss during the sample collection, transportation and pre- preparation for observation in the conventional methods. Here, we develop a new field- based instrument VOLCAT (Visual Observation Laboratory Capturing Ash Transition) which can take microphotographs of ash particles automatically and transmit with the Internet to realize quasi-real-time characterization of ash particles to contribute evaluation of ongoing eruption. The VOLCAT provides sample-preparation system with a sample capturing module, wash, dry and sieving system with ultrasonic cleaner, hotplate and sieving modules which can drive automatically. A USB microscope captures the microphotographs of the particles and transmits into a FTP server for a time interval with 30 minutes at the shortest. The VOLCAT is a portable system which consists of main body and control box, is approximately 68 kg in weight, and works by external commercial power supply or mobile batteries.

The first performance of the VOLCAT is the 2017-2018 eruption at Shinmoedake volcano, Japan. We installed the VOLCAT on the 6 km ENE from crater of Shinmoedake from November 8th, 2017, to time of writing (May 1st, 2018). The VOLCAT sent microphotograph in every 8 hours to the FTP server. We got 4 microphotographs of ash particles in 07:51 and 23:51 of March 13rd, 07:51 of March 14th, and 07:51 of March 15th up to May 1st. The comparison with eruption record confirmed us that the ash particles captured by the VOLCAT are derived from Vulcanian eruptions at Shinmoedake. The microphotographs well capture color and shape of the volcanic ash particles. We conclude that the field-based monitoring of ash particles with our VOLCAT is useful for evaluation of ongoing eruption.

Detection and tracking of high-content ash volcanic clouds

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The Colima volcano is the most active of Mexico. Its explosive activity includes explosions lower than 3 Km high that affect life in nearest populations. Prevailing winds transport volcanic ash and its impact includes the disruption of activity at nearest airport and also alters air traffic of Pacific area. Colima volcano is monitored by a permanently system of HD cameras placed 4000 m high at the mounts around volcano. This work proposes an image processing system that classifies volcanic clouds in high content ash or high content water vapour. The algorithm is based on the different wavelength absorption/dispersion of light depending on water content in a cloud. Additionally, motion detection algorithm traces the trajectory of volcanic cloud.

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Application of in situ volcanic ash measurements via unmanned aerial systems at Sinabung volcano, Indonesia

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The main drawback to current airborne ash studies is the inability to provide a representative particle size distribution of volcanic ash clouds after an eruption has begun, due to a bias towards larger particle sizes in ground deposits where fine ash may be deposited far from source, and satellite imagery as a result of limitations in spectral, temporal, and spatial resolution. To improve the community's capacity to accurately measure inputs needed to produce effective numerical models of airborne ash transport, we have chosen to use a Small Unmanned Aerial System (sUAS) to characterize volcanic ash in situ while airborne, and determine the size distribution, abundance, and nature of volcanic particles smaller than those currently being measured. The sUAS can fly directly into an ash cloud to measure the finer ash particles (<30 µm) that do not settle in deposits but present health hazards to the nearby population. To test this method, we selected Sinabung volcano (North Sumatra, Indonesia) as our test site, because of the regularity of ash emission and the proximity of adequate locations from which surveys can be launched. We outfitted our DJI Phantom 4 with an Alphasense optical particle counter to obtain the size distribution within the ash cloud of particles in the range of 0.25 - 32 µm. The sUAS' flight path include vertical profiles to assess the particle size heterogeneity within the cloud which in turn, helps validate both computational modeling and satellite imaging techniques currently in use while also testing a newer and possibly safer method of monitoring natural disasters.

Distribution of ash-fall deposits from Vulcanian eruptions and minor ash emission of Sakurajima Volcano

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Distribution of ash fall from small-scale Vulcanian eruptions and ash emissions of Sakurajima Volcano (Japan) are mapped. We installed 29 (in 2011)–53 (in 2012) ash collectors in the downwind area of the active craters to detect the ash fall distribution. The samplers were installed in an area from 2.2 to 43 km away from the crater. We obtained 33 isopleth maps between 2011 and 2015. The distribution of the ash fall is affected by local meteorological conditions. A negative correlation between the aspect ratio of an isopleth and average wind speed at ground level suggests that the width of distribution area of an ash fall is strongly controlled by the near-ground wind speed. The direction of the isopleth axis for larger masses is affected by the local wind direction. The direction of the distribution axis of an ash fall is more consistent with the wind direction at higher altitude than at ground level. In rainy conditions, a second maximum of ash fall can appear distally, while there appears to be negligible influence from the depositional mass-distance relationship.

Based on the distribution maps, we obtained the minimum mass of the ash fall during each survey period. These masses ranged from 70 to 40,520 t. The distribution maps suggest that each prominent eruption (Vulcanian explosion) produced 890–5140 t of erupted material. The distribution maps also indicate that weak and continuous ash emissions also produced 120–906-t/h volcanic ash.

Three-dimensional and densitometric measurement of individual ash particles (n>>100), and calculation of terminal velocity profiles within hours of sample receipt

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Ash is the most frequent and widespread volcanic hazard that reaches a global scale. The terminal velocity of individual particles is a fundamental parameter when modelling travel distance, and predicting fall-out. The size, shape and density of a particle are factors that contribute to how fast it will fall. Here we provide a quantitative and reproducible X-ray micro-computed tomography method that measures all three factors from 100s of individual particles in a single scan. These factors are then used to calculate terminal velocity, per particle, using a novel Python code. We demonstrate that including density and shape factor leads to greater, and a wider range of, travel distances compared to using grainsize alone. The entire workflow from sample receipt to terminal velocity calculation can be completed in a matter of hours. The method has been designed using standard laboratory X-ray systems, and can be made field-deployable.

S01.26 Talk

Utilization of weather radar data to volcanic hazard prediction system

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Recently, researches for monitoring volcanic eruption clouds by weather radar have been progressing. It is also expected for weather radar to play an important role to create initial conditions of atmospheric transport models to forecast volcanic ash distribution in the atmosphere or ashfall on the ground. On the other hand, development of a volcanic hazard prediction system is being promoted by National Research Institute for Earth Science and Disaster Resilience (NIED) in the project "Integrated Program for Next Generation Volcano Research and Human Resource Development". Meteorological Research Institute (MRI) has provided outputs of JMA-RATM, the atmospheric transport model developed by the MRI, to the system. The NIED also plan to utilize weather radar data to the volcanic hazard prediction system, therefore, the authors considered how to utilize them.

Roughly speaking, there are two ways to utilize weather radar data for the volcanic hazard prediction system. One is a "direct" method, and the other is an "indirect" method. The former is a method of inputting weather radar data, or volcanic ash quantity derived by weather radars, directly into the system. The latter method uses weather radar data to create initial conditions of atmospheric transport models, and inputs their result to the system. The former mainly aims to monitor hazards in several kilometers from the volcano, while the latter mainly targets widespread hazards.

In this presentation, we will introduce these two methods and the volcanic eruption monitoring researches using weather radars in Japan.

Quantifying grain size and shape for non- equant ash particles

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Volcanic ash dispersion forecasts are sensitive to the input particle size distribution (PSD). Dispersion models are less sensitive to particle shape than particle size, however, shape can affect how we measure size. While volcanologists report PSDs in terms of sieve mesh sizes, dispersion models often use numerical sedimentation schemes calibrated using volume- equivalent sphere diameters. Where particles have very irregular shapes, the two measures are not equivalent. We measure the size and shape of volcanic ash particles from three silicic eruptions of Katla, Iceland, termed the 'needle layers' for their extremely elongated shapes; and another silicic Katla tephra, the Vedde ash, notable for its flat platy particles. We use different 2D (SEM, optical microscopic) and 3D (X-ray tomographic) imaging techniques, as well as traditional sieving, to explore the impact of extreme shape on particle size measurements. We then explore the implications of different size measurements on predictions of particle settling velocity and distal volcanic ash concentration forecasts.

S01.26 Poster

Abstract ID: 676 for Cities on Volcanoes 10 (Auto-Generated June 13, 2018 2:13 pm)

A new way to reduce the impact from tephra fallout during Etna explosive eruptions

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The frequent number of explosive events at Mt. Etna, in Italy, over the last ten years, has made necessary the improvement of volcanic ash monitoring and forecasting system at the Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo (INGV-OE). Tephra fallout produced during Etna lava fountains largely impact the population living on the volcano flanks. In addition, during one of the most powerful paroxysms, large clasts fell in proximal areas injured tourists and hikers. To reduce risk, the Italian Department Civil Protection (DPC) asked and funded INGV-OE to do a research project finalized to three specific objectives. First, identify the plume scenario (i.e. weak plume scenario (WPS) and strong plume scenarios (SPS)) based on 1-D plume model. Second, forecast characteristics of tephra deposition using near real time observations. Third, identify the region possibly impacted by large clasts (>5 cm). Two algorithms were developed to measure the column height. One from the calibrated images of two visible cameras installed on the S and W flanks of the volcano, respectively; and the other one from satellite data using a procedure based on the computation of the volcanic plume-top brightness temperature at 10.8 mm. The analysis of lava fountains that occurred between 2011 and 2015 provided the opportunity to differentiate between weak, transitional and strong plumes. The uncertainty associated with eruption source parameters, while maintaining a fixed plume height, was also assessed. In the near future the implementation of these products into the INGV-OE - monitoring room will guarantee a better and timely information to civil protection authorities charged of risk prevention at different levels of responsibility.

Spectroscopic colorimetry of volcanic ash for monitoring and reconstructing eruption style

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Observation in terms of seismicity, ground deformation (such as tilt, GPS, and strain), and gas monitoring are major and powerful tools to detect unrest of volcanoes, but it is also true that, even in most successful cases, forecast of eruption sequence by these methods alone does not work well. Eruptive materials can also be clues to know subsurface vent and magma conditions by means of petrological characterization (eg. origin, temperature, volatile content, ascent rate, and some important knowledge that control eruption), and they would help forecasting following sequence. But one problem is that, in most cases, only fine grain ash samples are available continuously at distal sites, although large-size samples are favorable to fully utilize such methods.

Ash particles are quite diverse in color, shape, density, crystallinity, porosity. Thus, the componentry of a single ashfall sample also can be highly variable and distinct among different eruption styles systematically. On the other hand, derivation of these data is very backbreaking task which had long been desired to be replaced by easier methods.

Here we show the systematics of natural ash colors in terms of spectroscopic colorimetry of more than 1000 samples by several different styles at volcanoes in Japan and other countries. The procedure of measurement is easy, and it is noteworthy that some transitions of eruption accompanied systematic color changes; color values indicating redness and yellowness are correlated with the amount of vesicular particles during vulcanian and strombolian styles. Color change also occurs in a different way at the transition when vent collapses significantly with increase of altered grains. Thus continuous monitoring by spectroscopic colorimentry of ash would help detecting phase transition much easily and faster than previous methods. Reconstruction of eruption sequence in the past might also be possible by adopting this method to deposits.

Numerical Simulation of Eruption Clouds for Assessing Volcanic Hazard to Cities in Japan

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The most prevalent volcanic hazard for cities is ash fall, due to its large spatial extent. In Plinian eruptions such as the 1707 Hoei eruption of Mt. Fuji, large amounts of ash are injected into the atmosphere and dispersed by atmospheric winds, with ash deposited a few hundred km from the volcano. In contrast, the ash injected by a caldera-forming super- eruption can travel globally, depositing widespread ash fall layers more than 1000 km from the volcano. To reconstruct past eruptions and assess the onset and timing of fall deposits, we performed numerical simulations of ash dispersal for the Hoei eruption and the large- scale eruption in Kyushu producing Aso-4 ash. Our numerical model is based on a combination of a pseudo-gas model for fluid motion and a Lagrangian model for particle motion (Suzuki and Koyaguchi, 2013). To simulate both cases, we used typical atmospheric conditions for winter in Japan based on reanalysis data. In the Hoei eruption case, the mass eruption rate was assumed to be 1.0×10^7 kg/s (Miyaji et al., 2011). The simulated plumes exceed 10 km asl and move horizontally at 10–15 km high. The clouds reach Yokohama (80 km from the vent) within 30 min and the deposition of ash fall starts 10 minutes later. In the Aso-4 eruption case, the mass eruption rate was set to be 1.0×10^{11} kg/s. As a result, the umbrella cloud radially spreads at an altitude of 30–40 km. The edge of the umbrella cloud reached the city of Osaka (500 km from the vent) at about 70 min, whereas the deposition of ash fall started at 150 min. These simulation results, especially the difference in the arrival time of cloud and fallout, can be useful in providing realistic dynamic hazard scenarios for cities impacted by volcanic ash.

Tool for short- and long-term planning for impacts of ash on airport operation and flights in South East Asia

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Containing just shy of a thousand volcanoes, Southeast Asia is one of the most volcanically active regions on Earth. This combined with a boom in local and international air-traffic, makes it an important location to study hazards linked to volcanic ash in the atmosphere. In order to estimate the hazard in a large region, the list of known volcanoes in Southeast Asia was updated, as well as their potential to erupt, and then combined with estimates of where the injected ash would be transported. Volcanoes were grouped into geographic zones and eruption probabilities were derived from the information for each volcano within the zone. For each zone, 8 eruptive scenarios were simulated and ash dispersal was tracked for five days, with a simulation starting every day for 6 years using reanalyzed winds. Approximately 150 TB of simulation data were produced, and combined with the zone probabilities. There are many potential uses for the information within this dataset, including the long-term absolute, conditional, temporal and spatial probabilities of ash occurrence. For this presentation we focus on studying the hazard from a given zone for two different conditional scenarios. In the case of a long-lasting eruption: Which regions will be impacted depending on the month? In the case of recorded unrest: Which region will be impacted if the unrest leads to an eruption? We developed a tool that has the ability to interrogate our dataset to produce monthly estimates of the spatial likelihood of getting ash above a given threshold at given flight levels. The tool enables aviation authorities to carry out short- to long-term planning for potential impacts on airport operation as well as flights.

What does volcanic lightning tell us?
Insights from the shallow submarine eruption of Bogoslof volcano, Alaska

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Volcanic lightning has become a useful addition to eruption monitoring because it allows remote and rapid detection of ash-rich plumes. Lightning creates radio waves that travel at the speed of light, pointing to the location and timing of hazardous ash emissions within minutes to tens of minutes of eruption onset. Previous work has shown that larger eruptions produce more lightning than plumes that are either too weak or juvenile-poor to become electrically charged. Although these findings improve our situational awareness during the earliest stages of an eruption, new questions have arisen. How do volcanic plumes become electrified? What is the role of magma-water interaction?

To shed some light on these issues, we consider the shallow submarine eruption of Bogoslof in Alaska, which produced >60 plumes from December 2016 to August 2017, with the highest reaching ~14 km above sea level. We examined lightning flash rates (from ground- based networks), mass eruption rates (based on plume height and umbrella growth in satellite), and shifts in vent conditions from submarine (wet) to subaerial (dry), based on seismoacoustic data. Results indicate that for smaller eruptions (<10^6 kg/s), wet plumes are less electrically active than dry ones. A plausible explanation is that water stifles the charging mechanism of smaller eruptions. In contrast, all eruptions >10^6 kg/s produced significant lightning regardless of vent water levels. We propose a conceptual model whereby smaller eruptions become electrified by near-vent charging, due to fragmentation and particle collisions in the conduit/jet. These processes may be dampened by liquid water. In contrast, plumes that develop into the upper atmosphere undergo charging by ice and gravitational settling, which is enhanced by liquid water, and ultimately takes over the electrification of the largest, most lightning-rich plumes.

Mitigating ash impacts from eruptions in the Alaska Aleutian Arc

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The Alaska Aleutian Arc is notorious for ash-producing eruptions and thus understanding the impacts of ash and its mitigation have been important to the Alaska Volcano Observatory (AVO). Drifting ash clouds and ashfall can threaten aircraft operations over Alaska, its surrounding waters, and beyond. Volcanic ash may significantly impact Alaskan communities, infrastructure, and human health. A well-coordinated response with consistent messaging facilitates the flow of timely, useful information to those at risk. A formal Interagency Operating Plan provides guidance for an integrated, multi-agency response to the threat of volcanic ash in Alaska. During ash-producing eruptions, AVO and its interagency partners work closely to issue timely warnings of volcanic activity and its impacts. Scheduled checks and automatic alarms on geophysical and remote sensing data as well as reports of observations by pilots, mariners and citizens can alert AVO staff to volcanic activity. Upon the onset of explosive activity, AVO coordinates eruption source parameters (e.g., timing, cloud altitude and dispersal direction) with the National Weather Service (NWS), Aviation Weather Unit and Volcanic Ash Advisory Center, who issue volcanic ash warnings and forecasts to the aviation industry. To warn people on the ground and at sea, AVO provides guidance about ashfall to the NWS Weather Forecast Office, who issue ashfall statements, advisories, and warnings for the public and marine communities. For events that may affect communities, the Alaska Department of Homeland Security & Emergency Management initiates multi-agency coordination calls with communities, focusing on impacts to health and infrastructure. AVO's web tools facilitate data sharing: Volcview for visualizing satellite data; volcano-specific web pages consolidating data streams, including ash fallout and cloud dispersion model results; and links to preparedness and mitigation resources. AVO's social media outlets also serve as a critical two-way information portal that aides in preparedness and mitigation of impacts from ashfall.

Operational modelling of umbrella cloud growth in a volcanic ash transport and dispersion model for aircraft hazard mitigation

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During large explosive volcanic eruptions, the buoyant ash plume will expand out laterally as a gravity current at the level of neutral buoyancy to form an umbrella cloud, spreading the cloud upwind and dominating ash transport and dispersion. Dispersion models are used to predict the transport of ash clouds and mitigate atmospheric hazards from volcanic ash but operational modelling activities do not typically include umbrella clouds. For large eruptions, this is a significant limitation in accurate forecasting.
To address this issue, an umbrella cloud scheme has been added to NAME (the dispersion model run by the London VAAC). It is designed for operational use when model runtime is important and limited information is available. The scheme requires estimates of the intrusion height and the volume flow rate into the umbrella cloud. In an operational setting, these parameters can be estimated using empirical formulae and observations of the eruption height. Subsequent observations can refine these estimates. For example, a volume flow rate can be inferred from a time sequence of satellite images or from deposit volume, or the intrusion height can be estimated from satellite imagery.
For the eruptions of Pinatubo (1991), Kelut (2014), Calbuco (2015) and Eyjafjallajökull (2010), we assess the umbrella cloud scheme using different estimates of volume flow rate. Results are validated using satellite observations of cloud growth. We find that the predicted growth of the umbrella cloud is particularly sensitive to different estimates of the volume flow rate. For a wide range of eruption magnitudes, our model gives predictions of radial spreading that agree reasonably well with observations when using a simple empirical formula by Bursik et al. [Bull. Volcanol. (1992)] to estimate volume flow rate from eruption height. We demonstrate further how subsequent observations can refine estimates of the volume flow rate, resulting in improved forecasts.

An intercomparison of two inversion methods for determining volcanic ash source terms using dispersion models and satellite observations

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Volcanic ash in the atmosphere poses a hazard to aviation. Accurate prediction of the atmospheric transport of ash clouds requires a good estimate of time-varying mass eruption rates (MERs) and ash injection heights. However, the source MER of the ash cloud, and the vertical distribution and time variation, are highly uncertain. Consequently, we use inversion techniques to constrain forecast models with satellite observations of ash clouds.

Here we compare two inversion methods: one established by Denlinger et al. (2012) and a second (InTEM) developed by the UK Met Office. Both use a Bayesian approach, assume Gaussian distributions for data and model uncertainty and make use of prior information to constrain model inputs. Different approaches are adopted when observations of ash clouds are insufficient to constrain the ash plume.

Using satellite-derived observations of ash clouds during the eruptions of Eyjafjallajökull (2010) and Grímsvötn (2011), we compare the two methods using SEVIRI data and the atmospheric dispersion model NAME. When an ash cloud is well observed by the satellite, both methods agree favourably, with reasonably consistent forecasts of the cloud position and ash amounts therein. Large differences in the predicted ash cloud exist, however, when ash cloud observations are lacking. Denlinger's method requires observational evidence of atmospheric ash to forecast the cloud. It therefore minimises false alarms but can miss predicting regions of undetected ash. In the absence of satellite observations, InTEM uses an assumed ash cloud source based on prior information. In poorly observed situations, InTEM may falsely predict ash in regions that are ash-free.

Both inversion methods contain transport errors in the dispersion model from uncertainties in meteorological data that increase with ash transport time. Accounting for these errors is an area for future research and development.

Observation of volcanic activity based on chemical analysis of ash leachate: an example of Shinmoedake volcano, southwest Japan

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Analysis of chemical components in ash leachate can be used as an indirect method to determine the chemical composition of volcanic gases and to observe volcanic activity. In this presentation, we introduce an effort to observe the volcanic activity of Shinmoedake volcano, one of the active volcanic peak of the Kirishima volcanic complex in southwest Japan, based on the chemical analysis of ash leachate.

Shinmoedake volcano erupted on 11th to 17th October 2017. To evaluate this eruption, we addressed chemical analyses of ash leachate. Ash samples were sampled on October 11, 12, 14, 15 and 16. As a result of analyses, 151~3600mg/kg of Cl and 17300~26500mg/kg of SO_4 were detected in the ash leachates, and their Cl/S molar ratios were ranged from 0.022 to 0.40. High water-soluble contents, reaching up to several tens of thousands of mg/kg, is one of the characteristics commonly observed in the ash leachate of the phreatic eruption. On the other hand, Cl/S of higher than 0.2 is commonly observed in the leachate of ashes emitted with high-temperature volcanic gases associated with magma ascending (e.g., Ossaka et al. 1983). Hence, high water-soluble contents with high Cl/S ratios in the leachate of the 2017 eruption of Shinmoedake volcano indicate that this eruption was not a typical phreatic eruption yet that was attributed to high-temperature magmatic gases. During the eruption, the time variation was also observed in the Cl/S ratios. On October 11, 12 and 14, Cl/S ratios were 0.31, 0.40 and 0.40, respectively. Cl/S ratios of next two days were obviously smaller than that of first 3days (0.055 on October 15 and 0.022 on October 16, respectively). And then, eruptive activity stopped at the predawn on October 17.

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S01.26 Poster

Measuring physical load required for removal of volcanic ash on roofs

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Globally, volcanic ash cleanup on roofs during eruptions are recommended to reduce the risk of collapse of buildings. However, effective removal of volcanic ash on roofs considering characteristics of ash fall, structures of buildings, physical features of the human body, and so on are unknown in spite of a hard and dangerous operation due to the height involved. The purpose of this study is to investigate exercise intensity during ash cleanup with a shovel on roofs through an experiment to reduce work burdens and improve workability in removing volcanic ash on roofs. Ten people between the ages of 20 to 50 who had not experienced in removing volcanic ash were sampled as workers. Each worker removed volcanic ash with a shovel for 20 minutes on a half-scale model of a pitched roof of a timber-framed house where volcanic ash from Mt. Kirishima and Sakurajima were accumulated. The heart rate of workers was recorded on physical activity meters. The physical activity intensity level was measured using The Borg Scale of Perceived Exertion (RPE). Shovel performances were evaluated by weight of volcanic ash removed from the roof. The maximum heart rates of workers were 120 bpm to 130 bpm and two times as high as the resting heart rates, and they reached two times when the workers removed wet volcanic ash whose water content was 18 %. The rating of RPE were 15 to 19. The shoveling performances were depended on individuals and they were boosted in removing wet ash. Appropriate ash cleanup methods according to physical features of workers and properties of volcanic ash could reduce physical workload and provides favorable workability.

S01.26 Poster

A new method to estimate the source vent location of tephra fall deposits and its implications

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Estimating the source vent location of prehistoric tephra deposits is critical to the reconstruction of their eruptive history and hazard assessment of the particular region. Given insufficient observations, estimating the source vent is hard. Here we present a new method to identify the source vent location of tephra deposits based on thickness or maximum clast size measurements. It couples a gradient descent method with either one of two semi-empirical models of tephra thickness distribution. Thickness and maximum clast datasets of tephra beds from the North Mono eruption, the Fogo A, Trego Hot Springs, and Rockland tephra deposits are used as examples in this study. Their subsets of different sizes and localized subsets are applied to demonstrate its applicability. The results also show that given insufficient sample sites, it is more appropriate to estimate the dispersal axis to constrain the source vent location instead of estimating the coordinates directly. Bootstrap aggregating and examining the surface of the cost function are proposed as measures to characterize the uncertainty in the results, which stresses the importance of *epistemic uncertainty*. The two semi-empirical models have their own advantages and limitations, but the one that assumes an exponential decay with distance to the vent is more robust in the case of sparse dataset. This method does not necessarily require additional information about the analyzed deposit and the potential vents. This flexibility ensures a broader extent of applicability for the method, which could help identify the vent location of tephra deposits using datasets of different size and quality.

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S01.28 - Linking magmatic fragmentation to explosive styles and eruption intensities

The control of conduit processes on magma fragmentation and eruption style at Rabaul, Papua-New-Guinea

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Rabaul in Papua-New-Guinea is an extremely active andesitic caldera complex that displays a large spectrum of eruption styles. Since 1878, four sub-Plinian VEI 4 and ten VEI1–3 (effusive, Strombolian, Vulcanian) eruptions occurred from Tavurvur and Vulcan, the two main active vents. We study the lava flows, bombs and pumices from these eruptions to explore how processes happening during magma ascent in the conduit control eruption dynamics at the surface. Two key parameters are primarily investigated: (1) magma ascent rates and (2) the ability of exsolved gas to escape during ascent.

We measured MSD (microlite size distributions) and MND (microlite number densities) of plagioclases and orthopyroxenes in 16 thin sections to constrain magma ascent rates. While orthopyroxene MSD are concave upwards, plagioclases MSD are straight, which imply a constantly increasing magma velocity during the penultimate part of the ascent. MND decrease from 1–3E+06 to 1E+04 mm^{-3} as eruption intensity increases from lava effusion to sub-Plinian eruptions, showing that microlite crystallization is gradually suppressed due to disequilibrium crystallization as ascent rates increase. Total porosities of samples from the same units increase with eruption intensity, ranging from 20-40% for lava flows, 30-75% for bombs and 70 to 90% for pumices, potentially reflecting a lack of time for degassing as magma ascent rate increases. Permeabilities range from 10^{-16} (bomb) to 10^{-10} m^2 (pumice). Linking permeability and connectivity with total porosity, we estimate a percolation threshold of 45 to 55 %.

The interplay between pressure gradient and magma ascent rate will be explored through 1D conduit flow modelling using Conflow v1.0.5 (Mastin 2011), to further interpret the textural and petrophysical results in terms of fragmentation dynamics. We aim to constrain which parameters dominantly control eruption intensity in a system where conduit dimensions, magma reservoir depth, and overall magma composition are kept constant.

Tracing rhyolite's path from storage to fragmentation: lessons from Chaitén 2008

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Magmatic H_2O is the primary component responsible for explosive activity during Plinian eruptions. An important working model for explosive fragmentation is that overpressure in H_2O-rich bubbles builds to critical levels and eventually drives rapid melt deformation and subsequent embrittlement. This implies that the magmatic H_2O content exerts first-order control on eruptive style, be it explosive or effusive. However, as the ability of volatiles to exsolve from the melt and degas depends on P and T-dependent volatile solubility, in addition to kinetic factors such as the characteristic decompression timescale, bubble growth and attendant melt deformation rates are complicated functions. In order to understand magma fragmentation, we therefore need to track how H_2O, T and P evolve with time, from the initial magma storage reservoir *en route* to the conduit where magma reaches the point of fragmentation. In this work, we analyse the 2008 Plinian rhyolite eruption of Chaitén volcano (Chile) in order to constrain the evolution of magmatic H_2O from start to finish, and to determine how and where rhyolite magma explosively fragments. Chaitén's 2008 eruption presents a unique natural case among many previously studied rhyolite eruptions in that it was carefully observed and thus provides information on initial magma storage parameters, in addition to key temporal aspects of explosive and effusive phases. We present a review of experimental, analytical and field observations that help explain distinct H_2O content ranges or "windows" observed in Chaitén's and other systems' pyroclastic deposits, and argue for an H_2O-content limit on explosive fragmentation amounting to about 1.5 wt.%. We conclude that indeed, the initial magmatic H_2O content is critical for guiding the course of rhyolitic Plinian eruptions, but the timing of eruption transitions hinge sharply on the effectiveness of degassing mechanisms that operate in the shallow conduit.

Silicic eruptive transitions of Las Nieblas eruptive unit, Laguna del Maule Volcanic Complex

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Laguna del Maule Volcanic Complex (LdMVC, 36°S), is located in the Transitional Southern Volcanic Zone of the Andes, and shows ~30 km^3 of silicic deposits (rhyodacites and rhyolites) emitted from >50 postglacial eruptive events (since 16 ky BP). Since 2007 LdMVC has shown a cortical uplift of >20 cm/y that could indicate the beginning of a new eruptive cycle. Thus, the study of silicic eruptive dynamics and transitions in this complex are relevant to understand and mitigate the effects of a possible future explosive silicic eruption in this area.

Las Nieblas rhyolitic unit is the youngest eruption of the complex (~1.8 ky, Judy Fierstein, AGU Chapman 2018). Based on the stratigraphic relationships of the deposits, this eruption began with an initial explosive stage, generating PDC and fall deposits, followed by an effusive stage with the emplacement of a ~1 km^3 lava flow.
Estimations of porosity and connectivity and bubble textural analysis have been applied to pumices from the PDC deposit by He-pycnometer and SEM images. Preliminary results indicate porosities of 0.20-0.74 and connectivities of 48-94%. The connectivity is constantly high (~80%) but decreases with high porosities. Pumice density ranges are wide (0.63-1.91 g/cm^3) but most pumices (~50%) have low densities (≤0.8 g/cm^3). Because of bubbles within PDC pumices are usually elongated and show complex shapes, we suggest that bubble collapse during the explosive magma ascent produced the decrease of pore connectivity and the partial pumice densification. Using a 1-D conduit model of magma ascent with degassing through permeable magma, we showed that densification may be a preliminary feature of the transition from explosive to effusive style. Funded by FONDAP project 15090013.

The size-dependency of shape of vesiculated volcanic particles. Insights from X-ray Microtomography an application to terminal velocity estimations

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The shape of solid particles is a fundamental parameter controlling their transport and sedimentation. Volcanic particles, in particular, are characterized by a wide range of shapes and degrees of irregularity, which are quantified by means of shape parameters. These are needed for implementing the shape as a quantitative parameter in drag formulas, which are in turn used by multiphase flow models for quantifying the interphase momentum coupling. The solid particles produced and injected into the atmosphere during explosive eruptions are characterized by varying ranges of sizes, which need to be taken into account when modelling volcanic processes. Additionally, other particle properties like density and shape are more or less size-dependent, particularly for the juvenile component of tephra. Consequently, acknowledging the grain size dependency of shape is important in volcanology, in particular when dealing with tephra produced and emplaced during and after explosive volcanic eruptions. A systematic measurement of the tridimensional shape of vesicular juvenile pyroclasts of Campi Flegrei fallout deposits (Agnano-Monte Spina, Astroni 6 and Averno 2 eruptions) varying in size from 8.00 to 0.016 mm has been carried out by means of X-Ray Microtomography. Data show that particle shape changes with size, since it is dependent on the distribution and size of vesicles that contour the external clast outline. Two drag laws that include sphericity in the formula were used for estimating the dependency of settling velocity on shape. Results demonstrate that it is not appropriate to assume a size-independent shape for vesicular particles, in contrast with the approach commonly employed when simulating the ash dispersion in the atmosphere.

S01.28 Poster

Magma fragmentation of low viscosity Strombolian explosions at Piton de la Fournaise volcano

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Basaltic volcanism is the most common form of volcanic activity on Earth. Although much less viscous than more silicic magmas, basaltic magma is nonetheless capable of erupting explosively, with Strombolian explosions representing the lower end of this scale. In such eruptions, shallow bursting of a bubble is considered the key dynamic in how the magma manifests at the surface. Little is understood however about the mechanisms which govern fragmentation of basaltic magma following this gas escape. Furthermore, a relationship between gas, magma properties and the grain-size distribution for Strombolian explosions has yet to be fully established.

To better understand this we analyse the July 30 to August 2 2015 eruption at Piton de la Fournaise, Reunion Island where over the three-day period multiple vents were active along a ~1 km fissure, hosting Strombolian activity and lava flows. Combining data from video recordings and photographs, as well as thermal imagery, we detail the eruption and classify the activity from three of these vents into regimes, each based on the explosion characteristics and observed method of fragmentation. Three distinct regimes were present as 1) Sheet-ripping to produce dominantly coarse particles (>10 cm), 2) Stretching to produce coarse and fine particles (<10 cm), and 3) Atomisation to produce dominantly fine particles. Each regime is described in terms of particle ejection velocities, trajectories, and particle distributions and their temporal and spatial evolutions across discrete explosions. Finally, we summarise the eruption by suggesting a model describing the eruption sequence and the dynamics which produced the various regimes.

Lightning-Induced Fragmentation of Ash Particles

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Lightning-induced volcanic spherules (LIVS) have been documented in ash fall deposits from several volcanoes, including those from the 2009 eruption of Redoubt and the 2016 eruption of Pavlof, both in Alaska, USA. These LIVS represent an important record of electrical activity within volcanic plumes. In this study, we examined a range of natural volcanic ash samples and conducted high-current electrical impulse experiments to reveal the fragmentation mechanisms and changes in grain size that can occur over very short timescales (<1 ms) during lightning discharge events. Experiments on pseudo-ash samples manufactured from rhyolites show that aggregates of very fine ash particles (< 32 micrometers) melt and degas to form vesiculated pumice fragments several tens of micrometers in size. In some cases, bubbles <5 micrometers expand and detach from the outer surface of the pumice to form hollow spheres of glass, one type of LIVS.

Natural volcanic ash from Redoubt contains pumiceous grains 13-72 micrometers in diameter that are tear-dropped in shape, contain vesicles <10 micrometers in diameter but no observable microlites, and have smooth glassy perimeters, unlike other ash-sized pumice that contain microlites and have rough perimeters. The Pavlof sample revealed 127 LIVS with an average size of 3.5 micrometers in diameter. The Pavlof LIVS are attached to larger ash grains or to each other, and are deformed at the attachment points.

Through comparison between the experimental and natural samples, it appears that the Redoubt sample contains pumice formed from lightning-induced vesiculation of ash, in addition to individual LIVS, and the Pavlof sample contains LIVS formed from individual vesicles that expanded and detached from vesiculating fragments. Based upon these experimental and analytical results, we hypothesize that lightning discharge can alter the grain size distribution of ash within the eruptive plume through vesiculation and fragmentation of individual particles or ash aggregates.

Understanding the maximum-likely eruption hazards at Mt. Tongariro, New Zealand

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The Tongariro Volcanic Complex in the central North Island of New Zealand is unusual in comprising many widely dispersed eruptive centers within an active graben. The complex has a highly irregular sporadic history of clustered very large explosive eruptions (0.5-1 km^3) occurring alongside more frequent small-scale events <0.01 km^3. In order to understand the "maximum likely" eruption hazard, we studied the deposits of the most recent major paroxysm 11,000 years ago. During a <200 year period at least six large-scale plinian eruptions occurred from multiple vents. We identified the main eruptive vent areas of these events, reconstructed details of their varied eruptive scenarios and calculated eruption column heights, volumes and mass eruption rates for the climactic phases. Sustained eruption columns reaching 20-33 km with mass eruption rates in the order of 10^8 kg/s occurred during four of the eruptions. Two events involving two separate sub-Plinian to Plinian eruption columns erupting simultaneously from different vent areas. One eruption is characterized by pulsating and repeated column collapse, producing large-scale pyroclastic density currents. Initial eruptions began from vents in the southern and central areas of the edifice. These were also the most active, often erupting simultaneously. Those in the central and northern part of the complex were active during the last and largest eruptive phase, producing four distinct tephra distribution lobes towards the NW, NE, SE and SW with a total volume of ≥2 km^3. These results show that eruptions of different sizes, different both contemporaneously and sequentially (during different wind fields) may be expected at this and similar volcanic centers, posing great challenges in volcanic hazard planning.

S01.28 Poster

Prediction of particle properties from observed eruptive activity: Evidence and implications for rapid risk assessment

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Fresh volcanic ash, whether airborne or as pristine fall deposit, presents a hazard to health, transport, industry, environment and infrastructure. The risk from these hazards is greatest where active volcanoes and densely populated areas coexist: in these areas, mitigation strategies must respond rapidly and effectively during periods of unrest and following an eruption. The rapid assimilation of volcanic ash particle characteristics permits timely improvements to risk management, monitoring and forecasting strategies. However, there have been no rigorous efforts to predict volcanic ash particle properties based upon the observed volcanic activity, Here, we present a set of analyses on natural and experimental pyroclasts with this goal. By simulating natural ash production using shock tube, abrasion and rotary friction apparatuses, the fragmentation regime and conditions can be controlled and pyroclasts can be fully retrieved.

In addition to particle size distribution and shape measurements that show consistent variation between experimental methods and eruptive activity, we present a novel analysis of surface composition. Using QEMSCAN, an automated mineralogy technique, we produced micron-scale maps of thousands of ash particles in each sample. The proportion of some phases, particularly groundmass glass, plagioclase and pyroxenes are found to vary significantly at particles boundaries compared to the bulk. The pattern of enrichment and depletion of phases is shown to relate to the fragmentation mechanism, and correlations between experimental and natural samples indicate a robust and repeatable signal.

The combination of these measurements allows a provisional 'map' to be drawn up that connects observed volcanic activity to characteristic particle properties. As more natural and experimental case studies are added, the map will continue to be improved and expanded. We anticipate this map may provide benefits to mitigation strategies at the case study volcanoes, while a more general application may be possible in the future.

Non-linear effects on stress and brittleness of viscoelastic fluids under transient deformation with large strain rate

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Flow-to-fracture transition of viscoelastic fluid is a fundamental problem in magma fragmentation processes during volcanic eruptions. It is considered that brittle fracture of flowing magma occurs when the strain rate exceeds some critical value close to 1/T, where T is the relaxation time. Strain rates may even exceed 1/T during brittle fracture. In these processes, a rheology model representing transient magma behavior at large strain rate and stress rate is required. Recent laboratory experiments demonstrate transient rheology of magma and magma analogues, but most models are still based on either a linear Maxwell viscoelastic model or a steady state viscosity model as a function of strain rate. Here we examine non-linear Maxwell-type rheology models. Three main factors that lead to the non- linear terms are (1) the convection of large deformation with stretching and rotation, (2) deformation and relaxation of internal structures, and (3) Brownian motion of particles under shear. We solved these models for given transient simple shear and pure shear. It is shown that for the same given strain rate, temporal change of stress, apparent viscosity, and brittleness of deformation significantly vary among the models, particularly when the strain rate is close to or larger than 1/T. The behaviors of one model are also quite different between simple shear and pure shear. Although the problem has already been known, it has not been systematically studied. We emphasize the importance of establishing a non-linear rheology model for magma in dealing with fragmentation phenomena and propose possible laboratory experiments toward the goal.

How do basaltic magmas fragment? A numerical investigation through the ascent dynamics of the 122 BC Etna Plinian eruption

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Among the different eruptive styles that a volcano can exhibit, explosive eruptions are the most intense and violent. As magma rises through the conduit, the confining pressure decreases, causing dissolved volatile species to exsolve from the melt, forming gas bubbles. As pressure further decreases, bubbles rapidly expand and accelerate, which may lead, ultimately, to magma fragmentation, the defining feature of explosive eruptions. The high viscosity of silicic magmas favours Vulcanian, sub-Plinian or Plinian explosive activity. Violently explosive eruptions are less common at basaltic volcanoes, but Plinian eruptions of moderate intensity, are known. For example, Mt. Etna (Italy) has produced infrequent Plinian eruptions, such as the one that occurred in 122 BC, which had an inferred mass discharge rate of $\sim 10^8$ kg/s. However, the mechanisms controlling magma fragmentation during highly explosive basaltic Plinian eruptions remain unclear.

Here we investigate the conditions which lead to fragmentation of basaltic magmas by adopting a multiphase, multicomponent 1D conduit model, and using the 122 BC Etna basaltic Plinian eruption as a test case. We investigate several fragmentation criteria: the strain-rate, stress, and inertial criteria. Our results show that, when fragmentation is achieved, it always occurs just a few meters below the vent. Furthermore, our results highlight that a strong and rapid increase in viscosity seems to be the key condition to achieve fragmentation. 4D crystallisation experiments performed at Diamond Light Source (beamline I12), at an undercooling consistent with that of basaltic Plinian eruptions, suggest that crystallization can occur within a few minutes, producing the increase in viscosity required to achieve fragmentation.

Pyrrotite oxidation as a proxy for air entrainment in eruption columns

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Entrainment of air by turbulent mixing into eruption plumes is a primary control of explosive styles. Degree of pyrrhotite breakdown has been proposed as a proxy for magma oxidation and cooling by entrained air in the 1914 Plinian eruption at Sakurajima (Matsumoto and Nakamura, 2017). To verify and further investigate the potential use of pyrrhotite oxidation for estimating eruption intensities from pyroclasts, we have examined the 1783 Plinian eruption of the Asama volcano, which has a similar eruption intensity and magmatic temperature to those of the 1914 Sakurajima eruption (VEI=4), and a small Vulcanian explosion of Sakurajima in 2017 with a plume height of <1000 m (VEI<1).

We found a variety of reaction texture of microphenocrystic pyrrhotite in the pumice of Plinian eruption and ashes of Vulcanian explosion as follows: (1) unreacted pyrrhotite, (2) pyrrhotite partially replaced by magnetite polycrystals, (3) magnetite polycrystals completely replacing pyrrhotite, (4) polycrystals of magnetite and hematite with relict pyrrhotite, and (5) pyrrhotite pseudomorph composed of magnetite and hematite. The oxidation progresses from (1) to (5) judging from the proportion of the relict pyrrhotite in the pseudomorph. The area fraction of magnetite and hematite for type (2) and (4) in the 1783 Asama Plinian-pumice is several tens of percent, which is similar to that for the 1914 Sakurajima Plinian-pumice. On the other hand, the proportion in the 2017 Sakurajima Vulcanian ash is <5 percent. This difference can be attributed to the duration in which temperature of pumice and ash particles were kept high in the eruption plumes. These results underscore the potential of pyrrhotite oxidation to constrain temperature and oxygen fugacity of eruption plumes that might reflect the fragmentation dynamics and contribution of surface water.

Insight on eruptive dynamics from the reconstruction of the Total Grain Size Distribution: examples from Campi Flegrei.

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The knowledge of the Total Grain Size Distribution (TGSD) of an eruption is one main factor for reducing uncertainty in quantitative forecasts of ash cloud dispersal. A few TGSDs have been made available in the literature, which were reconstructed by assuming that tephra deposits consisted of one single component. Since tephra are made up of multiple components, each having a specific aerodynamic behavior that depends on particle shape, density and size, we propose a procedure for reconstructing the TGSD by considering each component of the eruptive particle mixture.

In framework of the quantitative hazard assessment of tephra fallout at Campi Flegrei, we applied the proposed method to the deposits of the Agnano-Monte Spina and Astroni 6 eruptions. Field investigation and laboratory analyses on samples collected from proximal to distal locations (up to the distance from the vent of about 460 km) allowed obtaining the input data for the reconstruction of the TGSDs of juvenile, lithic and crystal components by means of the Voronoi tessellation method.

Results show that the bulk TGSD is the combination of the overlapping of different component subpopulations. For all the identified components, the shape of the TGSDs, their size and their percentage of areal distribution were a function both of the range of initial grain size spectrum of each components and their different aerodynamic behavior inside the eruptive columns and the distal cloud.

In addition, we found that the spatial distribution and sample distance from the vent of the samples' locations represent one main source of uncertainty in the resulting TGSD. The integration, in the data set, even of a few additional samples, drastically changes the TGSD results, especially of those collected from the distal locations.

Finally, the integration of data from the distal locations allowed redefining the volume of fallout deposits of three studied fallout unit.

Volcanic ash aggregation enhanced by seawater interaction: the case of Secche di Lazzaro phreatomagmatic deposit (Stromboli)

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The Secche di Lazzaro formation (6.2 Ka) is a phreatomagmatic deposit situated in the southwestern part of the island of Stromboli (Aeolian Archipelago, Italy). Accretionary lapilli (AL) are particularly abundant in the lower part of the volcanic sequence and are characterized by strong cementation between the particles and an uncommon resistance to breakage. To understand the processes behind the formation of Secche di Lazzaro AL a multi-analytical approach was used on the lapilli aggregate (LA), and on single accretionary lapilli. In particular, we carried out granulometric analysis, Field Emission – Scanning Electron Microscopy (Fe-SEM and Electron Microprobe Analysis (EMPA), X-ray powder diffraction (XRPD) and a series of 3D imaging by X-ray micro-tomography (X-mCT). The granulometric analysis showed that most particles in the lapilli deposits have a diameter equal to phi -1 corresponding to 2 mm particles aggregates. The FE-SEM images provided the chemical distribution within individual lapilli allowing to identify rim and core zoning as well as to detect halite (NaCl) located both on the border of a single lapillus and on the juncture among different lapilli. Moreover, halite also occurs among different aggregates in a single lapillus, thus acting as a binding agent, as well as within rim pores. The EMPA, FE- SEM and XRPD analyses revealed the presence of different phases, mainly plagioclase, K- feldspar, halite, and clinopyroxene, together with volcanic glass. Finally, from the X-mCT analysis, we constrained the particle distribution and quantified the porosity of LA and AL. The work presented here shed new light into the formation of accretionary lapilli in phreatomagmatic eruption involving marine water. We demonstrated that seawater plays a fundamental role in enhancing aggregation and the presence of salt contributes to the stiffening of the particle and to the cementation of the deposit.

S01.28 Poster

Volume and total grain size distribution of an Hawaiian fountaining event: case study of the 1959 Kīlauea Iki eruption, Hawai'i

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The 1959 Kīlauea Iki eruption on Hawai'i generated a succession of spectacular fountains, most reaching hundreds of meters high. The 16 episodes of fountaining persisted intermittently (including repose periods of between 7 hours and 4 days) for 36 days. They produced tephra deposits that were dispersed several km downwind of the vent, and a much larger volume of clastogenic lava which drained into the Kīlauea Iki crater to form a >100 m deep lava lake. Field data from 215 tephra sample pits downwind of the vent allows 1) for the constraint of the total grain size distribution (TGSD) of the tephra deposit, and, 2) for the imperfect reflection of the episodic nature of the fountaining behavior: only five stratigraphic subunits from the total 16 fountaining episodes can be mapped in the field. Isopach maps of these subunits are generated, and, by the application of empirical deposit thinning relationships, volumes of each subunit are estimated. In combination with detailed observations made in 1959, our field data allow us to assign stratigraphic subunits to either single or aggregates of several fountaining episodes. The most voluminous stratigraphic tephra deposits are linked predictably with the highest fountaining, not with the longest in duration. In fact, a minimum fountain height of >100 m is required for Kīlauea Iki to allow downwind tephra dispersal due to the vent's location 100 m below the crater rim. The end of high fountaining episodes produced ash-rich partings, which are found on top of the lapilli-sized products of many episodes. This study outlines the dependency of tephra dispersal on fountain height and emphasizes the remarkable capability of an episodic Hawaiian fountaining eruption to generate a seemingly monotonous downwind tephra deposit.

S01.28 Talk

Real time geophysical monitoring of grainsize distribution during volcanic eruptions

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Real time geophysical monitoring is fundamental tool for tracking and understanding volcanic activity and real time hazard assessment. Among the key parameters needed to inform forecast models, real-time tracking particle size distribution (PSD) of pyroclasts leaving the vent coupled with plume modeling has probably the highest potential for improved hazard assessment and effective management of volcanic crises.

To fully explore the potential of thermal monitoring system in providing vent leaving syn- emission PSD in real time, coupled with eruption source parameters, we developed a fast, low processing power, algorithm to process PSD from small scale explosions. We selected Stromboli volcano (Italy) as our validation site as it is a reliable particle emitter with well known PSD and eruption characteristics. We analyzed a series of small scale Strombolian explosions occurred in 2012. Our approach allows us to link the dynamic relation between PSD and eruption source parameters over very short timescales.

The explosions actually begins with a gas jet that has the maximum recorded vertical velocity (above 150 m/s). The gas jet is quickly (after a few 10ths of a second) followed by the particles. The particles increase in number, but decrease in size and speed with time, until they reach a steady level, resulting in stable MDR throughout the event. By analyzing high temporal resolution thermal profiles across the explosion jet we reconstruct PSDs and their temporal evolution. High temporal resolution PSD data coupled with eruption source parameters provide essential information for the understanding and quantification of magma fragmentation in Strombolian regimes. Our method allows us to measure and tracks instantaneous mass fluxes during a single, explosive event and to quantify the instantaneous partitioning between number and mass of particles (i.e. fragmentation efficiency) which is variable but balances to stable MDR.

Characterization of magma fragmentation from different eruptive styles of Vesuvius volcano, Italy

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Among active volcanoes worldwide, a few are located in highly populated areas such as Vesuvius in Italy. Vesuvius is quiescent since 1944, but geological and historical records reveal a frequent violent explosive activity in the last 4000 years, implying severe hazards for the ~700000 inhabitants living in the red zone (the area having a high probability of being impacted by pyroclastic density currents) and more than 1 million people potentially affected by tephra fallout. For this reason, Vesuvius is among the most monitored volcanoes in the world. This study aims at analysing the distribution of tephra fallout deposits and grain-size data from several Vesuvius eruptions of different styles, ranging from Strombolian to sub- Plinian and Plinian, for characterizing the associated magmatic fragmentation through the total grain- size distribution (TGSD). Chronologically, we focused on the Avellino (3900 years ago) and Pompei (79 AD) Plinian eruptions, the Pollena (472 AD) sub-Plinian eruption, and the 1906 and 1944 violent Strombolian eruptions. The related TGSDs were estimated by means of the Voronoi tessellation method, which,beside a suitable number of local grain size distributions, requires the delimitation of the tephra loading (zero-line). TGSDs for the different eruptive styles are needed by tephra dispersal models for predicting or reconstructing the tephra loading and airborne ash dispersal. However, due to geological data limitations, field-derived TGSDs can be biased towards the coarse and fine populations. To encompass this issue, we performed a sensitivity study on the assumption behind TGSD reconstruction and we also estimated a few analytical distributions best fitting the field TGSDs. This study aims at better constraining the eruption source characterization at Vesuvius, crucial for robustly predicting tephra loading and airborne ash dispersal of future eruptions at Vesuvius.

Automated SEM/EDX morpho-chemical single particle (ash) analysis: A powerful tool to monitor active volcanoes and understand past volcanic activities

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Volcanic ash is of great interest to volcanologists because it delivers unique information on the eruption style. However, the componentry of the fine-grained fractions of volcanic deposits remains largely unexplored because component analyses of fine material (< 3phi) by conventional methods are very tedious and time-consuming.

Single-particle analyses by Scanning Electron Microscopy (SEM) coupled to Energy Dispersive X-ray Spectroscopy (EDX) is a powerful method to characterize any kind of particles in the range of tens of nanometers to hundreds of micrometers. The automation of the method allows characterizing quantitatively the size, morphology and elemental composition of thousands of particles within few hours. This technique has been extensively used in the study of the impact of aerosol particles on health and climate, as well as for applications in the mining industry and in geosciences. The newest advances in the acquisition and data treatment software makes this method extremely effective and meaningful because the former drawback of interpreting large and complex data sets manually is largely overcome.

The SEM/EDX method is being tested for different purposes: (a) monitoring of active volcanoes, (b) in depth studies of eruption mechanisms by studying older deposits and (c) modelling of ash dispersion and deposition. On the one hand, activity changes of active volcanoes can be detected through the morpho-chemical characterization of the emitted ash and aerosol particles as e.g. identifying/characterizing a new magma batch (Kilauea, Hawaii, USA) or determining the distribution and concentration of potentially hazardous sulphur-bearing aerosols in populated areas (Solfatara di Pozzuoli, Italy). On the other hand, the componentry of single layers can be extremely helpful to identify the juvenile material of a specific eruption episode (Azufral, Colombia and Eifel, Germany) and to understand the specific role and interactions between the various players (i.e. crystals, lithic, accessory, and juvenile clasts) during a volcanic eruption.

Quantitative texture analysis of the May 18th 1980 pyroclastic density current deposits of Mt St Helens: preliminary results

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The quantitative texture analysis (QTA) is an instrument of paramount importance for the modern study of pyroclastic deposits. Using remotely captured images and stereology it is possible to analyze the texture completely, quickly, accurately, with the possibility of automating an important part of the analytical process. The method provides critical information regarding the fragmentation efficiency of an eruption, segregation and bulking processes, flow dynamics during transport, as well as flow directions and deposition mechanisms.

During last decades we developed a series of hardware and software tools dedicated to QTA, which provides optical granulometry data, morphological clast descriptors and clast fabric information. The analyses are based on scaled images acquired remotely (by drones or telephotography) processed in order to extract the maximum information. The images, properly segmented, are analyzed with image analysis programs developed in our labs and diverse texture parameters are calculated. Among them, optical granulometry, clast morphology and grain shape fabric.

QTA have been applied along the extensive outcrops across the pumice plain of Mount St Helens, which expose up to 40 meters of debris avalanche and pyroclastic flow deposits from the 18 May 1980 eruption. In this work, besides giving an overview of the used methods, we show a preliminary analysis of the textural data collected during five campaigns at Mt St Helens. Textural data obtained are used as complement to classic volcano-sedimentology information and, together, allows an integral study of each depositional unit. Such analyses show vertical and longitudinal variation along any of the depositional units and can be useful to decipher the complex depositional scenario. Fluctuation in texture parameters and changes in fabric indicators, suggest the mixing of different pyroclastic density currents, forced to diverge or merge due to the presence of debris avalanche hummocks along their paths.

S01.28 Poster

Stratigraphy of the post-caldera explosive volcanism of the La Primavera Caldera Volcanic Complex, Jalisco, Mexico

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The Primavera Caldera Volcanic Complex (PCVC) is a Quaternary rhyolitic complex located in the western part of the Trans-Mexican-Volcanic-Belt (TMVB). The Primavera caldera was formed 95 ky ago (Mahood, 1980; 1981) with the eruption that produced the ignimbrite called Toba Tala. After the collapse, an internal lake formed along with several domes and stratovolcanoes that were emplaced along the ring-fault, inside, and outside the caldera. The activity of these volcanoes produced a complex set of pyroclastic deposits that was poorly understood. To define the Primavera post-caldera explosive activity, extensive fieldwork was performed to define the stratigraphy of pyroclastic deposits and their relationship with their lavas and domes from which they were vented. This detailed correlation was assisted by granulometry, componentry, whole-rock chemistry, and U/Th dating in zircons. With this information we have characterized at least eight subplinian to plinian eruptions separated by paleosols or lahar deposits that have been dated between 88.9 and 44 ky. Distribution of air-fall deposits and deposits of pyroclastic density currents indicate that these eruptions were sourced at four different sites (Nejahuete, San Miguel, Planillas, and Tajo).

In the Total Alkalies vs. Silica (TAS) diagram and SiO_2 vs K_2O, all pumice and dome samples are peralkaline rhyolites (72.5-74.7 wt. % in SiO_2) with high K_2O contents (3.95-4.8 wt. % in K_2O). Careful granulometry, componentry, density, and modal analyses of the deposits indicate that they have subtle differences in color, vesicularity, and crystal contents for which we have been able to distinguish their source.

Therefore, a new evolution model of the PCVC is under construction based on all the new evidence gathered in this study and other parallel projects of the P15 geothermal project CeMIE Geo (Centro Mexicano de Innovación en Energía Geotermica).

Key words: Primavera Caldera Volcanic Complex, Stratigraphy, Plinian and subplinian eruptions, Pumices, U/Th dating.

Ash variability reflecting unexpected range and hazardous fragmentation processes on the recent eruptive activity at Piton de la Fournaise (La Réunion Island, France)

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It is commonly accepted that lava flows represent the main emitted magmatic volume in basaltic shield volcanoes, as at Piton de La Fournaise (PdF). In addition, eruptive activity at PdF occurs mostly within the non-populated caldera and generally does not cause any risks to the population. However, historical observations and recent monitoring data suggest that some eruptions at PdF produce unusual explosive phases that can affect the surrounding environment of the volcano. A comprehensive sampling of tephra from some major historical (Piton Chisny, 1860 eruption) and recent (April 2007 and 2014-2018 events) eruptions allowed us to perform systematic grain size, componentry, morphological, textural and chemical analysis in order to characterize tephra formation. This integrative and innovative approach reveals very different characteristics of the studied tephra reflecting different fragmentation processes. Various intensities of primary fragmentations from tephra emitted during Hawaiian fountaining and weak Strombolian explosions are the most common fragmentation mechanisms observed (Piton Chisny, 2014-2018 eruptive sequence). Two unusual fragmentation processes occurred during the April 2007 eruption. First, a distal ash plume that affected the populations along the eastern coast of the island, was alimented by repeated explosions triggered by the interaction between the Tremblet lava flow and the sea water. Few days later, a major ash plume formed during and following the collapse of the summit caldera. The 1860 ash was probably emitted during a phreatomagmatic phase and linked with a caldera enlargement. These latter ash is then compared to relatively different and more recent phreatic and phreatomagmatic tephra from Karthala volcano (Comoros). More recently, we have evidenced plug pressurization-driven fragmentation within the September 2016 eruption at PdF which produced transient ash plumes. To summarize, the comparison of old and recent ash highlights a wide range of hazardous fragmentation processes in a basaltic context.

Tracking the multiphase explosive activity of the rhyolite, subplinian Kaharoa eruption of Tarawera volcano (New Zealand): new insights from tephra deposits

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Mid- to large-scale eruptions typically consist in a composite succession of individual eruptive phases, characterized by: (i) quantifiable intensities and magnitudes, (ii) specific dynamics of the volcanic processes involving the rising and erupted magma, and (iii) styles of the resulting eruptive activity. Similar eruptive phases may repeat sequentially during an eruption or may alternate with phases of different activity. This makes the time-variant evolution of eruption behaviour hard to constrain, particularly at active volcanoes with limited or not available historical records. Detailed field studies of tephra deposits and investigations on their sedimentological and textural features provide the main source of information to understand the complex sequence of events typical of these eruptions.

In this context, we investigate the AD 1314 Kaharoa eruption, the youngest, rhyolite eruption of Tarawera volcano. The eruption developed from multiple vents distributed on an 8-km-long lineament across Mt. Tarawera. The eruption exhibited a complex succession of events, including initial sub-Plinian to Plinian explosions with associated pyroclastic density currents (PDCs), and extrusions of lava domes. This study focuses on the explosive phases recorded in the Kaharoa deposit, dispersed in proximal to medial sites. Preliminary results from field observations, grain-size and componentry analyses indicate that the Kaharoa eruption was an episodic (occurrence of short time breaks) and unsteady (fluctuations in mass discharge rate) eruption. The stratigraphic architecture of the Kaharoa tephra sequence consists in several pumiceous lapilli-bearing units, interbedded with layers of ash. While the lapilli units are interpreted as the results of the deposition from individual convective columns, origin(s) of the ash layers are still under investigations. Lapilli units' sedimentological features suggest a slightly different evolution for each event, characterized by changes in eruption intensity. Furthermore, in proximal area this fall- dominated sequence is capped by PDC deposits, suggesting important changes in the eruption dynamics.

Sub-second parameterization of eruptive dynamics of some 2017 explosions at Stromboli volcano, Italy

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The explosive basaltic eruptions at Stromboli Volcano (Aeolian Islands, Italy) are highly dynamic and display shifts in style and intensity on short time and length scales, that cannot yet be predicted. Within minutes, the observed eruptive behaviors can change from passive outgassing through isolated bubble bursts, accompanied by the ejection of pyroclasts to heights of 100s of meters. The frequent eruptions (several each hour) of Stromboli have created persistent issues for management agencies because the site is highly accessible to visitors; this creates a need to balance the strong popular interest in viewing explosions against the issue of public safety. Identifying the processes and features that underpin the observed rapid temporal shifts in eruption style and intensity is essential for risk assessment and for the safety of the thousands of tourists who visit Stromboli each year. To understand what drives the changes in style and intensity of explosions, we link high-speed (500 frames per second), high-definition (2560 x 1920 pixels), ground- and air-based observations of eruption dynamics (such as ejection velocity and mass eruption rate) with (1) in-flight grain size distributions, and (2) geophysical signals. Our goal is to attribute the observed styles and transitions of explosions to variations in physical processes in the vent and shallow conduit. This presentation will focus on fine-scale variations of pyroclast ejection velocity within short-lived explosions from a single very active vent in September 2017, and touch on the diversity of eruptive behaviors.

S01.28 Poster

Characteristics of the Fallout Pumices from two stages of the Millennium Eruption in Changbaishan volcano, NE China

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Changbaishan volcano located on the border between China and the Democratic People's Republic of Korea, is one of the largest active volcanoes in China. The 946 AD eruption with VEI of 7 (also called the Millennium eruption) is considered to be one of the largest eruptions in the past 2000 years. The eruption history and the stratigraphic sequence of Changbaishan volcano have long been the focus. The stratigraphic division of fallout pumices in the past millennium is controversial, especially for the mixed colored pumice (erupted from the Yuanchi stage) above the greyish-white pumice (erupted from the Chifeng stage). In this study, it is believed that two pumice phases should be classified into the Millennium eruption through the detailed field exploration. The greyish-white pumice in Chifeng stage is relatively homogeneous, with angular shape, normal grain sequence and good sorting. The eruption of Yuanchi stage is in the pulsing pattern, and the strata show interbedding of rich yellow pumice layer and rich black pumice layer. The pumices with angular shape show inconspicuous grain sequence and good sorting. Both the granularities of the pumice particles from two stages fall into the air-fall field in the median diameter versus sorting diagram. The Chifeng pumices are comendite in composition, and have large, continuous vesicles and thin vesicle walls. The Yuanchi yellow pumices are trachyte in composition, have continuous vesicles but thicker vesicle wall than the Chifeng pumices. The Yuanchi black pumices with the lowest vesicularity are also trachyte, but have obviously lower SiO_2 content than the yellow pumices. The differences are also showed in the trace and rare earth element abundances. The above results show that the eruptive intensity of the Yuanchi stage is weaker than that of the Chifeng stage and the several magmatic compositions reveals a complex magma system under the Changbaishan volcano.

S01.28 Poster

The influence of post-depositional processes on distal tephra beds: A case study of the 12,900 BP Laacher See Tephra at Paddenluch outcrop, northeastern Germany

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The c. 12,900 BP Plinian eruption of Laacher See Volcano, Germany, deposited a widespread phonolitic tephra bed across much of Europe. Its wide dispersal makes the Laacher See Tephra (LST) an important isochrone for the Allerød interstadial that connects the tephrochronological records of Central Europe with the North Atlantic and the Mediterranean.

While the distal LST occurs in the same stratigraphic and palynological context providing consistent age brackets for the eruption, it shows variations in sedimentological characteristics between locations, such as thickness, contacts, scatter and bedding, and in the compositional range of glass shards. Some studies even report two or more distinct LST beds that have been interpreted as precursor eruptions although the evidence for this is weak. The aim of this paper is to identify post-deposition processes that could result in duplication of a single tephra layer.

Field measurements such as deposit thickness, isomass maps and grain-size distribution are often used to reconstruct the nature of prehistoric volcanic eruptions, including eruptive volume, eruption dynamics, magnitude and column height. It is thus important to understand the factors that influence the preservation potential, nature and degree of reworking of the primary tephra bed within the sedimentary record to reduce uncertainties in the obtained field data, in particular regarding accurate thickness measurements.

We evaluated post-depositional processes that could have modified primary LST layer(s) at Paddenluch near Ruedersdorf, Germany. Here, we sampled LST from cores and profile exposures, and varied coring sites and core number to assess their reliability and efficiency for tephra measurement, sampling and sedimentological analysis.

Our study suggests that post-depositional, periglacial processes can generate significant variation of a single, primary LST horizon, including bed thickness, internal sedimentary structures and secondary layers, even over several meters at exposed profiles. The findings are discussed in relation to previous reports of precursor eruptions.

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S01.29 - Reconstructing the recent histories of active volcanic system as a key for volcanic hazard assessment. Developing new tools and sharpening old ones

New unspiked K-Ar ages of Holocene lava flows and pumices from the Ecuadorian arc

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In the northern Andes, the Ecuadorian arc presents more than 80 Quaternary volcanoes, including 25 active during the Holocene. Reconstruction of the past eruptive history of these volcanoes is essential to understand their activity frequency and eruptive dynamics evolution, and for hazard assessment. The groundmass unspiked K-Ar dating method is particularly suitable for dating young subduction lava flows, which contain low K and high Ca contents. Our youngest ages obtained for Holocene lava flows from Tungurahua and Chimborazo volcanoes and Calpi cones range between 8 ± 2 and 4 ± 2 ka, with a K content of about 1.5-2%, and a radiogenic argon content varying between 0.06 and 0.18%, for a narrow density range groundmass. These new ages are consistent with stratigraphy and morphologic observations, and are in agreement with previous published ^{14}C age determinations. We also performed K-Ar measurement on pumice glass shards from the Chalupas ignimbrite, which originate from an ultra-plinian eruption and constitute a major stratigraphic marker in Ecuador. The pumice blocks were gently crushed by hand in an agate mortar, sieved, then grains were separated using heavy liquids. Such procedure allows to preserve massive structure of the glass shards and remove altered or vesicular shards. We obtained the age of 216 ± 5 ka, which agrees with a previous unpublished $^{40}Ar/^{39}Ar$ age (211 ± 14 ka), and is in agreement with age models of Pacific marine cores, where tephra of this eruption were founded. Our results therefore show that the K-Ar dating method on groundmass can be successfully applied for fresh Holocene lava flows, and for pumice glass shards of the most explosive eruptions, which cannot be dated by the $^{40}Ar/^{39}Ar$ technique due to ^{39}Ar recoil occurring during irradiation.

S01.29 Talk

Geochemistry and stratigraphy of Late Pleistocene to Holocene Icelandic volcanic eruptions recorded in marine sediment cores southeast of Iceland

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Large Icelandic explosive eruptions can have regional to global impacts. To reconstruct the temporal evolution of the Late Pleistocene Icelandic explosive volcanic activity, we geochemically and stratigraphically investigated tephra in four up to 10 m long marine sediment gravity cores obtained during RV Poseidon Cruise 457 at distances of 60-180 km southeast of Iceland. Using major element analyses of volcanic glass shards, we determined their provenance and distinguished individual layers stemming from the same volcanic systems. More than 50 ash layers with predominantly basaltic compositions reveal changes in activity at the Icelandic volcanic systems from the Late Pleistocene to the Holocene. Our results show that Grímsvötn has been the most active volcanic system with phases of particularly high activity at the time of GI-8 and 12 (Greenland Interstadials). Based on the studied tephras, Kverkfjöll volcanic system was most active between the end of GI-3 and 27 ka BP, when the wide-spread Fugloyarbanki tephra was produced. This is in stark contrast to the minor activity attributed to this system in the Holocene, at which time we observe higher activity at the Bárðarbunga and Hekla volcanic systems. Katla volcanic system shows increasing activity towards the younger phases of the studied Late Pleistocene record. The rhyolitic shards of Vedde composition in the deeper sections of the cores suggest silicic eruptions at Katla Volcanic system since at least 50 ka BP. Finally, we geochemically characterize basaltic tephra layers of unknown Icelandic volcanic provenance. Our study extends the Icelandic eruption record much further back in time (from ~14 to approximately 68 ka BP) than previously inferred from the terrestrial Icelandic deposits and to higher resolution than determined from distal deposits.

S01.29 Poster

^{14}C and U-series disequilibria age constraints from the P1-P17 eruptions at Sete Cidades volcano, Azores

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Carbon-14 dating is the preferred technique for dating young geologic materials, but studies have suggested that volcanic degassing can result in erroneously old ^{14}C dates [1]. We obtained ^{14}C data from paleosols and ^{226}Ra-^{230}Th ages in associated pumices from the youngest eruptive sequence of Sete Cidades volcano (P1-P17), São Miguel, Azores. ^{226}Ra-^{230}Th disequilibrium in a P1 glass separate indicates a maximum eruptive age of 4440 ±195 y. ^{14}C ages of paleosols below P1 and P3 are older than corresponding ^{226}Ra-^{230}Th ages, at 7293 ±141 y cal BP and 7698 ± 172 y cal BP, respectively. Similarly, the ^{226}Ra-^{230}Th maximum eruptive age of glass separated from the P8 eruption is 2659 ±55 y, whereas the age of the paleosol sampled directly beneath P8 is older (3054 ±194 y BP). In contrast, paleosols sampled from below the most recent eruptive deposit (P17) at multiple field localities are within error of each other (476 ±56 cal y BP and 585 ±68 cal y BP), while ^{226}Ra-^{230}Th maximum eruptive ages in glass separated from two different P17 sampling sites are 762 ±14 y and 730 y ±15 y. Additionally, ^{14}C ages of the modern terrestrial gastropod Cornu aspersum demonstrate the effects of dilution from a range of current outgassing levels at three active stratovolcanoes on São Miguel, Sete Cidades, Fogo, Furnas, and the extinct Povoação volcano. Modern gastropods sampled at Furnas and Fogo, where there is evidence of extensive present-day degassing, have ^{14}C ages of 394 ±97 y cal BP and 1324 ±60 y cal BP, respectively. In contrast, there is currently no apparent outgassing occurring at Sete Cidades or Povoação, and modern gastropod ages from these volcanoes are post- bomb. These data highlight the utility of combining multiple dating methods when investigating eruptive recurrence intervals in Holocene volcanic systems.

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A one-shot wonder or a continued volcanic threat? Rangitoto Volcano, Auckland City

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Rangitoto volcano is the largest (~2 km^3) volcano in the Auckland Volcanic Field (New Zealand) with the youngest known activity (550 yrs B.P.). It is an island that lies within the Waitemata Harbor immediately north of the city. Recent cryptotephra studies and drilling through the lava stack on Rangitoto have raised the possibility that volcanism has occurred this site, for possibly as long as 7000 years. If true, this is a major potential threat for the
1.5 million population of Auckland. In this study we re-examined the main tephra sequence downwind of Rangitoto on a neighboring island. The deposition pattern is unusual for a fall origin with the greatest thicknesses (1.2 m) preserved above the high-tide mark within bays, thinning onto ridges. These deposits are poorly sorted, show cross bedding and accretionary lapilli, along with accidental lapilli. We interpret these as base surge deposits formed during the submarine and emergent growth of Rangitoto. The tephra buries an archaeological site and is well dated at ~600 yrs B.P. Its alkali basaltic composition is matched only to a remnant peak of a mainly buried edifice on Rangitoto. All subsequent lavas on Rangitoto are a contrasting sub-alkaline, higher silica basalt, including a 140 m core sequence to the base of the lava pile below sea level. A ~550 yr sub-alkaline basalt tephra found above the surge- related deposits indicates that the edifice was constructed over ~50 years. With both the emergent and volumetric phase of volcanism of Rangitoto accounted for by the units studied, any earlier volcanism must have been volumetrically minor, submarine/emergent with tephra not deposited in the primary downwind direction. These findings imply that Rangitoto, like most other of the Auckland volcanoes formed in single eruption episode.

Constraining chronology and time-space evolution of Holocene volcanic activity on the Capelo Peninsula (Faial Island, Azores): The paleomagnetic contribution

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Faial is one of the most volcanically active islands of the Azores Archipelago. Historical eruptions occurred on the Capelo Peninsula during A.D. 1672–1673 and more recently in
A.D. 1957–1958. The other exposed volcanic products of the peninsula are loosely dated within the Holocene. Here, we present a successful attempt to correlate scoria cones and lava flows yielded by the same eruption on the Capelo Peninsula using paleomagnetic data from 31 sites (10 basaltic scoriae, 21 basaltic lava flows). In the investigated products, we recognize at least six prehistoric clusters of volcanic activity, whereas 11 lava sites are correlated with four scoria cones. Dating was conducted by comparing our paleomagnetic directions with relocated paleosecular variation Holocene reference curves of the geomagnetic field from France and the UK. We find that the studied volcanic rocks are younger than previously believed, being entirely formed in the last 8 k.y., and that the activity intensified over the last 3 k.y. Our study confirms that paleomagnetism is a powerful tool for unraveling the chronology and characteristics of Holocene activity at volcanoes where geochronological age constraints are still lacking.

Reconstruction of stratigraphy and time- series variation in composition of ejecta of the An'ei eruption, Izu-Oshima

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In Izu-Oshima, a large-scale eruption that is referred to as the An'ei eruption began in 1777. The outline of this eruption has been unveiled based on geological surveys and analyses of historical records (Nakamura 1964; Tsukui et al. 2009). However, the variation of eruption style and sequence and their relations to the deposits are not studied in detail yet. It gradually becomes clear in this study that the proportion of phenocrysts of basal scoria is different by its stratigraphic level.

From field surveys, it was proved that the basal scoria layer can be divided into major two units: the lower basal scoria unit (Unit A) that is poor in plagioclase phenocrysts (Pl) and the upper basal scoria unit (Unit B) that is richer in Pl. The proportion of Pl in the basal scoria is the key to reveal the chronological order between the basal scoria layer and lava flows.

We conducted whole-rock analyses of A- and B-scoria and lavas. The results of these analyses are that B-scoria is most abundant in Al2O3. As the magma of Izu-Oshima is generally rich in Pl as a result of flotation and concentration of Pl in magma chamber (Aramaki and Fujii 1988), it is expected that the magma abundant in Pl erupts in the early stage of eruption. Field observations and compositional analyses, however, suggest that Pl- poor magma was discharged in the beginning.

We analyzed plagioclase by EPMA. Regarding the basal scoria, the anorthite value of Pl in A- scoria is higher than B-scoria.

Based on these results, the products of the An'ei eruption have different petrological features for each unit. It is suspicious if the magma process of the An'ei eruption is explained only by concentration of Pl in single magma chamber. It is a future issue to reveal why such compositional differences occurred.

Building a high-precision millennial eruption record for Mt Taranaki using radiocarbon and paleosecular variation dating

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Establishing high-resolution stratigraphic and geological records is vital for understanding the frequency and magnitude of hazards a volcano poses to its surrounding community. In particular, the youngest part of the geological record helps to determine the current volcanic state if strong time-variability of volcanism is suspected. The last pulse of volcanism at the 2518 m stratovolcano, Mt. Taranaki (New Zealand) is denoted as the Maero Eruptive Period. This 1000-yr long period is represented by a series of block-and-ash flow (BAF) and associated deposits in Taranaki's northwestern river catchments. Here we used radiocarbon dating along with paleosol and stratigraphic relationships to improve the resolution of the sequence of events. We identified 10 episodes, some consisting of multiple eruptive events, over the last millennia, with the shortest quiescence represented by near-consecutive events and the longest seen in the latest pause of ~150 yrs. This analysis helped to uncover a shift in the geochemical composition of Taranaki magma during the eruptive period, which is also distinctive from previous Taranaki episodes. Attempts were made to further refine the Maero event ages by comparing the paleomagnetic directions of clasts from the BAF deposits with the New Zealand paleosecular variation curve. The results were consistent with the radiocarbon ages, but the precision was insufficient to better constrain the ages of closely timed individual events. Paleomagnetic imprecision may result from the settling of clasts during deposit cooling, a typical challenge for such studies on unconsolidated deposits. Our results provide more precise constraints on the ages of the last 10 eruptive episodes from Mt. Taranaki's recent history and indicate that some eruptive episodes could be decadal in length.

Geology of the Nevado Coropuna volcanic complex

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The Nevado Coropuna volcanic complex (NCVC), located in the northernmost CAVZ (15°3' S, 72º39' W), includes several edifices, aligned WNW-ESE above Neogene ignimbrites. Adjacent composite volcanoes include the Late Pliocene, eroded Sunjillpa to the WNW and the glacially eroded, 0.6-0.25 Ma-old Cunciacha to the ESE. Located on the west flank of the Western Cordillera, the asymmetric volcanic complex shows stubby lava flows overlying the NE, 4500 m-high plateau, contrasting with long, inverted lava flows and debris-avalanche deposits filling deep valleys draining the steep SW flanks. The central, highest NCVC is a cluster of five, aligned lava domes reaching 6160 and 6330 masl. The dome cluster and its voluminous lava flows overlie an old stratovolcano with inverted lava flows dated at 1.02 Ma. The 0.4 Ma-old base of dome cluster is overlain by lower lava flows c. 270 - 254 ka, middle lava flows c. 118 - 108 ka, and the uppermost lava domes 70 – 60 ka. A high-spatial resolution DEM shows six vents on the domes and one collapse scar open to the south. NCVC has grown atop a caldera as shown by AMS data collected on Early Quaternary ignimbrites dipping away west, south and east of NCVC, and by abnormal contacts with both adjacent volcanoes to the WNW and the ESE. All lavas show two major compositional fields of high-K andesites and dacites (SiO_2 57-67%wt). Harker diagrams and trace elements suggest AFC magmatic processes. Although CNVC tephra and PDC deposits represent a small volume, we observed Late Glacial Plinian fallout are scattered and Holocene ashfall layers are associated with three lava flows, the youngest being 1700 to 2400 yr old. The Nevado Coropuna ice cap c. 44.1 km^2 is arguably the largest in the world tropical belt.

Redefining the limits of $^{40}Ar/^{39}Ar$ geochronology

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For volcanic settings, which typically have populations and assets in close proximity to volcanic centres, determining the timing, likelihood and rates of production of different types of activity is essential for long-term contingency planning. Of critical importance is knowledge of the time-style relationships of geologically recent eruptions, the timing of which is often unknown due to the sparsity of verifiable eye-witness accounts of eruptions, as well as the attainable resolution of geological dating techniques (e.g., $^{40}Ar/^{39}Ar$ geochronology) for late-Holocene volcanic materials. The retrieval of age data from preserved volcanic deposits and coupling of this information to eruption style is a vital first step to better anticipate the timing and impact of volcanic eruptions on civilization.

This contribution will provide an overview of recent advances in approaches to $^{40}Ar/^{39}Ar$ dating and associated technology that are allowing geochemists to redefine the boundaries of $^{40}Ar/^{39}Ar$ geochronology. We will also examine how Bayesian modelling analysis of age profiles from Ischia can be employed to resolve volcanic eruption histories. Our aim is to better inform volcanic hazard assessments and improve the resilience of communities that reside within the shadow of active volcanic systems. It is fair to anticipate that technological innovations will continue and technique refinement will allow measurement precision to improve. The presentation will show we have truly begun to bridge the gap between $^{40}Ar/^{39}Ar$ geochronology and the proliferation of written records, such as those associated with the European 'Age of Discovery'.

Constraining the tempo and frequency of eruptions that dispersed ash over central Honshu (Japan) between 30 and 50 ka

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The Lake Suigetsu core, obtained from a small tectonic lake in central Honshu, is the most precisely dated sediment record for Japan. Due to its high sedimentation rates, small catchment and incredibly low energy environment, the core resolves a very comprehensive record of ash (tephra) fall from moderate to large eruptions reaching central Honshu over the last 150 ka. Here we present detailed investigations of tephra fall events recorded in the annually laminated (varved) and intensely dated (^{14}C) sediments of Lake Suigetsu directly underlying the thick AT tephra, spanning between 26 (30 ka) and 39 (50 ka) meters in core depth. In addition to four visible tephra layers, high-resolution analysis of the sediments (using density separation techniques) has revealed even more tephra layers recorded as non-visible markers (cryptotephras). Specifically, we identified a further twenty-five microscopic markers in these precisely dated sediments, which provide significant new insight into the tempo and frequency of lower magnitude and more distal eruptions reaching central Honshu. Major element glass geochemistry obtained from these tephra layers are compared to new and published proximal datasets, to correlate them to their source volcano and specific eruptions. This shows that these layers originate from volcanoes across Japan, and most notably records repeated activity from Aso caldera (Kyushu) and illustrates significant changes in its magma evolution. We also identify and precisely date large magnitude eruptions from Ulleungdo (500 km NW of Suigetsu) and Changbaishan (980 km NW), which are not reported in proximal eruption stratigraphies. These include the distally recognised U-Ym tephra (Ulleungdo), which is an important tephra marker owing to its close chrono-stratigraphic association with the Laschamp geomagnetic excursion (~40 ka). These layers are therefore not only useful for volcanology, but provide important markers in sedimentary archives (palaeoclimate and archaeological records) suitable to investigate the impact of these events.

New insights on Mondaca volcano (Chile): A new site to understand rhyolitic eruptions

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The Mondaca volcano is a rhyolitic emanation center that lacks deep geological reconnaissance studies. It has been described as an extensive lava flow 8 km long, also known as the "Vulcano tongue". In addition, a set of proximal pyroclastic sequences have been recognized but not studied. This eruptive center is located in the upper course of the Lontué River and despite there has been no reported activity in historical times researchers attributed its age to the year 1762 according to a chronicle written by Abate Molina.

This volcano is immersed in the Descabezados Volcanic Group. This group is dominated by two adjacent stratovolcanoes, an ancient basaltic shield and numerous siliceous-type flank cones and chimneys. Among these is the Quizapu volcano, which has presented an intense historical activity, located between the Descabezado Grande and Co. Azul stratovolcanoes. This complex has given rise to some of the most important eruptions recorded in Chile and South America, such as the effusive eruption of the years 1846-47 and the Plinian eruption of 1932.

Recent fieldwork on the products has provided a new radiocarbon dating showing an age of 1230 +/- 30 years before Present. Also, our work shows that pyroclastic deposits were significantly larger and can be found up to 13 km away from the emission center confined to the valley of the Lontue river over lahar deposits.

Ongoing research will investigate further the petrology and geochemistry of the products that gave origin to Mondaca to shed light on the dominant subvolcanic processes in this area as well as to raise geological information in terms of its eruptive history. The above is highly relevant to the understanding of the evolution of Large silicic magma systems in a place with an important amount of volcanic manifestations, of varied compositions, within a radius of a few kilometers.

1 million years of volcanism on Ascension Island: stratigraphy, $^{40}Ar/^{39}Ar$ geochronology and petrology

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Ascension is an ocean island volcano located in the South Atlantic, ~ 90 km west of the Mid- Atlantic Ridge axis. The volcanic rocks define a transitional to mildly alkaline basalt- hawaiite-mugearite-benmoreite-trachyte-rhyolite sequence, spanning a wide range of eruptive styles over ~ 98 km^2 of land. The central and eastern sectors of the island are predominantly composed of pyroclastic deposits, trachyte and rhyolite lava flows and domes. Northern, southern and western regions comprise mafic lava flows and scoria cones.

We integrate a new stratigraphy, $^{40}Ar/^{39}Ar$ ages, and petrological data to reveal the timing, style and driving forces behind volcanic activity on Ascension. During the last 1 Myr, > 75 explosive eruptions have occurred, with the last one at ~ 60 ka. Throughout this period, sub-Plinian and phreatomagmatic eruptions have been common, sometimes associated with pyroclastic density currents. In addition, felsic lava flows and domes, as well as basaltic lava flows have been dated to shed light on timescales of effusive volcanism on Ascension. The most recent eruptions occurred at < 1 ka, pre-dating the beginning of Ascension's historical record [1]. Petrological data reveal the closed-system nature of the magmatic plumbing system and highlights the role of fractional crystallisation in the production of the range of magmatic compositions found on Ascension [2]. High volatile concentrations suggest that potential eruption triggers are either volatile over-pressurisation or external factors not recorded in the crystals. This has significant implications for anticipating any future activity at Ascension.

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S01.29 Talk

Paleomagnetic Dating of the Neostromboli Sequence

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The Neostromboli volcanic sequence is characterized by packages of lava flows and scoria beds erupted from the summit of the Stromboli volcano, and by scoria cones and flows issued from eccentric vents and fissures. Available radiometric ages constrain Neostromboli activity in the 14-4 ka age window, but the chronological relations of central vs. peripheral activity are still poorly constrained. Furthermore radiometric and paleomagnetic ages of some of the eccentric eruptions are strikingly inconsistent. Here we report on the paleomagnetic dating of thirty-four sites from Neostromboli products. Seventeen are new paleomagnetic directions, while additional seventeen directions are age recalculated from published measures by Speranza et al. (2008) with the recent SHA.DIF.14K geomagnetic field model. We show that the beginning of Neostromboli sequence could be much younger than the commonly accepted ≈14 ka onset, providing our (oldest) data an age of ≈9 ka BP. The eccentric San Vincenzo lavas, paleomagnetically dated at 6,894-6,652 or 6,422-6,073 yr BP, are significantly younger than the 12.5±2.6 ka BP provided by groundmass Ar/Ar dating, and then they belong to the last Neostromboli phases. According to our paleomagnetic dating, the San Vincenzo products occurred in a temporal window similar to the Secche di Lazzaro phreatomagmatic eruption (between 7-6 ka), associated with the main flank collapse of the Sciara del Fuoco. In summary, the fine resolution allowed by paleomagnetic dating allows to propose an innovative chronologic scheme for the Neostromboli activity: i) the early stages were comprised between 9-8 ka and characterized by summit lava flows blanketing both the SW and northern volcano flanks; ii) after ≈7.5 ka lateral eruptions became dominant from peripheral cones and fissures. We suggest that the intense flank activity, associated with some phreatomagmatic eruptions, contributed to the progressively weakening of the volcano and repeated collapse events, leading to the Sciara del Fuoco formation.

Last volcanic activity and recent seismic unrest in the Chiles volcano area

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Chiles volcano (4748m a.s.l.) belongs to the Chiles-Cerro Negro Volcanic Complex and is located on the Western Cordillera. Its summit is at the border between Ecuador and Colombia. Chiles is a stratovolcano located 130 km NE of the Quito city and 24 km W of the city of Tulcán in the province of Carchi.

It is composed mainly of lava flows of different sizes, distributed radially along its flanks. Additionally, it presents a sliding scar on the northern flank that reaches 1 km in diameter in the E-W direction. This volcano consists of two main litho-stratigraphic units affected by glacial erosion: CHILES I (600-270 ka) characterized by lavas of andesite-basaltic to riodacite composition; and CHILES II (75-20 ka) by lavas of andesitic to rhyolitic composition.

Between 2013 and 2015, an intense seismic activity has been recorded at the Chiles volcano area, four seismic swarms occurred. On October 20th, 2014, an earthquake of magnitude 5.9 occurred, located on the SW flank of the volcano, and on October 22nd, the largest number of earthquakes per day was recorded with 8246 events. Additionally, in 2018, a new swarm occurred near the Chiles-Cerro Negro complex, but much smaller than the one registered in 2014. This activity has been located mainly towards the south and southwestern part of the edifice; however, no superficial activity happened.

To look for recent deposits we carried out a drill in a peat bog of 5m deep in the southwest, founding 12 layers of volcanic ash. Organic sediments below the main layer of the peat bog were dated (9 samples) by ^{14}C method, with age range between 6900 and 140 years BP. However, none of these layers belonged to the Chiles volcano, which implies that the volcanic complex did not had significant explosive activity during this period

S01.29 Poster

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S01.30 - Environmental and societal impacts of past volcanic eruptions integrating the geosciences with the historical, anthropological, and archaeological sciences

The response of the climate system to explosive volcanic eruptions during the Common Era

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Volcanic eruptions cause global-scale changes to the climate system via the direct effect of radiative forcing anomalies and the ensuing influences on and feedback to major modes of ocean-atmosphere variability. Climate model simulations suggest a larger degree of cooling following eruptions than proxy temperature reconstructions, and disagreement persists about the subsequent state of the El Nino Southern Oscillation system.

Here, we use two recent temperature reconstructions to investigate the response of the climate systems to volcanic eruptions. Our new NTREND field reconstruction of Northern Hemisphere summer temperatures shows coherent, broad-scale cooling associated with large tropical eruptions: 96% of reconstructed grid points show composite mean colder temperatures and an average response across all grid points and all eruptions of -0.44C. Cooling persists in some cases for 2 or more years following eruptions and different eruptions reveal different magnitudes and spatial patterns that are not clearly associated with estimated radiative forcing. The PAGES2k Oceans2k High Resolution (HR) reconstruction of tropical sea surface temperatures shows cooling of the western Pacific and Indian Ocean in response to well-dated tropical eruptions since 1600 CE but no statistically significant response in the eastern tropical Pacific, suggesting a reduction in the tropical Pacific temperature gradient but not a canonical El Nino pattern. Climate models simulate an overall larger cooling in the western Pacific and Indian Ocean than the reconstructions and produce a variety of anomalies in the eastern Pacific. Our results here provide a new benchmark comparing proxy reconstructions and model simulations and may help identify possible sources of disagreement.

S01.30 Talk

The Huayruro Project: mapping the Calicanto Inca area buried by the A.D. 1600 Huaynaputina eruption, with geophysical imaging and remote sensing

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We present geophysical and remote sensing observations near the Quinistaquillas town (southern Peru), in the framework of the HUAYRURO Project. This Inca zone was buried during the A.D. 1600 Huaynaputina eruption, the most important volcanic phenomenon of the last 400 years. The eruption had a global impact, due to the volume of emitted ash (2-3 times the one emitted by Vesuvius in A.D. 79). This lead to a 1.13°C cooling of the planet and caused a worlwide agricultural crisis.

During the eruption, the Calicanto-Chimpapampa zone was covered by ashes and pyroclastic flows, with a thickness in the range [1 - 20] m. From 2015 to 2017, remote sensing and geophysical methods were deployed to map a ~ 1 km*2 km area, up to 3-m depth.

A multi-spectral drone was first used to acquire visible and thermal infrared data 1) to obtain a high resolution photogrammetric DEM (resolution: 1.23 cm) and 2) to detect the buried walls. Then, several 3D geophysical methods were performed to get a fast and precise location of the structures:

- An EM31 electomagnetic survey (Geonics instrument) and magnetic observations (GEM systems proton magnetometer) were tested for a fast mapping of the area;
- An IDS Ground Penetrating Radar (with antennas of 200 MHz) was used to obtain the precise location of the buried walls;
- All the methods were georeferenced using a Trimble R6 differential GPS.

In this work, several exemples of combination of these methods are presented. Finally, this methodology allowed us to propose a complete map of the structures at Calicanto, now used by the archeologists to excavate the town. This study shows the potentialities of the joint use of drone-based remote sensing and geophysical imaging for the promotion of archeological sites.

S01.30 Poster

Not just a nice piece of art work: innovations that integrate the humanities into building resilience to geohazards

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Understanding hazards, managing risk and building resilience requires interdisciplinary research that engages with communities at risk. While the social and physical sciences have been working to bridge this gap, less attention has been paid to the role that humanities and arts can play not only in understanding risk, but also in empowering communities to respond and cope to the challenges posed by geohazards. This presentation will introduce the methodologies and results from an innovative project funded by the UK Research Council that brought together different disciplines with the aim of engaging with communities vulnerable to volcanic hazards through past and present cultural expressions around volcanos.

The project,' Explosive Transformations: Cultural Resilience to Natural Hazard on St Vincent and Montserrat' brings literary studies together with volcanology, international development, and the institutions responsible for future emergency response to volcanic eruptions. There are three main aims: the first is to examine how insights from literary, artistic and wider cultural expression (oral storytelling, poetry, song) can provide new insights in to understanding past volcanic eruptions and its impacts. The second aim is to understand the role that narratives of past volcanic events play in cultural life, community memory, and the shaping of island identities. Finally we also wish to explore way that this knowledge might usefully be employed to help with social response and readiness for future events, particularly amongst highly vulnerable social groups.

By exploring insights from poetry, oral history and music, the presentation will introduce the innovative collaboration and approaches applied by this project and show how a combination of methodologies from the humanities, social sciences and physical sciences not only provides insights into past eruptions but also strengthens responses to the challenges posed by the risk associated with volcanic eruptions.

6th-century Eruptions of Mt Haruna in Japan and Their Social Consequences

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Much work has been done by archaeologists in Gunma Prefecture on the sequential eruptions of Mt Haruna. The social consequences have been tracked throughout the region: abandonment and then restoration of agricultural fields, destruction of elite residences, and behaviour of people and horses in escaping tephra-fall or not. Considerable collaborative work has been done on estimating direction and speed of pyroclastic flows, with up to 17 layers of tephra deposit determined. The geographical spread of each stratum informs on differential directional deposit within the short eruption timespans.

Paleomagnetic dating as a tool for determining the succession of volcanic eruptions in an area of important archeological activity

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Central Mexico is characterized by a sustained volcanic activity since thousands of years, as also indicated by the historic volcanoes Jorullo and Paricutín built during the last three centuries. Several studies have shown that pre-historic eruptions (no written records) have affected the local communities close to the eruption centers, like in the case of Xitle volcano in the basin of Mexico. The timing of volcanic eruptions is of upmost importance to evaluate the possible impact on local communities, which often cannot be resolved by traditional geochronology methods like C-14. Therefore, paleomagnetic studies offer alternatives for the time-sequencing of individual events of the eruption history in a region and correlate them with the evolution of local communities.

Ceboruco volcano Mexico) has been active since about 1 ka, starting with a plinian eruption of 3-4 km^3 of material. Another 3-4 km^3 of lava flow material was expulsed, for which no ages are available, except for the 1870 flow. Paleomagnetic studies have been done to contribute to the recent eruption history of Ceboruco. From seven post-plinian lava flows site- and flow-mean directions were determined. These are indistinguishable, indicating they must have been emplaced during a very short time, less than 50-100 years. The overall mean direction was used for paleomagnetic dating, providing a possible age range of 1000-1140 AD, which indicates that the effusive period indeed followed very closely the plinian eruption. Afterwards, there was an inactive period of about 730-870 years before Ceboruco's last activity in 1870.

These results are important for analyzing the related volcanic hazard. Furtheron, these (pre-) historic eruptions already had a severe impact on the environment and the settlers living around Ceboruco volcano. Recent excavations revealed that ancient sites had been covered by ashes from Ceboruco, indicating probable affectations during a future eruption on the present population.

Lava-river interactions and secondary hazards associated with the 1783-84 Laki fissure eruption

Frances Boreham, Katharine Cashman Alison Rust,

University of Bristol, UK

The 1783-1784 Laki fissure eruption had a devastating impact on local Icelanders and across northern Europe. Eye-witness accounts of the eruption and its impacts have allowed volcanologists to reconstruct the events of the eruption in great detail, but studies have primarily focussed on eruption chronology and climactic effects. Contemporary writers also describe significant disruption to the local hydrology, and numerous rootless cone groups across the lava flow record violent lava-water interactions. Little attention, however, has been paid to these interactions despite the considerable damage they caused.

To better understand lava-river interactions and resultant hazards, we combine analysis of contemporary accounts of the Laki eruption with observations from fieldwork, aerial photographs and high resolution digital elevation maps. Laki lava flows interacted with and disrupted local rivers of varying sizes, causing flooding that destroyed numerous farms and dwellings and cut off access for aid and evacuation. Contemporary sources also describe how rivers controlled the course of the lava flow lobes and, in some cases, caused the flow to halt unexpectedly. Physical records of lava-river interactions are preserved in fourteen rootless cone groups across the lava flow, half of which formed where observers recorded flooding, and provide evidence for the additional hazard to people and property posed by explosive lava-water interactions.

Importantly, we conclude that lava-river interactions can create serious secondary hazards from lava flows, including flooding, rootless eruptions, diversion of lava flows and disruption of access for aid and evacuation. Yet lava-river interactions are rarely included in lava flow models or hazard maps. Contemporary accounts of the Laki eruption demonstrate how damaging these hazards can be, and why they should be taken into account in future lava flow hazard assessments.

Progress in the knowledge of the flank eruptions occurring on Etna over the past 2,700 years

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The historical period of Mt Etna spans about 2,700 years, even though Diodorus Siculus cites volcanic events that forced the Sicanians to emigrate well before the first Greek settlements in 734 BC. Despite the long historical period, there are many limitations for a volcanological use of the iconographic and documentary sources. There are very large gaps and, for instance, no valuable accounts particularly during the medieval epoch. Furthermore, the preserved documents are too imprecise to identify the lava flows, so that most of their ages were first attributed by pioneering geologists during the XIX century on the basis of the morphology of flows. In this period, the publication of the first geological map of Etna by Sartorius Von Waltershausen constitutes a turning point in the studies on historical eruptions. Waltershausen's mapping and dating of the lava flows on analyzing the historical sources influenced all successive works up to the geological cartography of the XX century. Recently, thanks to an interdisciplinary approach comprising stratigraphy, historiographical studies and the dating of the lavas, it has proved possible to define for the first time a comprehensive assessment of the historical flank eruptions of Etna. In this frame, the present state of knowledge on the historical eruptions has evidenced that during the Greek-Roman and medieval epochs up to the XVII century flank eruptions commonly involved the middle-lower slopes, impacting mainly the south sector of the volcano with the location of the eruptive fissures sometimes below 1000 m a.s.l. This eruptive behaviour of the volcano has radically been modified following the occurrence of the large 1669 eruption since the opening of the fissures was mainly concentrated in the upper-middle slopes between 1600 m and 2500 m a.s.l. This revised chronology represents considerable progress for long-term eruptive models, petrological and hazard studies.

S01.30 Talk

Data-mining history: A tale of three volcanoes

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The historic record of global volcanic eruptions is limited in duration and, even where it exists, is affected by under-recording. Regionally, the recording rate improved dramatically during the age exploration, as seen by a significant increase in the number of reported eruptions in Latin America after the arrival of the Spanish in the 16th century. Spanish chronicles provide not only eyewitness accounts of eruptive activity, but also detailed accounts of immediate impacts of and response to volcanic events, as well as the regional legacy of volcano-related disasters. These accounts can be data-mined, as illustrated here by a review of some of the archival information available for three volcanoes in Guatemala: Agua, Fuego, and Santa Maria.

Agua has not erupted historic, but has been the source of numerous lahars, including (1) a collapse of the summit in 1541 that destroyed the first city of Guatemala only 14 years after its foundation, (2) a magma-injection-triggered (?) lahar that appears related to eruptive activity at neighboring Fuego in 1717, and (3) numerous rain-triggered events, the most recent of which was in 2010. Neighboring Fuego is a persistently active open system volcano characterized by Strombolian activity, lava flows and occasional paroxysms; importantly, it has had at least 7 VEI 4 eruptions since the arrival of the Spanish, the most recent of which was in 1974. Long-dormant Santa Maria volcano came to life in October 1902 to produce the second largest eruption of the 20th century. We illustrate ways in which eyewitness accounts, surveys and newspaper accounts of activity at all three volcanoes can be used to both extend our understanding of volcanic behavior and evaluate the impact of different events in time and space.

Impacts of a Pre-Cursory Eruptive Activity on a Thriving Bronze-Age Civilization, Santorini

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During the Late Bronze Age, the Aegean witnessed one of the largest volcanic eruptions in human history when the volcano of Thera (Santorini) erupted. This eruption destroyed the thriving Cycladic culture on the island, whose remnants remain buried under a thick layer of volcanic deposits. The center of a thriving, successful maritime trade network across the Aegean and Mediterranean, in close communication with the Minoan culture on Crete, was incinerated during this period of volcanic activity. Regions across the Aegean and Mediterranean Seas were impacted with ash fall, pyroclastic flows and surges, earthquakes, tsunamis, possibly climate change, and in all likelihood illness or plague. It appears the Cycladians had advanced warning of the impending eruption and escaped in their small boats to nearby islands such as Crete. Using combined geological and archaeological criteria, an inferred timeline of physical and sociological events prior to the main devastating eruption can be constructed by also applying contemporary studies of cultural responses to inhabiting active volcanological terrains and to historic large eruptions.

Reconstructing the Late Bronze Age intra-caldera island of Santorini, Greece

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In this work, we attempt to reconstruct the topography of Santorini before the cataclysmic Late Bronze Age (Minoan) eruption which, according to many authors, contributed to the decline of the Minoan civilisation. During the Late Bronze Age, the island of Santorini had a semi-closed caldera harbour in the northern part of the present-day caldera, inherited from the 22 ka Cape Riva Plinian eruption, and a central island similar to the present-day Kameni Islands, which is referred to as 'Pre-Kameni'. The size and age of the intracaldera island which existed prior to the 3.6 ka Minoan eruption have been constrained using a photo- statistical method, complemented by granulometry and high-precision K-Ar dating. The topography of Late Bronze Age Santorini is reconstructed by creating a new digital elevation model (DEM). Pre-Kameni and other parts of Santorini were destroyed during the Minoan eruption, and their fragments were incorporated as lithic clasts in the Minoan pyroclastic deposits. Photo-statistical analysis and granulometry of these lithics, differentiated by lithology, constrain the volume of Pre-Kameni to 2.2–2.5 km^3. Applying the Cassignol-Gillot K-Ar dating technique to the most characteristic black glassy andesite lithics, we propose that the island started to grow at 20.2 ± 1.0 ka soon after the Cape Riva eruption. This implies a minimum long-term lava extrusion rate of ~0.13–0.14 km^3/ky during the growth of Pre-Kameni. However, because this value is only one seventh of the average growth rate during the much shorter lifetime of the present-day Kameni Islands (~0.9 km^3/ky since the Minoan eruption), it is possible that Pre-Kameni grew up in a short period at higher lava extrusion rates. If so, the extrusive activity may have declined, and possibly the island of Pre-Kameni was dormant by the Late Bronze Age.

S01.30 Talk

A multidisciplinary study of Lake Nemi emissary: petrology, engineering and archaeology from the tunnel excavated within the volcanic structure

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Lake Nemi is a maar in the Alban Hills volcanic province South of Rome. Because of its territorial advantages, including the rich soil and the attractiveness of the site, the area has been inhabited for millennia and it is historically well known for its temples. A number of drainage tunnels - emissaries - were excavated within the volcanic structure to drain the raising water of the lake; the draining water was channeled to irrigate the fertile countryside of Ariccia, on the outer side of the volcano. One of these tunnels has been re-activated in the early 20th century to lower the lake level and recover Emperor Caligula's party ships.

In addition to its historical and cultural significance, this tunnel, which has been only minimally lined, gave us a unique opportunity to access the structure of the volcanic edifice from within and to study the technology utilized to excavate the tunnel over 27 centuries ago. We will present the results of our multi-year, multidisciplinary study of the Nemi emissary. The study includes a petrological and geochemical analysis of the variability of the volcanic material sampled in the emissary. We observed significant textural variability which can be associated to the eruptive phases. Our 3D laser scanner model of the tunnel enables us to see the relationship of the volcanic materials encountered in the tunnel with the Nemi volcano edifice for a high definition model of the structure.

The mechanical heterogeneities of the volcanic edifice were the greatest challenge encountered by those who excavated the tunnel, both because of their hardness and their orientation with respect to the direction of development of the tunnel. Our investigation of the mechanical variability of the materials is supporting a parallel study for the reconstruction of machinery used for the excavation.

S01.30 Talk

An active volcano dams a lake: Potential extreme hazards as the Antuco volcano devastating event, Southern Andes, Chile, 37.4°S

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Antuco volcano is located in the Southern Andes Volcanic Zone at 37.4° S, the main cone rises to 2.979 m a.s.l., has an estimated volume of *ca*. 60 km^3 and an historic record of 17 eruptions of basalt between 1739 and 1911 AD. Antuco has two main units, an early stratovolcano (EA) that began its building at *ca*. 150 ka, directly on top of stratified Miocene rocks and over the northeastern flank of Sierra Velluda volcano. The late unit is the Late Holocene cone nested within a sector collapse caldera that affected EA. From its beginnings, Antuco dammed an Andean range valley forming the Laja lake, whose historic water level (*ca*. 1.400 m asl with a volume of 6 km^3), has varied remarkably due to the lava piles in its outlet, underground drainages and fluvial erosions. At 6.2 ka EA collapsed toward the northwest, generating a 5 km^3 debris avalanche that travelled 20 km along the Laja river valley. This event was triggered by a Bandai type phreatomagmatic eruption, leaving a 4 km wide horse-shoe shape theater. The debris avalanche blocked the Laja lake outlet, raising its level up to 1.600 m a.s.l., increasing the Laja lake volume up to *ca*. 50 km^3. Water infiltrations into the volcanic system triggered powerful phreatomagmatic explosions producing extensive PDCs that reached 40 km filling the Laja river valley. According to botanists, diatoms and pollen disappeared from the lake at *ca*. 1380 AD, so our hypothesis is that the violent lake outburst took place by that time, causing a gigantic extremely high energy flood that covered 5.000 km^2 of Chile's Central Depression, reaching the Coastal Range, 140 km far and leaving a huge fan (*ca*. 50 km^3 of reworked basaltic sand), that reached the Pacific ocean along the Biobio and Itata river valleys.

S01.30 Talk

The Ilopango Tierra Blanca Joven (TBJ) eruption, El Salvador: a major Holocene event of Central America, stratigraphy and hazards implications

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The Ilopango Caldera is a 17 x 13 km volcano-tectonic structure located in El Salvador and is one of the active volcanoes of the Central American Volcanic Arc, which in turn forms part of the Pacific Ring of Fire. Four large explosive eruptions were recognised during the last 57,000 years: TB4, TB3, TB2 and TBJ that correspond to the last phases of formation of the caldera.

The TBJ (Tierra Blanca Joven-Young White Earth) eruption occurred about 1500 years ago, between 430 and 535 AD, with an estimated emission volume of at least 80 km^3 of magma.

The TBJ eruptive products, of dacitic composition, covered enormous areas that surpassed the present territory of El Salvador. Dense and dilute PDCs filled the depressions near the Ilopango lake with thicknesses of up to at least 70 m and reached distances of at least 40-50 km from the vent, covering completely what today is the actual city of San Salvador. Ash coignimbritic deposits of the last stage of the eruption were found along the whole El Salvador Country. Deposits related to this last phase were also reported in Guatemala, Honduras, Nicaragua, Costa Rica and the Pacific Ocean. The TBJ eruption was one of the greatest Quaternary eruptions of Central America, where its large eruptive products, considerably affected the Mayan populations living in Salvadoran and near territories at that time. The TBJ may have been the cause of the collapse of the economic and cultural progress of the Maya empire at the end of the Classic Period, since the last C^{14} dating of Dull et al. (2010) dates the eruption to AD 536, which coincides with a Mayan period known as “hiatus”, in which, the civilization appears to have not progressed.

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S01.30 Poster

The 1902-3 eruptions of the Soufrière, St Vincent: impacts, relief and response

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Volcanic activity at long-lived volcanoes is often repetitive, so that past eruptions may be used as templates for scenarios of future events. Investigation of contemporary accounts of past eruptions can help to provide new insights both into the physical events themselves, and their wider social and economic impacts. Retrospective analysis of the contemporary colonial and scientific records of a major explosive eruption of the Soufrière of St Vincent from 1902-1903 reveals how this significant and prolonged event presented challenges to the authorities charged with managing the crisis and its aftermath.

In a small-island setting vulnerable to multiple hazards, the spatial footprint of the volcanic hazard and the nature and intensity of the hazard effects were rather different to those of other recurrent hazards such as hurricanes. The eruption affected the same parts of the island that had been impacted by prior explosive eruptions in 1718 and 1812, and hurricanes in 1831 and 1898, with consequences that disproportionately affected those working in and around the large sugar estates. The official response to the eruption, both in terms of short-term relief and remediation, was significantly accelerated by the existence of mature plans for land-reform following the collapse of the sugar market, and ongoing plans for rebuilding in the aftermath of the destructive hurricane of 1898.

The picture that this analysis helps to illuminate provides insights both into the nature of the particular eruptive episode, and the human and social response to that episode. This not only informs discussion and planning for future explosive eruptions on St Vincent, but provides important empirical evidence for building effective responses in similar multihazard contexts.

Revisiting the climate impact of the c. 12,900 yr BP Laacher See eruption

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The large explosive eruption of the Laacher See volcano c. 12,900 yrs BP marks the end of explosive volcanism in the East Eifel volcanic zone (Germany). In this paper, we review the current evidence for the impact of the Laacher See Eruption (LSE) on the immediate and wider environment as recorded in a range of terrestrial proxies, including the impacts of this event on contemporaneous Final Palaeolithic hunter-gatherers in Europe. In particular, we highlight how the impacts on humans and their mechanisms likely changed from proximal to distal impact zones. In the light of recent advances in the modelling of volcanically-induced climatic forcing, attention has turned again to the eruption's potential influence on Northern Hemisphere climate. We present revised model simulations of the radiative impacts of the LSE using a global stratospheric aerosol model and new sulphur dioxide (SO_2) emission estimates. These new models prove significantly improved insights into the impacts of this major eruption on Northern Hemisphere climate, with attendant implications for ecological and cultural impacts.

S01.30 Talk

The Keys to the Past: A Mixed-Methods Approach to Reconstructing the 1812 eruption of La Soufriere St. Vincent

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Research is becoming increasingly interdisciplinary, complex, and dynamic, meaning there is a need to complement one method with another and to understand multiple methods to promote collaboration, produce superior research and to facilitate communication. The usage of a wide range of qualitative and quantitative data and integrating them in creative and compelling ways with a pragmatic underpinning, can provide deep investigations into the impacts of volcanic eruptions on society, which are inherently complex and dynamic. The 1812 eruption of La Soufrière volcano on the Lesser Antilles island of St. Vincent was reconstructed with a mixed-methods approach in mind. Findings have found that the eruption produced ash fall, pyroclastic density currents (PDCs), volcanic earthquakes and lahars that impacted 129 plantation estates, leading to 43 documented deaths. There was also documentation of PDCs travelling uphill; the temporary absorption of two key river valleys; a debris avalanche generated from the creation of a new crater and; a breakout- lahar one or two years later after the disintegration of a pyroclastic-dam. This eruption occurred during the slavery era where there was a reliance on slave labour to cultivate the island's sugar monoculture. This eruption also forced the emigration of the indigenous Kalinago and the purchasing of land for displaced African slaves. Lastly, a key aspect of this eruption was that due to estate owners receiving loans, the focus was to "return back to normal" and not to adapt, essentially meaning that the dimensions of vulnerability and risk did not change as a result. With these results, there will be a discussion on handling silenced voices, partial records, lay-descriptions based on selection bias that conveyed the time period's fascination of romanticising nature, and combining the disciplines of volcanology, historical geography, the social sciences and disasterology within historical and social volcanology investigations.

The number, timing, strength and climate impact of large volcanic eruptions during the Holocene - a year- by-year inventory from polar ice cores

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Volcanic eruptions have been identified as a primary driver of climate variability, impacting surface air temperature, atmospheric circulation and hydroclimate. The observational record of the timing of volcanic eruptions, their locations, magnitudes of sulphate aerosol injection and atmospheric life-cycle, however, is often incomplete, with gaps in our knowledge of past volcanic activity increasing dramatically before the Modern (pre-1800) era. This shortage in observational data strongly limits our understanding of the sensitivity of the Earth system to volcanism and the vulnerability of social and economic systems to the climate impact of past and future eruptions.

The Holocene (i.e. the past 11,700 years) saw a number of eruptions with sulfur injections exceeding the range experienced by modern human societies. To better quantify the probability of a large-magnitude, climate-impacting eruption – for example, comparable to that of Tambora in 1815 – to occur somewhere on the globe, continuous and complete global volcanic eruption histories are required. To link any past volcanic eruption to environmental and societal consequences often taking place far afield from the eruption sources, precise and accurate knowledge of the exact timing of past eruptions is invaluable. Ice cores extracted from the polar ice-sheets in Antarctica and Greenland yield information on both timing and magnitude of past eruptions as they contain a stratified, continuous and complete time series of volcanic fallout over many millennia from all eruptions that have emitted large amounts of sulfuric aerosols into the atmosphere with an almost calendar-age precision.

Here, we demonstrate how we can extract comprehensive data on the timing, magnitudes and source locations of past volcanic eruptions, using a bi-polar array of ice-core records from Greenland and Antarctica and employing novel, precisely dated, high-time resolution, tephra and aerosol measurements from ice cores. We will also discuss Greenland ice-core evidence of the historic 79 AD Mt. Vesuvius eruption.

S01.30 Talk

Starting new act of Unzen volcanic area

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Shimabara City Office

The activity of practical using volcanic disaster for the future is started at the Mt.Unzen volcanic area. As a matter of fact for five years eruption on Mt. Unzen volcano gave a chance which had been erupted since 1990, and it had devastated human's life, houses and nature cause of pyroclastic flow and debris flow. But at the begging, it absorbed people as side of the special feature sightseeing spot. The pyroclastic flow occur cause of more powerful eruption, so many people lost their lives and residents' life style was completely changed, should live evacuate shelter such as gymnasium and community center or temporary houses. Long distance commute route was chosen the way of go to work and school hardly. As a result of much agricultural area feeding animals such as cow, pig and hen, killed by the hunger or flood and burnt by flame. Also piled sediment of volcanic ash turned big changed for vegetation. But after erupt ended, people changed their thought by the warm heart or support and charity from other areas little by little.

And local residents start to act for use as sightseeing spot, ruins elementary school building burnt by pyroclastic flow stand in a small district and some houses people used to live are preserved original place for disaster memorial. These disaster remains are crowded by many visitors. We established " Unzen UNESCO Global Geopark", and activity for point out earth history and volcano. This gives visitors to enjoy leaning volcanic eruption and disaster prevention. Through the eruption, people are begging to think about the future of residence and others also start new activity.

Mapping waiata koroua (traditional prose) of the Tarawera Eruption, 1886; and its relevance to contemporary natural hazards preparedness and response

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The Tarawera Eruption in 1886 significantly impacted on Māori tribes residing in the central North Island of Aotearoa New Zealand. This region remains a significant volcanic risk to distal tribal groups such as Ngāti Haka Patuheuheu, and yet they remain disengaged from the agencies dealing with volcanic risk. Ngāti Haka Patuheuheu retention of kawa (cultural principles), tikanga (practices) and taonga (waiata koroua and pūrākau) contains relevant knowledge to assess and manage volcanic risks. This kaupapa Māori-based research sought to develop a culturally relevant and responsive volcanic risk information resource, drawing on the collective worldview, experience and knowledge of Ngati Haka Patuheuheu, and neighbouring tribes. A kaupapa Māori research and ethical framework based on Māori cultural imperatives formed the 'Te Whetūmārama Framework'. This framework provides the basis for participant recruitment, data collection and analysis. Data was gathered through wānanga (culturally immersed workshops), hui (cultural meetings) and semi-structured interviews. A volcanic risk information resource was developed around two waiata koroua (traditional prose) about the Tarawera Eruption. The first waiata koroua was composed prior to the eruption, while the second waiata koroua was composed in response to the Tarawera eruption. For each of the waiata koroua, a GIS-based volcanic risk information resource was created including whakapapa (genealogy), waiata koroua, pūrākau (a bibliographic sketch), spatial paepae (mātauranga Maori-Western Science interface), mahere (GIS plotted map) and whakaahua (images). The research shows Te Kooti used waiata koroua to communicate volcanic risk and readiness; waiata koroua communicates the psycho-social effects of the Tarawera Eruption upon individuals and the collective; waiata koroua contains traditional knowledge, values and practices around disaster events, which can contribute to a broader understanding of volcanic risk, and consequently preparedness activities. Finally, waiata koroua provides a culturally responsive approach to engaging indigenous communities usually disengaged from the emergency management sector.

Revealing the age of a volcanic eruption in the Kula volcanic field (Turkey) eye- witnessed by Bronze-age people

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Çakallar volcano, located in Manisa, Turkey is one of the youngest members of Kula volcanism. Çakallar volcanism initiated with a hydrovolcanic eruption depositing a thin ash layer of ~1 km radius. Çakallar volcano and other nearby small scoria cones were built by Strombolian activity which also resulted in a scoria cover on the hydrovolcanic ash layer. Çakallar volcanism ceased with a cone breaching basaltic lava flow originating from the eponymous cone. Human footprints were discovered in hydrovolcanic ash near Çakallar volcano in 1968. More recently, a rock painting on a nearby rock shelter has been interpreted to depict the eruption of Çakallar volcano. This would define this pictograph as a unique site where humans demonstrably eye-witnessed a volcanic eruption and possibly artistically recorded it. Determining the age of the Çakallar volcanism accurately is thus important, both due to its volcanological and cultural significance. Several attempts to date these prehistoric treasures are debatable due to the difficulties in dating young basaltic products. Existing age estimates range between ca. 250 ka and 10-2 ka, and radiometric dates are limited and discordant. We used two independent modern methods to date the Çakallar scoria cone and the associated lava flow. Six samples from the rim of the main Çakallar scoria cone and an associated basaltic lava flow were dated for cosmogenic exposure ages. In addition, three crustal xenolith samples collected from scoria deposits directly overlying the footprints were dated using Zircon Double Dating. Using ^{36}Cl cosmogenic dating and combined U-Pb and (U-Th)/He zircon methods, we found that Çakallar volcanism and the age of the footprints is younger than the most recently published radiometric age, and dates to the Bronze age.

S01.30 Talk

Combined Volcanological and Environmental Study at Prokosko Jezero, Bosnia Herzegowina

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Explosive volcanic eruptions have a direct impact on the environment in the vicinity of their vent but can also have an impact on far distal sites. The comparison of environmental records from near the volcano and far away from them helps to understand a possible effect of the eruptions on the environment and human settlements.

Here we report results from an integrated archaeological, paleoenvironmental and volcanological research from the sediment core Prokosko Jezero, close to the Neolithic tell settlement Okoliste in Bosnia Herzegowina. The retrieved sediment core is 11.7 m long, changes in the sediment composition and pollen content reflect the climatic development back into Late Glacial times, plant successions show human interactions with the landscape.

The site Prokosko Jezero is more than 400 km away from Italian volcanic fields. It recorded at least 18 eruptive events. The volcanic ashes have been provenance-fingerprinted and correlated to their source, as well as to tephra layers in other distal sites. The study contributes to a more detailed knowledge of the eruptive history of Italian volcanoes and supports the comparison of environmental records around the Adriatic Sea. We discuss the results in the light of possible impacts of the eruptions and the over-regional environmental development.

S01.30 Poster

Timing and dispersal of Middle Pleistocene caldera-forming eruptions in the Main Ethiopian Rift

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While recent studies suggest the presence of *Homo sapiens* in north Africa circa 300,000 years ago (Middle Pleistocene), the East African Rift remains a critical region for understanding human evolution and its relationships to environmental, geomorphological and climatic stimuli. Numerous hypotheses have been proposed to link characteristics of the Rift environment and climatic change to hominin palaeodemography, yet little attention has been paid to the role that volcanism would have played in shaping the Rift habitability. The Main Ethiopian Rift (MER) hosts more than a dozen Quaternary caldera volcanic complexes suspected to have formed during the Middle Pleistocene. New Ar-Ar dates suggest that the seven largest calderas of the MER formed between 360,000 and 100,000 years ago. These eruptions produced widespread tephra fallout deposits and filled the Rift valley with ignimbrite, which drastically remodelled the landscapes and disrupted ecosystems and hydrological systems, and potentially isolated populations in regions of the Rift. We integrate stratigraphy and geochemistry of erupted products with new geochronological evidence to quantify the dispersal of these colossal events, by correlating proximal deposits with tephra in sediment records and at archaeological sites. We focus on the caldera- forming eruption of Shala volcano, which produced the largest Pleistocene caldera (17 km across) of the MER, at ca. 180,000 years ago, more recently than previously estimated. Successful correlation of the deposits of the eruption to distal tephra horizons identified in lake sediment records show that widespread ash fallouts reached at least 300 km SW of Shala. Further constraints on the tephra dispersal of these major eruptions in the MER will constitute a robust database for modelling ecosystem impacts of these eruptions, and the implications for contemporary early human populations.

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S01.32 - Analysis, monitoring and modelling of flank dynamics and mass-wasting from source to society and back again

Intra-eruptive lahars on an active volcano: a combination of earthquake and rainfall effects

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Lahars represent one of the most dangerous phenomena that may occur on active volcanoes, during or just after a main eruptive phase but also during period of volcanic quiescence. Popocatépetl is the one of the most active volcanos in Mexico. The largest lahars recorded at this volcano are directly associate with the Plinian eruptions occurred during the late Pleistocene and Holocene that inundated the surrounding basins. Rain-triggered soil slips are common processes during the rainy season, which in most of the cases transform to lahars along main ravines. The M7.1 earthquake that occurred on 19 September 2017, with its epicenter at ~ 70 km SW from Popocatépetl volcano, produced the most intense ground shaking ever felt in Mexico City and drastically affected the center of Mexico. The earthquake triggered several landslides on the upper volcano slope that consists of unconsolidated ashes from recent vulcanian explosions and alternation of pyroclastic flow and fall deposits from past eruptions. The main landslide resulted in a large mudflow that inundated the Huitzilac ravine up to 10 km of distance, with maximum flow depth of 10 m. Based on InSAR images analyses, this event occurred the same day of the earthquake. Two weeks later, on 4 October, 35 mm of rains had fallen over 10 hr, with 24 mm accumulated in only 40 minutes. This rainfall remobilized material from previous landslides, and triggered a main lahar that was observed at San Juan Tehuxtitlán town. Both lahars consisted of highly viscous mud flows, with more than 60% of silt fraction, and containing abundant tree trunks. This event represents a unique opportunity to perform a multi-hazard risk assessment at Popocatépetl volcano, and to investigate how to set up a warning system for events not directly associated to the eruptive activity.

Piton de la Fournaise Flank Displacement following the March 2007 eruption

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The April 2007 eruption of Piton de la Fournaise was the biggest eruptive crisis of the 20th and 21st centuries for the volcano. InSAR captured a large (1.4 m) co-eruptive seaward slip of the volcano's eastern flank, which continued for more than a year at a decreasing rate after the end of the eruption. Co-eruptive uplift and post-eruptive subsidence were also observed. While it is generally agreed that volcano flank displacement might be induced by fault slip, we investigate whether this flank displacement might have been induced by a sheared sill, as suggested by observations of sheared sills at Piton des Neiges. To test this hypothesis, we invert a quadrangular curved source submitted to coeval pressure and shear stress changes. Post-eruptive displacement is well explained by slip and closure of a large fracture sub parallel to the topography (5 km by 8 km). The amount of closure is too large and the closure time too short to be explained by a thermally compacting sill, allowing to rule out the sill hypothesis. Co-eruptive displacement can be explained by a smaller (2 km by 2 km) fracture at the same location, submitted to a zero overpressure and a shear stress drop, which confirms that the determined structure is not a sill. We conclude that the fracture is a detachment fold, shallow enough to induce the observed coeval uplift. Observations are consistent with a rate weakening rheology for the patch which ruptured during the April 2007 eruption, while the creeping part of the fault is consistent with a rate strengthening rheology.

S01.32 Talk

Large flank collapse of Las Cañadas volcano at ~480 ka: record from debris avalanche deposits at water galleries in La Orotava Valley (Tenerife, Canary Islands)

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Large catastrophic flank collapses are common at ocean volcanic islands and often recognizable due to their morphology as large U-shaped valleys. However, post-collapse volcanic activity can infill such amphitheaters, thereby obscuring them. We have taken advantage of the existence of a dense network of deep sub-horizontal galleries drilled for groundwater extraction at Tenerife (Canary Islands). Specifically, a survey at selected water galleries in La Orotava Valley, one of the most iconic and old known examples of such structures, has been performed. The landslide plane and the debris avalanche deposit (DAD) associated to the large flank collapse which produced the depression around 534-523 ka can be identified at several galleries opened at high altitude. In addition, we have identified a different and younger DAD conformably interbedded between the lava flow deposits infilling the collapse structure in its western side. This western DAD forms a simple layer dipping 15º at the high altitude zone, whereas at low altitudes its morphology is flatter and more complex, with some galleries crossing two DADs interbedded between the lava flow deposits. It covers a subaerial area of around 10 x 4 km with a mean thickness of around 40 m; dimensions of the deposit on the submerged part of the island north flank are unknown. The conformable nature of this DAD, its geometry and the abundance of phonolitic clasts suggest that its source was a large flank collapse of the old Las Cañadas III edifice. Dating by Ar-Ar method of three lava flow deposits located below and above it at two different galleries produced an age for the collapse episode of 487 - 472 ka. Our results show that the number of flank collapses at ocean volcanic islands can be currently underestimated due to the burial of their scars and deposits by later volcanic activity.

High-resolution numerical modelling of large-scale lateral gravitational collapse in a small oceanic volcanic edifice

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The physics of large-scale/ slow gravitational deformation in oceanic volcanic edifices is incompletely understood. Here we study, through numerical modelling, the rheology and strength parameters more suitable to localization of deep/ long-lasting failure, during the gravitational collapse of a small volcanic edifice.

We performed a high-resolution 2D systematic study (MVEP2 code), for different rheologies (viscous, viscoplastic, viscoelastoplastic – with/ without strain weakening), and strength parameters (viscosity - 10^21-10^23 Pa.s; cohesion – 1-100 MPa; friction angle - 15°-40°) for a small volcanic edifice (4.5 km high, 30 km long), assuming strong substratum (no slip basal boundary condition), during 10 Myrs.

We consider viscosity of 10^22 Pa.s for the volcanic edifice (for lower viscosity there is extreme flattening, and for larger viscosity the edifice remains practically undisturbed). There is localization of deep/ long-lasting failure for the models with visco-plastic/ visco- elasto-plastic rheologies with strain weakening, low friction angle (15°), and low cohesion (1-10 MPa).

We performed additional 3D tests (LaMEM code), for a conical volcanic edifice with dimensions/ rheology/ strength parameters equivalent to those considered in the 2D tests. We included a weak layer underlying a sector of the volcanic edifice, and observed the gradual development of a slump structure. The propagation of plastic failure was initially progressive (propagating from the core to the more distal sectors), and later retrogressive (affecting the headwall of the arcuate scar).

These tests constitute the base for the understanding of the slump structure on Pico Island's SE flank (Azores, Portugal), active since ca. 125 kyrs.

S01.32 Talk

Automatic classification of flow processes in a volcanic ravine for impact assessment and rapid response

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A large number of sediment-laden flows occur along tropical volcanoes during the rainy season. The automatic detection and characterization of those processes is of paramount importance for local authorities to provide a rapid response, especially in remote areas. An automatic classification method based on seismic data is here presented. This method was developed at Volcán de Colima, one of the most active volcanoes in Mexico. We analyzed 2- years of continuous seismic dataset gathered along the Southwestern flank of the volcano, in La Lumbre basin. The monitoring site is equipped with a vertical geophone installed on the channel bank, a videocamera, and an antenna transmitting data in real time to Colima city. Processes ranging from small hyperconcentrated flows to large lahars were analyzed. A straightforward correlation was found between the amplitude of the seismic signal, the stream power and sediment concentration. This information was used to design a detection algorithm based on two intensity-duration thresholds. The thresholds were calibrated with a trial-and-error procedure and results validated using the video images. Small hyperconcentrations (flow depth < 0.5 m, flow velocity < 1 m/sec) are detected when the signal envelope remains over the value of 1.8 · 10-3 mm/sec for at least 10 minutes. Lahars (flow depth > 0.5 m, flow velocity > 1 m/sec) are detected when a threshold of 8 · 10-2 mm/sec is exceeded for at least 3 minutes. The algorithm successfully identified all the 23 lahars that occurred during two years of monitoring and did not produce any false positives. In the near future, this detection algorithm will be integrated in the monitoring station of La Lumbre and will provide information on the channel activity to local authorities in real time.

S01.32 Poster

Dynamics of Cotopaxi volcano debris avalanche

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Cotopaxi volcano, located 60 km southeast of Quito and 45 km north of Latacunga, is one of the largest active stratovolcanoes in Ecuador. Its proximity to cities and its long eruptive history justify revisiting its hazard assessment. Cotopaxi debris avalanche occurred approximately 4.5 ka and corresponds to one of the largest events in its recent history. The debris avalanche deposit (DAD) is the main source of information about this event because the landslide scar is completely hidden by posterior activity.

The DAD has a typical hummocky topography visible in the north and northeast of the Cotopaxi National Park and covers over 70 km^2. A total of 587 hummocks were identified, which present facies derived from the volcanic edifice (andesite blocks), facies derived from the substrate (fine rhyolitic material coming mainly from the Chalupas ignimbrite) and mixed facies. Classic mapping was completed with high-resolution drone surveys in order to calculate the error on the hummocks number and volume estimates.

According to our research, the Chalupas ignimbrite played a major role in the destabilization and subsequent avalanche of Cotopaxi Volcano acting as a weak basal layer. The apparent minimum volume of Cotopaxi volcano DAD is estimated between 1.1 km^3 and 1.6 km^3, a range that locates it among the mid-sized debris avalanches in Ecuador. The H/L mobility factor is calculated at 0.125, and the ratio (A/V$^{(2/3)}$) is estimated between 51.90 and 66.63. The maximum speed, calculated ≥73 m/s, is high compared to other similar debris avalanches such as Mount St. Helens.

S01.32 Poster

InSAR time series analysis of deformation behavior and numerical modeling of flank instability at Pacaya Volcano, Guatemala

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Edifice collapse represents one of the most dangerous volcanic hazards threatening communities and infrastructure near volcanoes. In Guatemala, 9,000 people live less than 5 km away from the summit of Pacaya volcano, an active basaltic stratovolcano which shows evidence of past episodes of flank collapse. Additionally, regional field studies have highlighted factors which could promote failure of the southwest flank, such as: presence of a weak layer of tephra and ignimbrite pyroclastics below the edifice, the south-sloping regional slope, and preferential loading of the southwest flank by lava flows since 1961. To assess the hazards posed by this volcano, a better understanding of the deformation behavior and the factors promoting flank instability, as well as the triggers necessary for collapse, is required. Interferometric Synthetic Aperture Radar (InSAR) is a useful tool for remote monitoring of surface deformation. This technique is used to quantify surface deformation at Pacaya volcano, using Radarsat-2 radar images acquired between September 2010 and November 2017. InSAR time-series analysis is performed in order to examine the evolution of deformation throughout this period and discern whether flank motion at Pacaya is episodic or continuous. Subsequently, a 3D Mixed Boundary Element Method, which combines the Direct Method and the Displacement Discontinuity method, is used to model the sources of observed deformations. This method accounts for realistic topography, which is substantial at Pacaya. Additionally, it allows modeling perturbations from reservoirs of any shape, tensile cracks and shear faults, as well as take realistic source interactions into account. The latter is of particular importance for modeling the slip surface in the unstable SW flank of Pacaya. A Monte Carlo neighborhood algorithm is used to invert the InSAR data and solve for the most likely model.

S01.32 Poster

Tectonics, trigger, and timing of the catastrophic sector collapse at Usu volcano, Hokkaido, Japan

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Usu is one of the most active volcanoes in Japan and is located at the southern rim of Toya caldera in Hokkaido. The edifice comprises a basaltic to andesitic stratovolcano surmounted by many dacitic lava domes and cryptodomes. Catastrophic sector collapse occurred during its eruptive history, as evidenced by the presences of an amphitheater and a debris avalanche deposit. The debris avalanche deposit displays well-preserved hummocky topography. The hummocks consist of andesite blocks from the stratovolcano, and non- welded rhyolitic pyroclastic flow deposits and unconsolidated fluvial deposits, both from the basement of the stratovolcano. Tephrostratigraphy and radiocarbon dating of charcoals within the debris avalanche deposit suggest that the sector collapse occurred at ca. 16 ka. The age of sector collapse, combined with previous geochronological data, suggest that the activity of Usu volcano commenced with an andesitic explosive eruption at 18–19 ka, followed by stratovolcano building between 18 and 16 ka, and a sector collapse event at 16 ka. After the sector collapse, Usu remained a dormant for about 15,000 years. The activity of Usu resumed with a rhyolitic Plinian eruption in AD 1663. Dacitic dome-forming eruptions occurred in AD 1769, 1822, 1853, 1910, 1943–1945, 1977–1978, and 2000. The sector collapse occurred within 3000 years from the onset of stratovolcano building. We suggest that the sector collapse was triggered by a basaltic explosive eruption that occurred during the latest stage of stratovolcano building. Overloading of andesitic lavas on weak substratum (soft pyroclastic flow deposits and fluvial deposits) may have also contributed to the instability of the edifice. The direction of sector collapse is controlled by regional tectonics. Usu volcano is geologically unstable in terms of the weakness of the substratum beneath the stratovolcano, and has the potential for future sector collapse.

Submarine Landslide Risk offshore Mt Etna?
Insights from high-resolution 2D/3D seismic data

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Significant advances have been made in our understanding of Mt Etna's submerged continental margin in the past decade. The available hydro-acoustic and seismic datasets show remarkable seafloor structures, resulting from subsurface deformation, directly off the prominent terrestrial volcano edifice. Several studies show the presence of mass wasting deposits at the continental margin as well as tectonic and fluid-escape features. A prominent amphitheater-like structure in the lower continental margin may represent a remnant scar of such landsliding events or the outcome of repetitive margin instabilities. Despite the lack of a significant volcanic hazard, all offshore observations agree that the continental margin offshore Mt Etna is an area prone to submarine hazards caused by gravitational instabilities. Due to the widespread occurrence of mass wasting indicators like scarps, scars and mass wasting deposits, and the proximity of some of them to the coast, potential landslides have to be evaluated for their tsunamigenic potential.

To assess the near-subsurface deformation and areas prone to mass wasting, we acquired high-resolution 2D/3D reflection seismic datasets offshore Mt Etna in 2012 and 2016. At the central continental margin, 3D seismic data reveal fault bound ridges at the seafloor, which indicate active seafloor and sub-seafloor deformation. The scar of the prominent amphitheater accompanies extensional faulting at its steep (40°) head-scarp. This active deformation off Mt Etna could result in small- to medium scale mass wasting events. Numerical modelling shows that a collapse of the first ridge at the head-scarp could be capable of generating a tsunami, which would reach the densely populated coast within 5 minutes.

S01.32 Poster

From slow spreading to catastrophic collapse: 3D seismic reconstruction of the 1888 Ritter Island sector collapse

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On March 13 1888, the western flank of Ritter Island (Papua New Guinea) collapsed and slid into the Bismarck Sea triggering a tsunami, which devastated the coasts of the neighboring islands. In 2016 onboard RV Sonne, we collected a high-resolution P-Cable 3D seismic cube imaging Ritter Island's failed volcanic edifice and the adjacent mass-transport deposits in unforeseen detail. The 3D seismic data reveal that Ritter Island was affected by gradual spreading along a deep-seated detachment surface over a long period before the collapse. The associated displacement was transferred into the neighboring seafloor sediments causing the formation of compressional structures. A scoria cone located in front of the failed western sector of Ritter Island controlled the distribution of deformation and induced shearing within the volcanic cone. This structural destabilization likely preconditioned the catastrophic collapse, which was most likely accompanied by a phreatic explosion caused by the contact of the hot, hydrothermally active volcanic core with seawater. During the 1888 collapse, most of the cone and the western flank of Ritter Island disintegrated entirely and travelled as a highly energetic mass, which eroded deep into the previously deformed seafloor sediments. The hummocky topography west of Ritter Island is primarily the result of the interplay of compression and erosion and only partly related to deposition of transported blocks from the failed cone. We show that only 2 km^3 of the transported or deformed material contributed to the genesis of the 1888 tsunami, while the predating deformation affected approximately 15 km^3. This result is in agreement with first-order landslide tsunami simulation performed with VolcFlow. Our results show the complexity in reconstructing volcanic landslides and highlight the great potential of 3D seismic data in the interpretation of volcanic mass-wasting processes.

Constraining geomechanical properties for assessing volcanic instability

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In volcanic regions, reliable estimates of mechanical properties of rocks, integral to volcanic events such as inflation-deflation cycles and instability caused by magmatic intrusions, or gravitiational collapse caused by progressive loading are crucial for building accurate models of volcanic phenomena. Rock properties are often simplified or estimated because of a lack of data. However, targeted laboratory experiments can examine material properties, elucidating larger system behaviour. At Pacaya volcano in Guatemala a VEI-3 eruption in May 2010 led to slip of up to 3m of the SW flank, and the scars of historical collapses are evident in the landscape (1.). Here, we took lava samples from Pacaya with a range of porosities and measured the tensile strength - a threshold that must be exceeded to initiate failure and slip - and frictional behaviour of the material during sliding. Tensile tests using the Brazilian tensile test method showed a porosity-dependence of strength, that scales to the uniaxial compressive strength previously examined (2.). Rotary shear tests involved applying a defined axial load and slip rates up to 1.5m/s, to simulate slip to understand landslide initiation and runout. We found that the frictional properties are highly rate-dependent, and that the porosity has a significant control on the rate of comminution – offering clues to the progression of sector collapses in heterogenous volcanic edifices. Input of these process-specific rock behaviours into slope stability and deformation models influences the resultant instability, demonstrating that increased parameterisation of rock properties will improve accuracy of hazard assessment.

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The 2015 hurricane-induced lahars at Volcán de Colima, México: seismic characterization and numeric modeling

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On 24 October 2015, the hurricane Patricia hit the Volcán de Colima, one of the most active volcanoes in Mexico. The hurricane was announced as category of 5, but it rapidly weakens after landfall. Up to 400 mm of rain fell over the 30 h. Along the La Lumbre ravine, on the western slope of the volcano, lahars started around 8 PM (GMT) and lasted for more than 5 hours. A monitoring station located on the middle reaches and equipped with a rain gauge, a geophone (10 Hz), and a video camera recorded the event.
The seismic signal and the video images were analyzed in attempt to identify the timing of main pulses, their sediment concentration and maximum flow peak discharge. Data show that the lahar was characterized by three main pulses, in the range of debris flows interspersed by more dilute tails as hyperconcentrated flow. Maximum flow depths were estimated of 6-7m in average at the monitoring station, with a maximum peak discharge of 900 m3/s. Main peak flows show maximum amplitude at 7.5mm/s, with frequencies ranging from 10 to 20Hz.
The FLO-2D model was here used to simulate the observed event, the flow hydrograph was reconstructed based on the seismic signal an the estimated maximum peak discharge. Based on different values for the rheological parameters and for the manning coefficient, simulations produced reasonable estimates of flow runout, thickness and velocity along the lengths of channel.

S01.32 Poster

Evidences of instability on the south- western sector of Tenerife (Canary Islands) – Platanita DAD

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This contribution deals with the new geological map at the 1:10.000 scale of a portion of Tenerife in Canarias and with the characterization of a debris avalanche deposit (PDAD) discovered on the SW sector of the island. Lithostratigraphic units (25) above and under the Platanita debris avalanche deposits have been mapped on a surface of about 50 km^2. In the portion of PDAD deposit still outcropping there are not hummocky morphologies but the deposits lie on faults oriented NNW-SSW, opposite to the debris avalanche dispersion direction in a portion of land still preserving the characteristic horse shaped morphology. The PDAD have been described by means of sedimentological (granulometry and componentry analysis) and petrochemical analyses. PDAD shows a fine matrix and a disequigranular blocks component having a polimodal granulometric distribution as normally happens in DA deposits. Granulometric analyses show about 5-15 % of clays inside the deposit. Clast's chemical analyses of alkaline lava (from tefro-basanite to trachi-basalt, basalt and basaltic trachi-andesite) and sub-alkaline lava groups (basaltic trachi-andesite and trachi-andesite), involve the lithotypes that are presents under the PDAD deposits. The same chemical typologies form the succession covering the PDAD, inside the Platanita debris avalanche sector collapse. $^{40}Ar/^{39}Ar$ ages has been determined on the lava flow outcropping above and belowe PDAD. Debris avalanche deposits are generally loose deposits. At the contrary PDAD is uniformly welded by a fine cement that resulted to be composed by microgranular authigenic phillipsite and k-feldspar. The origin of welding has been interpreted as due to hydrothermal circulation inside the PDA. PDAD show the evidence of a previously unknown instability on this sector of Tenerife. The alteration of the PDAD deposit is a further evidence of the presence in the past of hydrothermal aquifers on the island.

Estimation of the peak flow-discharges of the June 26, 1877 lahar in the proximal drainages of Cotopaxi volcano (Ecuador)

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The peak flow discharges of the June 26, 1877 lahars, in the proximal drainages of Cotopaxi volcano have been estimated by applying the super-elevation principle and the forced vortex equation. The methodology consisted in using aerial imagery and Digital Elevation Models (DEM) to locate the drainages and the curves in which the principle was applied. The zones of interest were located between 2-5 km downstream from de glacier edge.
The data for the equation was collected in the field. The detailed mapping of the 1877 deposits allowed the geometrical definition of the curve arc and the measurement of the flow run-ups and cross sections. The topographic measurements required for the curve arc, run-ups and cross sections were obtained using a laser-telemeter handset. Additionally, an Unmanned Aerial Vehicle (UAV) was used to acquire detailed imagery and DEMs in some of these drainages in order to improve the measurements and the results.
The methodology was applied in the drainages that feed the Pita river to the north and the Cutuchi river to the south. In the north drainages the peak discharges are between ~2200 m^3/s (Victor Punina ravine) and ~5400 m^3/s (Pucarumi ravine). In the south drainages the peak discharges are between ~900 m3/s (San Lorenzo ravine) and ~2000 m^3/s (Alaques ravine). These discharges are considered as minimum values.
This knowledge will contribute to the improvement of the lahar's monitoring network installed at Cotopaxi volcano by defining detection thresholds in the proximal zones. Moreover, this study provides enhanced insights into the dynamic of the June 26, 1877 eruption. The results suggest that this event was smaller than previously thought.

S01.32 Poster

Dynamics of Mount Etna's submerged flank: Results from two years of seafloor geodetic monitoring

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The south-eastern flank of Mount Etna slides into the Ionian Sea at rates of centimetres per year. Continuous GPS measure highest rates at the coast and displacement is expected to continue across the shoreline, where satellite-based measurements are not applicable. No information on offshore movement has been available until we conducted the first ever acoustic direct-path measurements at a volcanic flank under water. A network of five transponders at the seafloor measured fault slip along the offshore extension of a fault related to flank kinematics from April 2016 until August 2018. We show that only the combination of onshore and offshore ground deformation data gives a clear picture of overall volcano flank dynamics, from which the true hazard of catastrophic flank collapse can be assessed. Our results demonstrate that seafloor geodetic investigations are capable of characterising the dynamics of submerged volcanic flank and provide deformation data at a resolution comparable to GPS.

S01.32 Talk

Hazard implications of large-scale edifice collapses: insights into complex landslide processes, tsunami hazards and modified eruptive behaviour following the Ritter Island 1888 collapse

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Volcanic-edifice collapses are among the most devastating volcanic processes, potentially mobilising rock volumes comparable to the largest magmatic eruptions. Resultant landslides may travel many kilometres, generate large tsunamis in island settings, and are often associated with eruptive activity. Although they are relatively infrequent, they represent a ubiquitous volcanic process. Our understanding of collapse mechanisms, associated hazards, and the impact of collapse on volcano-magmatic systems is often limited when studying ancient events, due to poor stratigraphic resolution and difficulties in sampling. Of the few historical events, the tsunamigenic1888 collapse of Ritter Island, Papua New Guinea, involved the largest volume, and provides an ideal case study for understanding collapse processes in an island setting.

The 1888 Ritter landslide was surveyed by the RV Sonne (SO252) in 2016, collecting geophysical data and a small number of samples across the entire deposit. This data yields deposit volumes and confirms the presence of compositionally and morphologically distinct areas of deposition, over ~80 km. While the proximal region is dominated by coarse volcaniclastic material, part of the disintegrated mass formed highly mobile flows, which triggered secondary seafloor failure and produced a mixed mud-rich deposit, beyond which lies a ponded volcaniclastic turbidite. The total volume of the deposits is much more than the collapse scar volume, showing the importance of seafloor sediment incorporation. When such seafloor interactions occur, reconstructions of landslide volumes and processes around volcanic islands can only be accurately achieved with the use of geophysical imaging. Volcaniclastic samples show distinct compositional and textural differences between pre- collapse material and that erupted during post-1888 regrowth of the Ritter submarine cone, suggesting that this deep-seated collapse modified the underlying plumbing system and led to a shift in eruptive behaviour.

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S01.33 - Volcanic degassing insights into volcanic processes, impacts and hazard

Challenges in UV camera-based real-time SO_2 flux monitoring: insights from 5 years of continuous observations at Etna ad Stromboli

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The advent of UV cameras has recently paved the way to volcanic SO_2 flux observations of much improved temporal and spatial resolution, and has thus contributed to expanding use and utility of SO_2 fluxes in volcano monitoring. Recently, the first examples of permanent UV camera systems have appeared that are now opening the way to routine fully automated monitoring of the volcanic SO_2 flux at high-rate, and continuously (daily hours only). In 2014, using funding from the FP7-ERC project "Bridge" (http://www.bridge.unipa.it/), we deployed a network of 4 permanent UV cameras at Etna and Stromboli volcanoes (Sicily) that has been operating regularly since then. Using a suite of custom-built codes, data streamed by the UV camera are automatically processed and telemetered, allowing nearly real-time visualization and analysis of SO_2 fluxes. Here, we summarise the key results obtained during the last 5 years of continuous observations (2014-2018) to demonstrate potentials and challenges in real-time continuous SO_2 flux monitoring with UV cameras. We show that the spatially resolved SO_2 flux time-series delivered by the UV camera allow effectively tracking migration in volcanic activity from the Central to New South-East Crater (Etna), and shifts in degassing activity along the crater terrace (Stromboli). At both volcanoes, the high temporal of UV cameras allows capturing the escalation in active (strombolian) SO_2 degassing that typically precedes onset of paroxysmal (Etna in 2014-2016) or effusive (Stromboli in 2014) activity, and to quantify for the first time the syn- explosive SO_2 budget for larger-scale explosions, including 2 paroxysmal lava fountains (Etna) and 1 major explosion (Stromboli). We finally demonstrate the ability of our automatic camera systems to capture temporal changes in SO_2 flux regime, and thus to "live" monitoring degassing and eruptive behaviors at active volcanoes.

Magma degassing during a rare post-paroxysmal rest phase Merapi of volcano (Indonesia): continuous survey and implications

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Since its sub-Plinian (VEI 4) eruption in November 2010, Merapi volcano has entered a rare rest phase, marked by low volcanic seismicity, minor ground deformation, gradual cooling of the 2010 lava dome, and 6 discrete explosive events in 2013-2014. Direct survey of its gas emissions has become impossible due to disappearance of the high-temperature fumarolic fields previously used for regular gas sampling. Here we report on the first data set for post- paroxysmal magma degassing at Merapi in 2014-2016, obtained from discrete measurements then continuous in situ MultiGAS survey of the summit crater plume emissions (H_2O, CO_2, SO_2, H_2S and H_2). Gas fluxes were derived from short-range SO_2 flux measurements using UV-cameras and scanning DOAS. Our results demonstrate a persisting though reduced upflow of hot magmatic gas through the volcano conduit. This magmatic gas clearly differs chemically from cooler fumarolic emissions from the crater walls and resembles, its bulk proportions of H_2O, CO_2 and total sulfur, to Merapi magmatic gas previously collected at 700-900°C during lava dome extrusion. However, it also displays higher SO_2/H_2S ratios at equivalent H_2/H_2O ratios and equilibrium temperatures, trending towards more oxidized conditions over time. We thus infer a separate upflow of magmatic gas derived from relatively shallow depth, that lately re-equilibrates with the cooling and likely more oxidized 2010 magma plugging the volcano conduit. A temporary increase of CO_2/SO_2 ratios recorded during the 2016 summer, without anomalous seismicity, possibly tracked a deeper influx of CO_2-rich gas. Gas precursors of a future magmatic unrest, hopefully detectable with our MultiGAS survey, actually include an increase of deeper-derived CO_2 (increasing CO_2/SO_2 and CO_2/H_2O ratios) and a decrease of SO_2/H_2S ratio at constant H_2/H_2O ratio, coupled with increasing SO_2 flux and seismic-geodetic signals of magma upraise.

S01.33 Talk

Evolution of eruptive process at Sabancaya Volcano (Perù) 2014- 2018

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Sabancaya Volcano (5960 m) is a stratovolcano located approximately 80 km southeast of the city of Arequipa in southern Peru. In the Holocene, activity at Sabancaya has included several Plinian eruptions which were followed by effusion of massive andesitic and dacitic lava flows that now cover large portions of the west, north and east flanks of the edifice.

The Volcanological Observatory of INGEMMET (OVI) uses geophysical and geochemical monitoring techniques to track changes in activity at Sabancaya. The first precursors of the current eruptive crisis were detected in 2014, when a slight but visible increase in fumarolic emissions was observed. Around the same time, sulfur dioxide (SO_2) emissions were detected for the first time. In 2015, volcano-tectonic and hybrid-frequency earthquakes set in, and their frequency of occurrence increased throughout 2015 and into early 2016. Clearly, magma was rising towards the surface. Finally, on November 6, 2016, the volcano erupted with an explosive ash emission.

Events similar to this first magmatic explosion have been occurring at Sabancaya ever since. Ash from these explosions travels up to 60 km downwind before it is deposited on the ground. This ash currently represents the main hazard at Sabancaya. Located as close as 20 km to the volcano, several communities in the Colca Valley are reporting negative impacts on crops and livestock, as well as more frequent occurrence of respiratory diseases and eye problems, particularly in young children. SO_2 emissions also remain high, with scanning DOAS instruments from the Network for Observation of Volcanic and Atmoshpheric Change (NOVAC) measuring average emission rates of about 2,000 tons per day and average plume heights of about 3 km above the volcano's summit. The local authorities are providing support to the affected population, as well helping them mitigate the ash hazards as best they can.

Continuous monitoring of diffuse H2 degassing at the summit cone of Teide volcano, Tenerife, Canary Islands

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The chemical composition of volcanic gases provides very important information on the degree of activity of a volcano. Hydrogen is a trace gas present in most volcanic emissions and is an essential participant in the redox reactions occurring in the magmatic gases. Due to its low molecular weight and low solubility in both groundwater and hydrothermal fluids, H_2 is an excellent indicator of the processes taking place in the magmatic systems at depth. In the last decades, scientists have made efforts to measure concentrations and fluxes of H_2 in volcanic fluids. However, studies regarding continuous measurement of H_2 in active volcanoes are very scarce to date. We present the results of diffuse H_2 emission monitored in a continuous mode, since the installation in November 2017 of a chromatography monitoring station (CMS) in SE flanks of Teide volcano. There is also a CO_2 efflux continuous monitoring station measuring at the same point. The station is equipped with a two-channel Agilent 490 micro-GC provided for the analyze of He, Ne, H_2, O_2, N_2, CH_2, CO_2, H_2S and H_2O. An embedded computer connected to the internet (WiFi, UMTS router, etc.) allowed for complete remote control of the instrument, the automatic transmission of data, and full automatic sampling of the gas samples. A very good correlation in the evolution of the CO_2 efflux and the H_2 concentration has been observed, which confirms a common origin for both species. The temporal evolution of the concentration of other gases showed a logical decrease in the N_2 and O_2 concentration when that of H_2 and CO_2 increases. This CMS constitutes a very powerful system in the field of volcanic surveillance, able to determine low concentrations of H_2 (1 ppmV), allowing at the same time to correlate variations in time of all natural gases measured.

S01.33 Poster

Extensive CO_2 degassing in the upper mantle beneath oceanic basaltic volcanoes: first insights from Piton de la Fournaise volcano (La Réunion Island)

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In spite of its major role on the atmospheric volatile budget, on climate, and to track magmatic transfers, mantle (CO_2) degassing below volcanoes is still poorly understood. Most of the studies on this scientific problematic lack constrains on the depth at which CO_2 degassing starts and the extent of this process in the mantle. In this study at Piton de la Fournaise (PdF) volcano, we couple geochemistry of low solubility gases (He, Ar, CO_2) in fluid inclusions (FIs) and petrology of magmatic inclusions on a set of olivine and clinopyroxene crystals from basalts and ultramafic enclaves.

After filtering for secondary effects affecting the composition of FIs, we constrain basaltic melt degassing over a large pressure range. At PdF, we show that extensive degassing occurs already in the upper mantle (4-1 GPa), up to the mantle-crust underplating depth (0.4 GPa) and is favored by multiple steps of magma ponding. Based on CO_2-He-Ar systematics, we calculate that basaltic melts injected at crustal depth (<0.4 GPa) have already exsolved ~94±5 wt% of their primary CO_2 content.
Based on the modeling developed in this study, we propose a new estimation of the carbon content in the mantle (C = 716±525 ppm) raising major implications regarding the volcanic carbon budget on Earth. Another implication of this work involves the possible bias between the $\delta^{13}C$ measured in volcanic gas emissions (<-6‰) and that of primary vapour phase (-0.5±0.5‰). It may be consistent with an early step of extensive CO_2 degassing within the upper mantle and constitutes an alternative to recycled carbon or mantle heterogeneity effects often invoked to explain the low $\delta^{13}C$ signature of some mantle reservoirs. This study opens significant implications on the budget of volcanic volatile emissions, chiefly regarding past and future contribution of volcanic CO_2 to climate dynamics and for volcanic gas monitoring.

Radon (222rn) concentration in subterrain water bodies in São Miguel Island (Azores)

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Radon (^{222}Rn) is a radioactive noble gas, resulting from the decay chain of Uranium (^{238}U). The volcanic context of the Azores archipelago, to which São Miguel Island belongs, explains the presence of several soil diffuse degassing areas (CO_2 and ^{222}Rn) and the existence of radon in the groundwater bodies.

Two surveys (summer and winter) were performed in 42 springs spread all over São Miguel Island. For each sample, the physical-chemical parameters (temperature, pH and electrical conductivity) were determined in situ, and the major element concentration (cations and anions) were determined in laboratory. The radon concentration was determined using the Rad7 Radon Detector (Durridge Company Inc.). The sampled waters are mostly of the Na- HCO_3 type with temperatures between 12.6ºC and 78.1ºC. The waters are mostly acid, with pH values in the range between 4.05 to 7.82. The majority of the samples correspond to poorly mineralized waters, with most of the springs showing low conductivity values (95 µS/cm - 1657 µS/cm; median= 222 µS/cm).

Radon values in the winter campaign range between 0.99 Bq/L and 551.64 Bq/L, and 1.42 Bq/L and 559.67 on the summer campaign. It's possible to observe that waters with higher temperatures have associated lower radon concentrations and higher electric conductivity values. As a radioactive gas, radon can be harmful to public health when present in supply water in high content. Nevertheless, all sampled springs which are abstracted for public supply present values between 2.25 Bq/L to 155.99 Bq/L, thus not exceeding the threshold established by current legislation. It's also possible to observe the expected inverse relation between the concentration of CO_2 and pH.

This work gives a contribution for a better understanding of interaction between volcanic systems and groundwater bodies, and allows to establish a reference line for radon in groundwater that can be used for seismovolcanic monitoring.

Automatic data acquisition system to measure dissolved CO_2 (CO_2 meter): data obtained during measurements performed in Ecuador and Argentina

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After water, carbon dioxide (CO_2) is the main gas dissolved in magma. Being easily exsolved compared to more soluble gas species, CO_2 is one of the main components of volcanic emissions both during quiescence and periods of unrest. Carbon dioxide is released from magma at depths and can condense and/or become dissolved in shallows aquifers existing around the volcano. Changes in the concentration of dissolved CO_2 in spring water can therefore be related to volcanic activity, especially when related to other parameters such as (water?) temperature and seismicity for example. For the purpose of continuous monitoring of dissolved CO_2 in spring water, an Automatic Data Acquisition System (CO_2 METER) has been developed.

This work comprises data collected during several campaigns at spring waters in Ecuador and Argentina between 2015-2017, performed in order to verify the reliability of CO_2METER system. Data obtained by CO_2 METER is in good agreement between concentrations of dissolved CO_2 and temperature when compared with existing data. At Palmira spring, a natural water source in close proximity to Guagua Pichincha volcano (Ecuador), CO_2METER registered a CO_2 concentration of 22.6%, comparable to similar concentrations acquired by Inguaggiato et al. 2010. In another campaign performed at Las Maquinitas hot spring near to Copahue volcano (Argentina) the CO_2METER registered an average dissolved CO_2 concentration of 1.4% and a temperature of 83ºC. These data compare well with measurements performed by Lamberti et al. 2018 (not published).

These first results provide validation for the CO_2 METER as an accurate means by which to measure dissolved CO_2 at spring waters. This fully automated system provides a promising tool for volcano observatories to provide real time continuous data, reducing timely dependence of routing measurements.

Behaviour of S-bearing compounds (H_2S and SO_2) emitted in air from the main hydrothermal-volcanic systems of Iceland

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The main sources of SO_2 and H_2S in air consist of (i) natural fluid emissions from active/quiescent volcanoes and (ii) anthropogenic activities. These gas compounds have a strong impact on air quality, since they are toxic and climate forcing agents. Notwithstanding, the behaviour of these S-compounds in air is poorly known, since relatively scarce are the available thermodynamic data as well as those deriving from direct measurements. Hydrogen sulphide is considered to be relatively reactive in the atmosphere as it tends to be oxidized to SO_2 by photochemical reactions, even though the efficiency of the H_2S to SO_2 conversion significantly decreases under dark, dry and relatively cold conditions. Oxidation processes are also affecting SO_2, since about 65% is transformed to SO_4^{-2} whilst the remaining 35% is removed by dry deposition.

This work presents the results of an empirical approach to investigate the behaviour of H_2S and SO_2 once they are released to the atmosphere from the main hydrothermal fluid discharges of Iceland, i.e. fumaroles, boiling and mud pools. Hydrogen sulphide and SO_2 measurements in air were carried out using a Thermo Scientific 450i Analyzer positioned at 4-6 fixed points at increasing distance and downwind from the emission sources, under different weather conditions.

The results showed significant variations in terms of H_2S/SO_2 ratios (from 30 up to 200) from the different gas emissions, which are not necessarily related to the composition of the emitting source. A mathematical model of the spatial distribution of air pollutants, coupled with a statistical elaboration of the measured data, has been applied to i) determine the rate of loss of H_2S and SO_2 at increasing distances from the source, and ii) discriminate the effects of physical (i.e. dilution) and chemical (e.g. oxidation of H_2S to SO_2) processes controlling the spatial and temporal dispersion of the S-bearing gases.

Satellite-derived sulphur dioxide (SO_2) emissions from the 2014-2015 Holuhraun eruption (Iceland)

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The six-month-long 2014-2015 Holuhraun eruption was the largest in Iceland for 200 years in terms of total lava volume, emitting huge quantities of sulfur dioxide (SO_2) into the troposphere, at times overwhelming European anthropogenic emissions. However weather, terrain and latitude made getting continuous ground-based or UV satellite sensor measurements challenging. We present Infrared Atmospheric Sounding Interferometer (IASI) data, providing the first timeseries of daily SO_2 masses and vertical distribution over the eruption period. We develop a new optimal estimation scheme to calculate daily SO_2 fluxes and average e-folding times every twelve hours. This gave SO_2 fluxes of up to 200 kt/d and a minimum total SO_2 mass of 4.4±0.8 Tg. The average SO_2 e-folding time was 2.4±0.6 days. These results broadly agree with ground-based near-source measurements, independent remote-sensing data, petrological estimates of SO_2 flux and model simulations of the eruption. Our results highlight the importance of high-resolution timeseries data to accurately estimate volcanic SO_2 emissions.

S01.33 Talk

Repeated episodes of magma degassing at Campi Flegrei cause geochemical anomalies, ground deformation and seismicity

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We discuss here thirty five years of compositions of the fumarolic fluids systematically sampled at Solfatara, the most active hydrothermal site of Campi Flegrei caldera. This geochemical data set, that can be considered as a unique example for the long duration of the observation period and the high number of data, is compared with the geophysical signals acquired by Osservatorio Vesuviano. Previous jointed interpretations of the geochemical and geophysical signals recognised the occurrence of magma degassing episodes as a main factor controlling the ongoing Campi Flegrei unrest. Here we update the geochemical and geophysical data series and we apply specific statistical algorithms to decompose the signals in different periodic and aperiodic components. The occurrence of magma degassing episodes is suggested by the correspondence of short time (1-2 year) pulses of ground deformation and clustered seismicity with anomalous peaks of CO_2/CH_4 and He/CH_4 fumarolic ratios that follow the geophysical signals. The CO_2/CH_4 and He/CH_4 fumarolic ratios are in fact powerful geochemical gas indicators of the injection of magmatic fluids into the hydrothermal system feeding Solfatara fumaroles. Sixteen of these events were recognised in the 1983-2018 period. These pulsed signals overlap a long period trend of ground uplift and of increase of CO_2 flux and background seismicity. The concurrent rise in the concentration of the fumarolic CO suggests that the long period trend of ground deformation is accompanied by the heating of the hydrothermal system. Referring to a recent interpretation that relates variations in the fumarolic inert gas species to open system magma degassing, we infer that the heating is caused by an enrichment in water of the magmatic fluids, an increased frequency of the degassing events and an increment in their flux.

S01.33 Talk

In-soil radon concentrations at Soufrière volcano, Guadeloupe: insights from field surveys and laboratory measurements

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An extensive radon survey on the summit sector of the Soufriere volcanic dome (Guadeloupe) revealed a relatively high in-soil gas concentration spanning, on average, from about 20 kBq/m^3 to 150 kBq/m^3. Notably, the most relevant emissions were measured along the TY fault, the main active structure of the Soufriere dome complex. However, background values seem likely related to the combining effect of hydrothermal activity (responsible of pervasive rock and soil alteration) and by the high soil humidity related to tropical weather. We performed a set of laboratory measurements on Soufriere soil samples, from dry to water-saturated conditions, to evaluate and quantify the contribution of soil humidity on our data collected in-situ. Soil porosity and permeability measurements were also performed. The results show the effects of water contents on radon emanation from soils. The comparison of field and laboratory measurements delineates complexities associated with multiple environmental factors that normally affect in-situ soil radon concentrations. These factors should be wisely considered when analyzing the radon signal for evaluating unrest episodes at active volcanoes.

S01.33 Poster

Radon measurements at Aso volcano during thermally detected unrest episodes

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Radon measurements at Aso Volcano were performed from May 2015 to January 2016. This period was characterized by a sporadic explosive activity, which marked the ceasing of a Strombolian phase, and was followed by moderate phreatomagmatic events. Radon data have been collected by means of an automatic station located at about 1.06 km from the active crater (crater 1) together with soil temperatures. Data were also analyzed in the light of local atmospheric parameters (JMA). Radon measurements been compared with ground- based (JMA data set) and satellite thermal data, the latter collected by the MIROVA system. Radon concentrations were fluctuating from 300 to about 1100 Bq/m^3 during May-July 2015, and they reached a minimum two weeks before the strong degassing that occurred at the beginning of August. This phenomenon was accompanied by the onset of marked thermal anomalies within the crater area (with apparent temperatures well above 300 °C). On August 8, 2015 the Volcanic Radiative Power (VRP) detected by MIROVA was slightly below 1 MW. Since then there has been an increasing trend in Radon emissions (up to about 900 Bq/m^3) that preceded the strong phreatic explosion of September 14. By the end of September, a new increasing trend reached a relative maximum (up to 1900 Bq/m^3) one week before the explosion of the 26 of October 2015. Then, radon data persistently fluctuated well above 900 Bq/m^3. This time span was accompanied by a general decrease of the detected thermal anomalies which were nearly coeval with the replenishment of the crater lake. A systematic analysis of radon data shows that radon emissions are inversely correlated with soil temperatures and that the contribution of atmospheric pressure marginally affect radon emissions. The spectrum of the radon signal shows the existence of both diurnal and semidiurnal peaks, typically observed during continuous radon measurements.

Ten years of continuous gas monitoring at Piton de la Fournaise volcano: results and perspectives

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Following the major caldera forming eruption in April 2007, a new gas geochemical network (DOAS, MultiGaS, soil CO_2 flux) has been installed at Piton de la Fournaise (PdF). The new network has permitted for the first time to characterize the fluxes and composition of inter- and intra-eruptive gas emissions at one of the most active basaltic volcanoes of the world. This unprecedented dataset demonstrates that, in spite of its high rate of activity, magmatic gas release at Piton de la Fournaise is very weak in inter-eruptive phases and essentially occurs during eruptions. During eruptions, SO_2 fluxes tightly correlate with lava extrusion rates with little if any evidence of pre-eruptive gas accumulation. Nevertheless, subtle change in the composition of summit fumaroles and soil CO_2 emissions clearly correlate with time evolution of volcanic unrest. The weak explosivity of the volcano has permitted to acquire unprecedented geochemical datasets very close to the active eruptive vents. Modelling of magma degassing by integrating high temperature gas and melt and fluid inclusions datasets suggest that PdF eruptions involve the rapid ascent of shallow and extensively degassed melts, pressurized by deeper sources. The generally low gas fluxes result thus from both the low volume of degassed magma stored at shallow depth whose fluids are efficiently scrubbed by the shallow hydrothermal system and the water table. Deep exsolution of CO_2 provides a potential long-term precursor for the detection of magma transfer and volcano unrest.

S01.33 Talk

Changes in thermal release by fractures during short-lived paroxysms on Etna volcano

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The thermal monitoring of shallow ground, is based on the principle that volatile emanations are the most durable volcanic phenomenon, we can detect on surface. Fumaroles are some evident expressions of this extensive and continuous discharge, where steam is the main heat carrier. Consequently, on active volcanoes, the accurate analysis of surface thermal release could contribute to fill the gap of volcanic observations, between eruptive events. For example the recent review of the geochemical methodologies applied to volcanoes of the Aeolian Arc, included some results from thermal monitoring of fumaroles (Inguaggiato et al., 2018). On Mount Etna, the relation between steam discharge from fractures and volcanic activity has been confirmed by the time variations of steam-heated soil flux (SHS_{Flux}, Diliberto et al., 2018). On Etna the SHS_{Flux} were evaluated by a set of temperatures values, recorded on a shallow profile of ground (at depth < 1m) from September 2009 to April 2012. This presentation shows a subset of the SHS_{Flux} data-set, monitored on the Northeast rift. The SHS_{Flux} is now compared to the total radiant energy, evaluated during 4 lava fountains erupted by the new crater rising on the flank of Southeast cone. The radiant energy data of lava fountains are from Bombrum et al. (2016), who examined the thermal infrared data supplied by a ground-based radiometer station. The SHSFlux variations, hourly recorded, appear correlated to the radiant energy, released during explosive activity. The quantifications of radiated energy by sustained lava fountains ($TRE_{Fountain}$) compared to the set of SHS_{Flux} data, are still few to be statistical significant. However, further correlations and a multi-parametric approach could confirm whether data supplied by continuous monitoring of SHS_{Flux} have the potential to detect some precursory heat loss by the network of active fractures, hours or days before those short-lived paroxisms.

S01.33 Poster

High-resolution modelling of atmospheric dense gas dispersion: the 1986 Lake Nyos limnic eruption case

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Atmospheric dispersal of a gas denser than air can threat the environment and surrounding communities if the terrain and meteorological conditions favour its accumulation in topographic depressions, thereby reaching toxic concentration levels. Numerical modelling of atmospheric gas dispersion constitutes a useful tool for gas hazard assessment studies, essential for planning risk mitigation actions. In complex terrains, microscale winds and local orographic features can have a strong influence on the gas cloud behaviour. We introduce a methodology for microscale wind field characterization based on transfer functions that couple the WRF mesoscale model with a microscale Computational Fluid Dynamics (CFD) model for the atmospheric boundary layer. The resulting time-dependent high-resolution microscale wind field is used as input for a shallow-layer gas dispersal model (TWODEE-2.1) to simulate the time evolution of CO_2 gas concentration at different heights above the terrain. Such modelling strategy was applied to review simulations of the 1986 Lake Nyos event in Cameroon, where a huge CO_2 cloud released by a limnic eruption spread downslopes from the lake suffocating thousands of people and animals across the Nyos and adjacent secondary valleys. A novel statistical criterion, based on the percentage of human fatalities depending on CO_2 concentration and exposure time, was also proposed to assess the CO_2 impact. This new approach allowed us to quantitatively validate the results, using the reported percentage of fatalities at several locations, and infer the time evolution of the gas flux from the lake during the limnic eruption.

S01.33 Talk

The simultaneous retrieval of volcanic sulphur dioxide and sulphate aerosols from TIR spectra: analysis of satellite and ground-based observations

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Remote sensing of volcanic effluents is a powerful tool for providing large-scale information on natural sulphur emissions in the atmosphere. Retrieval methods of volcanic sulphur dioxide (SO_2) in the thermal infrared (TIR) spectral region usually neglect the impact of the subsequently formed Secondary Sulphate Aerosols (SSA) and vice-versa. In this study, we report on an assessment of the combined sensitivity of pseudo-observations to the SO_2 emissions and the formed SSA after an idealized moderate stratospheric eruption. Three TIR satellite instruments are used: the Infrared Atmospheric Sounding Interferometer (IASI), the MODerate resolution Imaging Spectro radiometer (MODIS) and the Spinning Enhanced Visible and InfraRed Imager (SEVIRI). Our results show that the radiative interference, produced by the presence of SO_2 and SSA on the outgoing TIR radiation, is significant after a few days from the eruption. In particular, neglecting SSA may bias SO_2 retrievals. The SEVIRI and MODIS instruments present significant uncertainties. However, using IASI pseudo-observations, SO_2 and SSA masses can be retrieved as independent quantities. Basing on these preliminary analyses, we perform, for the first time, the combined retrieval of SO_2 and sulphate aerosols total masses using a ground-based remote open path Fourier Transform InfraRed (FTIR) spectrometer, which operated during a campaign at Masaya Volcano (25/03/1998). The retrieval is based on a non-linear least square fitting algorithm, minimizing the difference between modeled and measured spectra. The retrieved state vector is composed of the SSA and SO_2 total masses, as well as the % of H_2SO_4 by weight.

The results show masses of SO_2 and SSA of $1.87 \pm 1.11\ 10^{-3}$ and $0.44 \pm 0.2\ 10^{-3}$ g/m^3, respectively, and H_2SO_4 weight of 65.4 ± 18 %. So, the sulphate aerosols from the Masaya volcano were highly acidic. Further work will target the estimation of the mean size of these sulphate aerosols.

Eruption history and magma systems of Nyos volcano, northwestern Cameroon

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Lake Nyos is a maar volcano in northwestern Cameroon. It exploded in 1986, releasing a large amount of CO_2 that killed 1746 people. Geologic and petrologic study was performed to reveal the maar-forming eruption history and related magma systems. Eruptive deposits of Nyos maar are divided into 4 units (A-1 ~ A-4) in ascending order. There is no soil layer between these units. Unit A-1 is an explosion breccia composed of basaltic bombs (juvenile) and granitic (crustal) and peridotitic (mantle) xenoliths. Its limited areal distribution in the eastern lakeside indicates a nearby vent location (Vent1). Unit A-2 is well-sorted scoria fall deposits. The thickness decreases from north to east lakeshore. Unit A-3 is an extending basaltic lava flow. Its depositional level is highest at the north of the lake. These evidences suggest that the vent that erupted Units A-2 and -3 was located at the northern part of the lake (Vent2). UnitA-4 is the most voluminous pyroclastic surge deposit characterized by cross-laminated and fines-poor facies. The thickness is more than 30 m at the lakeside and it a makes depositional surface 1 km around Vent2. A scoria cone is situated 1.5 km northeast of Lake Nyos. Ejecta from the cone (scoria fall) directly overlies Unit A-4, suggesting that activity of the cone started immediately after the Nyos maar-forming event.

Phenocryst assemblage of juvenile materials is commonly olivine, clinopyroxene and plagioclase. Whole rock compositions are plotted into basanite and trachybasalt in TAS diagram. Juveniles from scoria cone show clearly higher MgO, Cr and Ni contents than those of Nyos maar at a given SiO_2, indicating different magmas were active between Nyos maar and scoria cone. The most violent Unit A-4 shows various composition on Harker diagrams, and the chemical trend can be well explained by contamination with granitic basement.

Evolution of Santa Ana crater lake (El Salvador) since the 2007 phreatic eruption: physical and chemical characteristics and lake gas composition

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Crater lakes are known to integrate most of the fluids and heat flux from a volcano. Changes in their chemistry, physical characteristics or gas emissions could thus be precursory signs of a future eruption. Santa Ana is one of the most active volcanoes in El Salvador and threatens the life of more than 1 million people. This stratovolcano hosts in its crater a hyper-acidic lake since the 1904-eruption. The lake survived the 2005-eruption and the small phreatic eruption in March 2007. However, the chemistry and physical characteristics of the pre- and post-eruptions lake changed drastically (Colvin et al., 2013). In particular, the post-eruption lake is hotter (28-65°C) than the pre-eruption lake (20-30°C during 2000-2005) (Colvin et al., 2013). From October 2010 to June 2017, the water temperature increased continuously up to 59.8°C. In March and June 2017, we measured the lowest pH (down to -0.01 ± 0.01) and highest concentrations of SO_4 (up to 47048 mg/l) and Cl (up to 71615 mg/l) ever observed during the post-eruption period. In addition to lake water monitoring, we studied for the first time the lake gas composition with a Multi-GAS instrument. Our results show CO_2/SO_2 ratios decreasing from March 2017 (17-63) towards more magmatic values (1-7) in June 2017 and April - May 2018. In conclusion, the physical and chemical changes observed in the lake since 2010 suggest an increase of gas and/or heat flux into the lake system.

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Continuous monitoring of radon for volcanic surveillance in the Canary Islands, Spain

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Monitoring of radon (^{222}Rn) and thoron (^{220}Rn) in ground and surface waters has become an important tool to forecast earthquakes and volcanic eruptions in the last decades. Radon anomalies have been related to an increase of the ground permeability, in the velocity of ground migration and temperature, and release of radon during magma intrusion (Silva et al., 2015). In order to improve the continuous geochemical monitoring program that INVOLCAN has in the Canary Islands, since 2002 a network of radon gas monitoring stations (SARAD RTM-2010-2, RTM1668-2 and RTM-2200) has been deployed. The current network includes four stations in Tenerife, three at La Palma, two at El Hierro and one in Gran Canaria. During these sixteen years of radon monitoring, this geochemical network has made it possible to detect geochemical precursory signals from both volcanic unrest processes and the submarine volcanic eruption of El Hierro in 2011-2012. For example, precursory geochemical signatures of radon degassing in the subsurface of the Tenerife Island were observed several months prior to the 2004 seismic-volcanic crisis (Pérez et al., 2007), and significant increases in soil ^{222}Rn activity and $^{222}Rn/^{220}Rn$ ratio from the soil were observed at two stations prior to the 2011-2012 submarine eruption off the coast of El Hierro (Padilla et al., 2013), showing the highest increases before the eruption onset and before the occurrence of the strongest seismic event ($M = 4.6$). These examples show that gas radon activity increases prior to the occurrence of major seismic volcanic events and periods of volcanic unrests can be efficiently used as an initial warning sign of the pressurization of magma beneath volcanic systems, together with other geochemical and geophysical data.

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First continuous degassing measurements at Reventador Volcano (Ecuador)

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Reventador volcano is located in the sub-andean zone of Ecuador. It is active since November 2002, when a VEI 4 eruption rapidly opened the system after 26 years of quiescence without significant precursors. Since then the activity has been characterized by the presence of numerous andesitic lava flows and small domes, discrete explosions with ballistic projectiles, long-lasting ash venting and short run-out pyroclastic flows.

Given the remote location of the volcano, installing a monitoring network has been extremely challenging, specially regarding permanent DOAS stations. According to the Washington VAAC alerts, the plume drifts to the West 75 % of the time, where no access exists. For this reason, we tested an original configuration. We located the DOAS station to the northeast of the volcano pointing directly above the crater area in order to cut the rising plume horizontally. This configuration allows to see changes in the SO_2 concentration of the gas plume. Over the 9 months since the installation of the instrument, average concentrations are of 300 ppm.m., with the highest values reaching 800 ppm.m. These highest values are generally associated to changes in the seismic and superficial activity.

Here we present the variations in SO_2 concentration associated to the recorded seismic signals and satellite observations of the plumes. Near-real time monitoring of the gas emission at Reventador could allow to infer changes in the activity style.

S01.33 Poster

Detection of globally significant CO_2 emissions from Katla volcano in Iceland

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Atmospheric carbon dioxide (CO_2) is regulated over the long term by geological sources and sinks whose magnitudes are poorly constrained. Volcanoes are a key geological source of CO_2 but global estimates of volcanic CO_2 flux are largely based on measurements performed on a fraction of actively degassing volcanoes, and large numbers of volcanoes without a visible gas plume are rarely targets for gas quantification.

We have made airborne measurements of a type not previously attempted to show that CO_2 emissions from Katla, a major subglacial volcanic caldera in Iceland, are of a globally important scale. Campaigns in 2016 and 2017 showed that Katla's sustained CO_2 flux (10-37 kt/day) is up to an order of magnitude greater than previous estimates of total CO_2 release from Iceland's natural sources. The lack of other likely geological or biological sources allows us to conclude that Katla's CO_2 plume is produced by magmatic degassing, making Katla one of the largest volcanic sources of CO_2 on the planet, and contributing up to 5% of global CO_2 emissions from non-erupting degassing volcanoes.
Katla last erupted 100 years ago and has been undergoing major unrest in recent decades. Further measurements conducted on subglacial volcanoes world-wide would establish if Katla is exceptional or if, instead, there is a significant previously unrecognised contribution to global volcanic CO_2 emissions.

Preliminary assessment of the origin and evolution of fluids discharged from Guallatiri Volcano

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We present the first study on the chemical and isotopic composition of gases and waters discharged from Guallatiri (18°25'S; 69°05'W; 6,073 m a.s.l.), with the aim to investigate their source(s) and the chemical-physical processes acting during their uprising toward the surface. Guallatiri is considered as the second most hazardous volcano in the north of Chile, located close to Guallatiri, Ancuta, Uncaliri, Chachacomani and Jancoaque villages, besides important international roads (e.g. Arica-La Paz Route), zones that could be affected by pyroclastic flows, lahars, volcanic avalanches or ash fall. Historical eruptive records are related to incandescence on the summit (1913 and 1959) and phreatic explosions (1960), all these with VEI 2. Guallatiri volcano has two fumarolic fields with strong and continuous gas emissions in the summit area and along its southwest flank. The measured outlet temperatures from the fumarolic vents ranged from 83.2 to 265 °C, whereas the gas chemistry showed the typical features of those from active volcanoes, being dominated by water vapor and CO_2 with significant concentrations of H_2S, SO_2, HCl and HF. The R/Ra ratios ($^3He/^4He$) of the fumarolic gases were up to 5.8, indicating a dominant mantle He source. Cold and thermal springs located in the volcano surroundings at distances ranging from 4.7 to 14 km from the volcano summit, have temperatures between 7.9 and 48°C and a calcium-sulfate to sodium-bicarbonate composition. The gas phase associated with these distal emissions showed relatively high H_2S concentrations and absence of HCl, HF and SO_2 due to (i) prolonged interaction of the magmatic fluids with hosting rocks and (ii) mixing with surficial aquifers. Chemical and isotopic compositions of gases are comparable with the active volcanoes Lascar and Irruputuncu, although Guallatiri gases are slightly enriched in H_2S and CH_4.

Airborne measurements of volcanic gas composition during eruption stage at Kuchinoerabujima volcano, Japan

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Airborne measurements of volcanic gas composition using an unmanned aerial vehicle (UAV) and Cessna were conducted at Kuchinoerabujima volcano, Japan from 2014 to 2016. As eruptions occurred in Aug. 2014, May 2015, and Jun. 2015 at the volcano, the access to the summit crater was limited because of the risk of sudden eruption such that airborne measurements were the only viable method to measure the volcanic gas composition. Multi- GAS and alkali-filter pack measurements were made on the leeward side of the crater and around the crater, using the Cessna and UAV, respectively. The observations using the UAV could measure the dense plume and quantify the gas species of H_2O, CO_2, SO_2, H_2S, H_2, HCl, and HF whilst the observations using the Cessna could measure only the diluted plume and quantify the gas species of CO_2, SO_2, H_2S, and H_2. The seven airborne observations enabled us to monitor variations in the volcanic gas composition. From 2014 to 2016, the SO_2/H_2S ratio decreased from 10 to 2.1. The H_2O/SO_2 ratio, H_2/SO_2 ratio, and Apparent Equilibrium Temperatures (AET) estimated using the volcanic gas composition increased after the 2014 eruption. The decrease in the SO_2/H_2S ratio might be attributed to changes in the condition of degassing magma. The airborne methods presented here highlight the utility of using the Cessna and UAV to safely conduct volcanic gas measurements during periods of volcanic unrest when traditional methods are not possible yet monitoring data are crucial for hazard mitigation.

Monitoring of regional radon concentration and gas component for detection of high potential spots of geothermal resource

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Indonesia has the largest geothermal potential and plans to greatly increase geothermal power output. The Ministry of Energy and Mineral Resources in Indonesia has targeted to raise geothermal capacity to 5,000 MW by 2025. However, high introduction cost for geothermal power generation, the cost for exploration to identify the geothermal reservoir in particular, will hinder it. Our research project from 2015 aims to develop advanced exploration techniques for geothermal resource to enhance the geothermal power output. As one of the techniques, radon measurement in soil gas has been implemented in the Wayang Windu Geothermal Field (WWGF). WWGF is a large steam production field to generate electricity more than 227 MW in West Java, Indonesia. More than 20 measurement wells with around 5 m depth were dug in WWGF to identify features of radon concentrations using an equipment DURRIDGE RAD7, an electronic radon detector capable of real-time monitoring. From the results of periodical measurements over one year, two temporal patterns of the radon concentration with the elapsed time were clarified, stability and decreasing patterns. Decreasing patterns were common in WWGF except the wells located near the faults or permeable fractures. Therefore, patterns may originate from difference in the movement of soil gas. To verify this hypothesis, gas component analysis was performed using the gas chromatography. One noteworthy result is that a high radon concentration and volcanic gas component, relatively high N_2/Ar ration and H_2S, were measured at a zone with no geothermal manifestation. This zone can be expected as a high potential spot of geothermal resource. Consequently, radon measurement is effective to enable highly accurate specification of the most suitable site of production wells that are located in permeable fractures, which can reduce the initial cost of geothermal power generation.

Evaluating effect of temperature on short- and long-term radon signal at Stromboli volcano

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In-soil radon concentration was affected by atmospheric and environmental parameters, such as temperature, pressure and humidity that may act in different ways on its release from soil(s). Hence, the continuous and near-real time acquisition of radon data because forecasting of earthquakes and volcanic eruption must be adequately supported by meteorological information. At Stromboli volcano, several years of continuous measurements at two automated stations have outlined the effect of temperature on modulated radon signal at (i) seasonal and (ii) daily scale. The yearly-long radon trend was inversely correlated with air and soil temperature, where the fall-winter period showed up to 500% increase on average than the typical values measured during the hot season (for ca. 500 Bq/m^3 on July to about 2500 Bq/m^3 on December). On a short-time scale the daily cycle of soil temperature seems produce the same effect than the longer one; but with different magnitude. In fact, on average, lacking in variation of other factors, daily temperature trend cause variations below the 10% on the 24h radon measures. This novelty allow us to take into account the contribution of this key atmospheric factor on the soil radon variations and, by using a statistical and a spectral approach, remove the temperature effect on radon signal.

S01.33 Poster

The association between volcanic fluid variations and seismic events in the Tatun Volcano Group, northern Taiwan

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Taiwan is located at the western edge of the circum-Pacific volcanic belt. Fumarolic activity is still common in the Tatun Volcano Group (TVG), where is one of the major geothermal areas in northern part of Taiwan. Fumarolic gas and water samples are collected to analyze their chemical compositions and isotopic ratios. The gas composition shows a similar result as those of low-temperature fumaroles in other parts of the world. H_2O is the major species of these gas samples, and CO_2 is the dominant component after de-watering. The high $^3He/^4He$ ratios indicate a mantle-derived degassing source in origin. The carbon isotopic values of CO_2 also exhibit a magmatic source. The results of long-term observation in this area show that there is no significant change in gas composition. However, since 2005 to 2007, SO_2/H_2S ratios from Da-you-keng varied from 0 to 3. Meanwhile, HCl concentrations also increased dramatically. A large gravity variation and volcanic earthquake swarms took place subsequently. Same process happened again in 2010. In addition, we observed another phenomenon that only HCl concentration increasing rapidly after a big tectonic earthquake in 2014. Integrating our observations with seismic and gravity data, we can associate fluid variations with two mechanisms. Firstly, the variations of fluid concentration, seismic events and gravity fluctuations occurred in a time series. We infer that magma chamber disturbance and/or deep fluid transportation might be the major cause. The other case, the variations are reckoned as the consequence of shallow hydrothermal reservoir disturbed by earthquakes, and the responding time is short and rapid.

Short timescale degassing dynamics in a very young plume revealed by proximal Unmanned Aerial System (UAS) measurements at Volcan Villarrica, Chile

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Volcanic gas emissions offer valuable insights into the dynamics of magma ascent and outgassing, and contribute an important source of volatiles to the Earth's atmosphere on geological timescales. Measurements of gas composition and flux are therefore critical to both volcano monitoring and to determining the volcanic contribution to global geochemical cycles. However, significant gaps remain in our global inventory of volcanic emissions, (particularly for CO_2 and H_2O, which require proximal sampling of a concentrated plume) for those volcanoes where the near-vent region is hazardous or inaccessible. Here, we demonstrate that Unmanned Aerial Systems (UAS) provide a robust and effective solution to proximal sampling of dense plumes in extreme volcanic environments. We present gas compositional data acquired using multirotor UAS, flown in both mapping and static hover configurations, from the summit of Volcan Villarrica, Chile. SO_2 concentrations measured in the young proximal plume during static hover span up to two orders of magnitude (≤120 ppm), and exhibit periodic variations that are well-correlated with other species. By combining molar gas ratios (CO_2/SO_2 = 1.48–1.68, H_2O/SO_2 = 67–75 and H_2O/CO_2 = 45–51) with the SO_2 flux (142 tonnes/day) from UV camera images, we derive CO_2 and H_2O fluxes of ~150 tonnes/day and ~2850 tonnes/day, respectively, consistent with the overall carbon-poor nature of the Southern Volcanic Zone. We observe good agreement between time- averaged molar gas ratios obtained from simultaneous UAS- and ground-based multiGAS acquisitions. Nevertheless, considerable plume dilution and homogenisation occurs over length-scales of <100 m, causing lack of clear short timescale structure in the ground-based gas timeseries. In contrast, the UAS-based measurements made in the young, undiluted plume show that active degassing through discrete, audible gas exhalations provides an important contribution to outgassing at Villarrica that modulates gas flux over timescales of tens of seconds to minutes.

Shifts in SO_2 degassing activity along the Stromboli volcano crater terrace imaged using UV cameras

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We report on high frequency (~0.5 Hz) automatic measurements of the SO_2 flux at Stromboli, obtained by a network of two permanent UV cameras. We use the high spatial resolution of the cameras to resolve the SO_2 emissions from the different active craters (NEC, SW and CC). We examine the period May 2017-present that is characterized by 8 major explosions, a short-lived lava overflown, and persistent Strombolian activity of variable intensity and frequency.

Our UV cameras, both located at ~500 m distance from the craters, allow imaging the volcanic gas plume from distinct viewing directions, thus permitting to spatially resolve degassing activity and explosions from the different active craters. Images are acquired, calibrated and processed automatically by an acquisition/processing module to obtain SO_2 flux time-series.

During the examined period, we identify several shifts in degassing activity between the craters, which is evidence of a change in intensity and direction of the gas flux streamlines. These shifts match well changes in infrasound location, VLP seismicity and explosive.

Interpretation of camera-based SO_2 flux variations, in tandem with seismic and infrasonic signals, enables to identify which portion (north or south) of the feeding conduits is more fluidized by gas. We demonstrate that robust SO_2 flux time-series can be obtained from automatic processing of UV camera data, making this technique an important tool for volcanic monitoring. Our results, as long-term SO_2temporal fluctuations, offer novel insights into the degassing dynamics within the shallow conduit systems of Stromboli volcano.

S01.33 Poster

Simulating the 18 March 2012 Mt Etna's eruptive plume Using the CHIMERE chemistry-transport model with an antidissipative scheme for vertical transport

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On 18 March 2012, a violent and short time paroxysmal eruption occurred at Mount Etna. Over the event , a large amount of SO_2 and volcanic ash was released into the atmosphere almost up to the tropopause. The highest part of the sin-eruptive SO_2 plume ejected at an altitude ~11.000 m. asl travelled towards the Middle-East extremely quickly, due to the strong westerly winds at this altitude, while post-eruptive fluxes had different trajectories depending on the wind fields in the lower troposphere.

A regional simulation of this event was performed using the CHIMERE chemistry-transport model. Modeling of volcanic products dispersion has two main critical aspects: knowing the source of gas and aerosols (timing, magnitude and injection height) and representing their long-range transport. For the source, we used the SO_2 emission fluxes observed by the ground-scanning spectrometer FLAME network. For the long-range transport, discrepancies between model and measurements are linked to excessive horizontal and vertical diffusion. In order to attempt minimisation of the numerical vertical diffusion, two simulations of the same event were performed: one with the classical Van Leer (1978) transport scheme and a further one with the antidissipative transport scheme of Després-Lagoutière (1999). This latter approach is designed to preserve the shape and focus of sharp peaks. An example of the interest of this new scheme is presented, basing on an idealized test case framework. The Etna eruption case-study simulation is presented and compared with satellite data to quantify the benefit obtained with the Després-Lagoutière, 1999 scheme.

S01.33 Poster

Smartphone sensor based measurements of volcanic gas emissions

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Imaging and spectral measurements of volcanic sulphur dioxide gas fluxes have been increasingly applied in volcanology over the last decades, leading to important scientific breakthroughs and improvements in volcano monitoring capacity. However, hardware costs, particularly for the imaging approaches are relatively high, based on off the shelf market available products. Here we report on highly novel low cost technology based on Raspberry Pi computers, and peripheral (essentially smartphone) cameras, which we have modified to develop very low cost UV spectrometer and imaging units. Using 3D printing to construct entire optical systems, we have therefore developed UV cameras and spectrometers, suitable for volcanic SO_2 monitoring applications. Here we report on the hardware development of these units, in addition to field validation of their performance on volcanoes, including comparative tests, with very favourable outcomes, against the currently applied technology. These devices have now been deployed on volcanoes in some ten countries and we are enthusiastic about prospects of this dissemination increasing. Given the low costs involved, these units have the potential to significatnly increase the spread of UV camera applications on volcanoes.

S01.33 Poster

Anomalous diffuse H_2 degassing prior to the recent magmatic intrusion at Cumbre Vieja volcano, La Palma, Canary Islands

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Hydrogen (H_2) is one of the most abundant trace species in volcano-hydrothermal systems and is a key participant in many redox reactions occurring in the hydrothermal reservoir gas. H_2 generated within the crust moves rapidly and escapes to the atmosphere, constituting an excellent geochemical indicator of magmatic activity. Cumbre Vieja volcano is the most active basaltic volcano in the Canaries, but doesn't show any visible gas emission, which obligates and focus upon a geochemical volcano monitoring program using soil degassing surveys. On October 7th (2017) a remarkable seismic swarm interrupted a seismic silence of 46 years in Cumbre Vieja volcano: more than 75 earthquakes were located beneath Cumbre Vieja. On October 13rd a second seismic swarm, was registered with more than 47 earthquakes. Here we show the results of soil H_2 emission surveys, carried out regularly since 2001. Soil gas samples were collected in 600 sampling sites at about 40 cm depth using a metallic probe and 60 cc hypodermic syringes, and stored in 10 cc glass vials. H_2 content was analysed later by a VARIAN CP4900 micro-GC. A simple diffusive emission mechanism was applied to compute the emission rate of H_2 at each survey. H_2 emission values were used to construct spatial distribution maps, allowing the estimation of the emission rate from the volcano. In the period 2001-2003, the average H2 emission rate was ~2.5 kg·d^{-1}. It increased significantly during the 2013-2017 period (~16.6 kg·d^{-1}), reaching the maximum value of the series (36 kg·d^{-1}) in June 2017; 4 months before the seismic swarms. H_2 emission surveys have demonstrated to be sensitive and excellent precursors of magmatic processes occurring at depth in Cumbre Vieja. Periodic H_2 emission surveys provide valuable information to improve and optimize the detection of early warning signals of future volcanic unrest at Cumbre Vieja volcano.

S01.33 Poster

Observed anomalous diffuse CO_2, He and H_2 emission rates from the summit crater of Teide volcano, Tenerife, Canary Islands

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The most obvious active surface geothermal features on Tenerife occur at the summit cone of Teide volcano. Here, a weak fumarolic system, steamy ground and high rates of diffuse CO_2 degassing are observed. Monitoring diffuse degassing is becoming an important geochemical tool for volcanic surveillance. Most of the diffuse degassing studies on volcanic-hydrothermal systems are primarily focused on CO_2. However, few studies of surface He and H_2 efflux measurements on volcanoes have been performed in spite of their geochemical relevance. Surface CO_2, He and H_2 efflux measurements have been performed at the summit crater of Teide volcano since 1999 (CO_2), and 2009 (He and H_2) respectively. This enables the estimation of diffuse CO_2, He and H2 emission rates and allows us to evaluate their temporal variations with the seismic-volcanic activity in and around Tenerife. The observed average value of diffuse CO_2 emission rate was 17.1 t d^{-1} for the period August 1999 to October 2016, and the observed average values of diffuse He and H_2 emission rates were 0.1 and 2.9 kg d^{-1} respectively during the period July 2009 to November 2016. After these periods, an increase in diffuse CO_2, He and H_2 emission rates was observed, reaching peak values of 176.1 t d^{-1} of CO_2 on February 7, 2017, 1.4 kg d^{-1} of He on January 4, 2017, and 35.6 kg d^{-1} of H_2 on May 22, 2017. After recording these peak values of diffuse CO_2, He and H_2 emission rates, about 15 seismic swarms were registered on Tenerife Island. These observed anomalous diffuse CO_2, He and H_2 emission rates from the summit crater of Teide seem linked to changes in the seismic activity of Tenerife; therefore, these geochemical observations are clear evidence of changing processes operating deep in the hydrothermal-magmatic system of Tenerife.

Nine years of monitoring diffuse CO_2 degassing from Taal volcanic crater lake, Philippines

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Taal volcano, in southwest Luzon Island in the Philippines Archipelago, is one of the most active volcanoes in the Philippines and has produced some of its most powerful historical eruptions. The volcano consists of a 15-22 km prehistoric caldera, occupied by Lake Taal, and the active vent complex of Volcano Island and the Crater Lake (TCL) which is 1.9 km in diameter. Several million people live within a 20 km radius of Taal's caldera rim, making the volcano a big threat to the Philippine population. Between 2008 and 2014, ITER/INVOLCAN has collaborated with PHIVOLCS and the University of the Philippines to perform diffuse CO_2 efflux surveys at the surface of TCL. In total, 17 surveys have been undertaken at TCL since 2008. The last three surveys were performed in March, May and November 2017. The CO_2 measurements were carried out following the accumulation chamber method by means of a portable soil CO_2 efflux instrument. In January 2016, an automatic geochemical station was installed to monitor diffuse CO_2 emission in continuous mode at the northpart of the main crater rim. On 14 March, 2017 the station measured a sharp increase in CO_2 emissions from ~0.1 up to 1.1 kg m^{-2} d^{-1} in 9 hours. Since that date, the average emission value has increased from 144 to 300 $g{\cdot}m^{-2}{\cdot}d^{-1}$. The CO_2 emission survey carried out on 16 March at the surface of TCL gave a value of 1,763 t d^{-1}, 2.8 times higher than the average daily value measured in the period 2012-2017. These results reveal significant variations from 2008 to 2017. Subsurface magma movement might be the cause for the observed changes in the total output of diffuse CO_2 emission at TCL.

Hazard associated with the release of volcanic gases in the village of Vulcano Porto and at Levante Beach (Vulcano Island, Italy)

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Since its last eruption in 1888-1890, La Fossa crater at Vulcano is characterized by intense fumarolic activity. Another fumarolic field is located at Levante Beach. Episodic "crises" occurred at La Fossa with increase of temperature, gas output and concentration of magmatic components in crater fumaroles. During the 1988-1993 crisis, accumulation of CO_2 in morphological depression provoked the death of two children at Vulcano Porto. Since 1989 systematic soil CO_2 flux investigations were carried out at the base of the cone, including Vulcano Porto area to monitor the gas output. The outdoor and indoor air concentrations of CO_2 and H_2 S were also investigated in 2007. Hazardous CO_2 concentrations were found in the basements of many houses, ground floor and depressed areas of Vulcano Porto. Also Levante Beach area is affected by an intense H_2S and CO_2 degassing. In April 2015, a child lost his senses while playing at Levante Beach; he was rescued to the hospital and doctors attributed his malaise to a high CO_2 air concentration. The Vulcano Medical Guard confirms the relative frequency of similar episodes. In 2015 and 2016 summers we performed geochemical surveys at Levante Beach (onshore and offshore) to assess the CO_2 and H_2S release to the atmosphere. The [CO_2] was frequently higher than in unpolluted air. [H_2S] displayed high values (max 43 ppm), frequently exceeding TWA (10ppm) and STEL (15ppm) thresholds. Offshore, gas concentration in atmosphere over the submarine fumarole vents displayed extremely high H_2S (max 1000 ppm) and CO_2 (8.6 vol%) values. Results indicate the occurrence of high and dangerous air gas concentrations, particularly of H_2S, near the onshore and offshore fumaroles and at the mud pool and confirm the persistence of a serious gas hazard for people in this highly frequented touristic site, even in no-crisis periods.

Comparison of Short and Long-term Sulfur Dioxide Gas Emissions and Seismicity from Active Volcanoes in Guatemala

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Volcanic activity in Guatemala has been intensified in the last six years, with some of the largest volcanic eruptions in the last few decades occurring within its most active volcanoes (e.g., Fuego 2012, 2015 and 2016; Santiaguito 2014; Pacaya 2014). In terms of the eruptive activity Pacaya is characterized mostly by Strombolian eruptions, while Fuego is characterized by Strombolian and Vulcanian activity, and Santiaguito by Pelean and Vulcanian eruptions, which produce ash, block lava flows, pyroclastic flows, and lahars. Four field campaigns (2014-17) at those volcanoes were conducted to obtain sulfur dioxide (SO_2) gas emission data, using a mini-DOAS (2013-17), a FLYSPEC (2015-17), and a UV camera (2016-17). These ground-based instruments take advantage of SO_2's selective absorption of UV radiation, to produce SO_2 column amounts that are converted to emission rates. Moreover, seismic data were collected and provided by the local monitoring institution, INSIVUMEH (Instituto Nacional de Sismologia, Vulcanologia, Meteorologia e Hidrologia), and other collaborators. Throughout this research, data from ground-based gas monitoring techniques and seismic stations were analyzed with the purpose of making interpretations in order to understand thoroughly the volcanic phenomena, eruptive activity changes and shallow conduit processes occurring within the volcanic systems. Preliminary results from mini-DOAS and FLYSPEC instruments indicate that the highest SO_2 emitter was Santiaguito with ~1190 t/d in 2015, while Fuego produced ~790 t/d in 2015 and Pacaya produced ~740 t/d in 2014. The gas data has been analyzed also to study the short-term changes in relation to RSAM data from the few seismic stations around the active volcanoes.

S01.33 Talk

Lago Albano, an anti-Nyos-type lake: the past as key for the future

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On 21 August 1986 almost 2,000 people were asphyxiated by a CO_2 cloud violently released by Lake Nyos, Cameroon. Post-1986 monitoring of Lake Nyos revealed that CO_2 steadily accumulates in bottom waters through regional magmatic degassing. The 1986 lake roll- over event triggered scientific research on volcanic lakes, creating a “Nyos bias”. In this study, a thorough review of the historical literature of the past 2500 years discloses that there is no clear evidence of Nyos-type bursts in Lago Albano’s past, contrary to previous ideas. In 1989 Lago Albano was affected by a large CO_2 pulse concomitant with a seismic swarm below Albani Hills volcano. Tracing back in historical literature, at least five similar anomalous degassing episodes occurred in relation with seismicity between 1829 and 1927. Partially T- and density-driven roll-over of the top-9 m of Lago Albano releases accumulated CO_2 each winter. This degassing dynamics avoids long-term CO_2 accumulation in bottom waters, as is the case at permanently stratified lakes in the tropics (e.g. Lake Nyos).

We conclude that Lago Albano is an *anti-Nyos-type* lake: sudden recharge and steady release of CO_2 (Albano) vs. steady recharge and sudden release of CO_2 (Nyos). Despite past evidence of hazardous events, (1) the intensive well pumping from the Albano aquifer might lower lake level, and hence decrease the CO_2 saturation pressure threshold, and (2) the absence of cold winters, hence avoiding yearly lake roll-over favoring CO_2 accumulation at bottom layers, are modern factors that rise the need to revise hazard assessment and future monitoring strategies. It is necessary to know the saturation state of CO_2 in bottom waters and physical lake stability at any time, in order to be prepared for a next anomalous co- seismic CO_2 degassing event near Lago Albano.

Relationship between SO_2 flux and volcanic tremor at Mt. Etna

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Magmatic degassing plays a key role in controlling volcanic eruption styles, and may also generate geophysical signals. A relationship between volcanic seismic tremor amplitude and degassing rate has been observed at active volcanoes during eruptions, but data are often equivocal and a clear physical process, which couples degassing with tremor, is still to be established. Of particular importance is the long-term relationship between quiescent degassing and tremor, and this has not been fully explored. In this study, we inspect the extent to which SO_2 emission rates measured by the FLAME-Etna scanning spectrometers network can track rapid variability in eruptive dynamics at Mt. Etna, via correlation of time- series flux data with seismic tremor records. SO_2 flux and tremor are explored in both quiescent and active-eruptive stage, comparing simultaneously the two data streams at both long- and short-time scale (<< 1 day) for ~2 years. Correlation analysis revealed that at long timescales the two parameters exhibited similar patterns and define two eruptive phases. On shorter timescales outgassing and tremor revealed strong correlations but at specific seismic frequencies depending on eruptive activity. In some cases, a lag time between the two signals was recognised. Our results demonstrate the importance of long- term observations and those short-term changes in the SO_2 outgassing-seismic tremor mirror eruptive transitions. Coherence between the geochemical and geophysical signals reveals a mutual physical mechanism of magma dynamics at both different temporal and eruptive activity scales at an open-vent volcano.

S01.33 Poster

Insight into eruptive activity of Stromboli by SO_2 flux observation

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Stromboli is one of the most active volcanoes in the world and well known for its fascinating persistent explosive eruptive activity, which define the eruptive strombolian style. Occasionally, the strombolian regime is interrupted by powerful strombolian explosions, violent paroxysmal events and silent lava effusion. This switch make Stromboli a unique place where explore how volcanoes works. Eruptive style and timing it is a reflection of magma-degassing processes, volcanic gases are the driving force that trigger eruption and their modulation over time. Here we explore the eruptive behaviour of Stromboli by observing 15 years of SO_2 flux data recorded by the ultraviolet scanning spectrometer FLAME array and looking back to literature data since 1974. Time series analysis at both long and short temporal window reveal that magma supply and dynamics at the shallow of the volcanic edifice tune the eruptive style of Stromboli. Shifts in eruptive regime are stages in which the volcano attempt to regain an equilibrium state of magma-degassing process, which is mirrored in the persistent strombolian eruptive activity.

S01.33 Talk

Small-scale volcanic aerosols variability and processes observed at Mount Etna during the EPL-RADIO measurement campaigns

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The EPL-RADIO (EtnaPlumeLab-Radioactive Aerosols and other source parameters for better atmospheric Dispersion and Impact estimatiOns) project aims at advanced understanding and characterisation of Mount Etna as a source of atmospheric aerosols, targeting emission processes from inner degassing mechanisms to near-source aerosol physico-chemical properties. This project brings a variety of innovative information gathered through the interactions between atmospheric sciences and volcanology specialists.

Measurement campaigns were carried out in the summer 2016 and 2017, observing the volcanic plume at close distance from the summit active craters and distally in the surroundings of the volcano. Information was collected through an integrated multi- parameter approach employing permanent and mobile techniques, in details: (i) distal permanent scanning multi-wavelength polarisation LiDAR with Raman capability, (ii) proximal mobile cascade impactors and (iii) a mobile optical particle counter, (iv) proximal and distal combination of two spectrally-complementary Microtops-II sun-photometers, and (v) complementary gas measurements by UV spectrometers and a Fourier Transform IR spectrometer.

The acquired information allowed the three-dimensional characterisation of the plume of Mount Etna in terms of aerosols properties, precursor gas species and environmental conditions. Small-scale variability of volcanic aerosols properties - within a few km from the volcanic source - together with potential inherent triggering and atmospheric evolution processes is discussed here. Our results allowed getting insights into volcanic plume burden and deepening our understanding of the process behind the production, evolution and small- scale impacts of volcanic aerosol from Mount Etna.

S01.33 Poster

Radon (^{222}Rn): a potential public health problem in quiescent volcanic systems at São Miguel Island, Azores

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Radon-222 is a radioactive rare gas continuously emanating in volcanic environments, even during periods of quiescent activity. When inhaled at medium to high concentrations, for a long period of time, radon can pose a potential problem of public health, leading in extreme cases to the development of lung cancer. In the Azores we investigated the risks from radon emanations to populations living in two active volcanic systems located in São Miguel Island: the caldera of Furnas Volcano and Picos Region Volcanic System, where is located Ponta Delgada, the biggest city of the Azores archipelago. Over the past 5000 years at least 10 eruptions occurred at Furnas Volcano and 30 at Picos Region.

The caldera of the trachytic Furnas Volcano hosts numerous visible hydrothermal manifestations, such as fumarolic fields, thermal and cold CO_2-rich springs, while the Picos Region is a basaltic rift zone with no visible gas manifestations. At both sites radon was surveyed in soils and indoor buildings. Radon activities in soils range from 0 to 387,527 Bq/m^3 at Furnas and between 559 and 70,400 Bq/m^3 at Picos Region. Indoor radon monitoring at Furnas Village reveals annual radon activities between 23 and 6403 Bq/m^3, with maximum peak values of 14,864 Bq/m^3 detected by continuous monitoring at selected sites. In Ponta Delgada City (Picos Region) radon activities varied between 47 and 1583, with maximum peak values reaching 6806 Bq/m^3.

In several buildings of both localities the radon health threshold recommended by the WHO (100 Bq/m^3) is widely exceeded. We thus highlight that potential risks from radon emanations must be taken into account at both sites, despite their different rock composition and activity level.

Ground-based hyperspectral TIR imaging of volcanic plumes: implementing pixel classification strategies for automated monitoring and data mining

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Continuing developments in detector technology have given rise to a new class of hyperspectral imagers combining the advantages of Broadband thermal infrared (TIR) imaging, commonly used to investigate the physical processes taking place during eruptions, and Fourier transform infrared (FTIR) methods, which provide high resolution spectral information in the same wavelength range that can be used to assess the composition of volcanic gases. We present the results of our observations of volcanic activity at Stromboli volcano with such an instrument, the Telops Hyper-Cam LW, which produces data cubes with spectral resolution of up to 0.25 cm^{-1}over the spectral range 875-1315 cm^{-1} (7.7-11.8 µm). We present a series of techniques based on curve-fitting and principle component analysis (PCA) to quickly extract spectral information from large high-resolution datasets and implement fast and reliable pixel classification. Those straightforward statistical methods can be implemented unilaterally to datasets acquired with a variety of observing conditions. They are computationally economical and our results show that they are more accurate when compared to more traditional Brightness Temperature Difference (BTD) indicators, which are commonly used to identify potential pixels of interest in large datasets from multispectral and hyperspectral satellite instruments. We downsample our data to simulate filter-based instruments and find that rapid changes in weather conditions around the vent and in the lower atmosphere - including but not limited to the presence of summit fog - render the establishment of meaningful thresholds for BTD indicators practically impossible. We then present the results of radiative transfer modeling to quantify sulfur dioxide (SO_2) in select images and compare our results to UV camera data obtained simultaneously. Though costly, we believe the added spectral information provided by hyperspectral imagers can be used to improve detection and quantification methods in the TIR, and move toward autonomous algorithms for continuous monitoring.

Past Gas: Using Melt Inclusion Data to Estimate Volatile Emissions for Auckland Volcanic Field Eruption Scenarios

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Volcanic gases can pose a significant hazard to nearby populations and agriculture. However, it is challenging to estimate magmatic volatile fluxes and assess gas hazard in long-dormant volcanic areas where neither directly measured nor analogue eruptive flux data are available. In lieu of suitable data, some researchers have measured volatile concentrations in crystal-hosted melt inclusions (MI) to estimate total gas emissions from past eruptions. Such data may also be used in eruption scenarios to estimate potential gas threats from future eruptions, such as in the dormant, monogenetic, basaltic Auckland Volcanic Field (AVF). The AVF underlies New Zealand's most populated city, Auckland (pop. 1.5M); future vent locations are unknown. The most recent AVF eruption took place ~600 yBP at Rangitoto Volcano, and analogue flux data is scarce. To provide critical scientific advice to emergency managers and lifeline organisations, eight detailed, research-based eruption scenarios are being developed for the AVF as part of the DEtermining VOlcanic Risk in Auckland (DEVORA) research programme. Here, we use MI and bulk rock chemistry to reconstruct magmatic volatile concentrations and emissions from Rangitoto and other past AVF eruptions. We then combine this data with hypothesized eruption scenario attributes (e.g. eruption volumes, duration) to estimate volatile emissions and fluxes for each scenario. Initial findings suggest that Rangitoto may have emitted >10 Megatonnes CO_2, >1.8 Mt S, >0.26 Mt Cl, and >0.37 Mt F, while fluxes for eruption scenarios based on these values are >400 tonnes/day CO_2, >57 t/d S, >8 t/d Cl, and >11 t/d F. Flux determinations may be combined with gas dispersion models to identify affected geographical areas and estimate the potential severity of gas hazard impacts. This, in turn, can improve emergency preparedness and planning for volcanic gas hazards in long- dormant volcanic areas.

Continuous gaschromatography highlights processes governing gas release from the underwater fumaroles of Levante Beach (Vulcano Island, Italy). Indications on severe gas hazard for bathers

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Submarine fumaroles bubbling within Levante bay at Vulcano Island are fed by a shallow hydrothermal aquifer at the boiling point. Apart from stream, the main emitted gas is carbon dioxide (95 to 98 vol.%). Minor components are hydrogen sulfide (1.5 to 2.5 vol.%), nitrogen, methane, oxygen and hydrogen. Helium is generally order of 1 or 2 ppm. Carbon monoxide is present at fractional levels of ppm.

We set up a Chromatographic Monitoring Station (CMS) on the fumarole with the highest flow, in order to evaluate the compositional fluctuations of the fumaroles and to ascertain the very shallow processes modulating gas release from the sea floor.

A microgaschromatograph was placed on the beach about 50 m far from the bubbling emission. A heavy metallic funnel was placed on the seafloor above the fumarole in order to collect the gas. A long silicone tube allowed the pressurized gas to flow to the CMS for the analyses. Gas composition (CO_2, H_2S, CH_4, N_2, O_2, H_2, He) was measured every 9 minutes for 6 days.

Compositional variations (e.g. H_2 between 337 and 372 ppm) showed very evident oscillations not due to changes in atmospheric pressure. A statistical analysis of the gas compositions (Fourier transform) was performed, allowing to evidence major cyclicity at 6, 12, 18 and 24 hours.

Although the short time of experimental acquisition impeded evidencing higher periods, we interpret the tides to be the primal process that modulates the concentrations of the fumarole gases, as tides determine the water thickness above the vents.

CO_2 and H_2S concentrations were also measured in atmosphere above this submarine fumarole, measuring extremely high H_2S (max 1000 ppm) and CO_2 (8.6 vol.%) values. This indicates a severe gas hazard for bathers who often approach the fumaroles for recreation.

S01.33 Poster

Insights into the degassing unrest of a dormant arc volcano using high spatio- temporal geochemical and geophysical observations of the fumarolic activity (La Soufrière of Guadeloupe, Lesser Antilles)

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We report on new discrete and continuous measurements of the chemical composition and mass flux of fumarolic gas emissions from La Soufrière volcano (Guadeloupe) during an ongoing phase of unrest. We show how the results relate to both the underground circulation of fumarolic fluids, as imaged from 3-D electrical resistivity tomography, and geodetic-seismic signals. Monthly discrete surveys performed with a portable gas analyzer (MultiGAS) reveal significant differences in the chemical proportions and fluxes of H_2O, CO_2, H2S, SO_2 and H_2 in gas plumes emanating from the different fumarolic vents on La Soufrière lava dome which, among other factors, depend on the vents location with respect to the underlying circulation of hydrothermal fluids. In particular, fumarolic emissions from the main central vents, more directly connected to boiling hydrothermal water at 80-100 m depth, are more affected by SO_2 scrubbing than peripheral emissions. Gas fluxes demonstrate an increased bulk degassing of the volcano over the past ten years, but also a recent spatial shift in fumarolic degassing intensity from the center of the lava dome towards its SE-NE sector and the Breislack fracture, in agreement with both extensometric and seismic evidence of fault widening in this sector. A permanent MultiGAS network was set up to continuously survey CO_2/H_2S and SO_2/H_2S ratios in plumes from the three main vents. The obtained high-frequency CO_2/H_2S time series reveal significant short-term variations that correlate very well with the onsets of seismic swarms, strongly suggesting the involvement of CO_2-rich gases. Our study thus provides an improved framework to monitor and interpret the evolution of gas emissions from La Soufrière in the future and to better forecast hazards from this dangerous andesitic volcano.

Diffuse soil degassing at Stromboli volcano revealed by continuous monitoring of soil CO_2 flux and ^{222}Rn concentration

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On active and quiescent volcanoes, among the other gases, CO_2 and radon are released both from the plume and/or by diffuse soil emissions. These two gases may be hazardous for human health if released in urban areas. To understand the release processes that determines their hazard it is important to study the gas variations related to the environmental parameters. Here we present a study on the continuous monitoring of soil CO_2 flux and radon concentration, coupled to environmental parameters carried out from 2007 to 2011 at Stromboli. The long-term soil CO_2 flux series shows a slow decreasing trend, not visible in ^{222}Rn activity, suggesting a possible difference in the source depth of the two gases, CO_2 being deeper and likely related to degassing at depth of the magma batch involved in the February–April 2007 effusive eruption. To minimize the effect of the environmental parameters on Rn and CO_2, two different statistical treatments were applied: the Multiple Linear Regression (MLR) and the Principal Component Regression (PCR). These approaches allow to quantify the weight of each environmental factor on the two gas species and show a strong influence of some parameters on the gas transfer processes through soils. Both gases record higher emissions during fall-winter than during spring–summer. Short-time variations on ^{222}Rn activity are primarily modulated by changes in soil humidity (rainfall), and changes in soil CO_2 flux are mainly ascribed to variations in wind speed and direction. The spectral analyses reveal diurnal and semi-diurnal cycles on both gases, outlining that atmospheric variations are capable to modify the gas release from the soil. The implementation of tools capable of removing (or minimizing) the contribution of the atmospheric effects from the acquired time series is a challenge in volcano surveillance.

S01.33 Poster

Estimation of deep-seated CO_2 emitted from Furnas do Enxofre degassing area (Terceira Island, Azores Archipelago)

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Furnas do Enxofre fumarolic field is the only visible degassing area found out at the volcanic Terceira Island (Azores Archipelago, Portugal). Fumaroles exhibit a typical hydrothermal composition with water vapour as the main component (>96 vol.%), followed by CO_2 and H_2S. Three soil CO_2 flux and temperature surveys were undertaken at Furnas do Enxofre area between July 2013 and August 2014, and carbon isotopic composition of CO_2 was measured during the last survey. A total of 916 soil degassing measurements have been performed in an area with approximately 5.5 ha. Soil CO_2 fluxes and soil temperatures ranged, respectively, from 0.15 to 21900 g m^{-2}-d^{-1}, and from 17.3 to 99.8 ºC. Carbon isotopic composition of the CO_2 fluxes collected in 99 sites ranged from -32.54 to -4.40 ‰, highlighting both a biogenic and a hydrothermal/volcanic origin for the CO_2 released in this degassing area. Significantly high CO_2 fluxes (50 to > 100 g m^{-2} d^{-1}) have been measured even in areas with clear biogenic isotopic composition.
Estimation of the amount of hydrothermal CO_2 emitted from this degassing area has not been possible using the commonly used geostatistical tools due to lack of spatial structure of the soil CO_2 flux data sets. Graphical statistical approach has been used to estimate the total CO_2 emission in the area that ranged between 2.67 and 7.60 t/d. A new methodology is here suggested to estimate the hydrothermal CO_2 emitted, based on the measured carbon isotopic composition of the CO_2 flux and the identification of the soil anomalous zones. The above mentioned hydrothermal CO_2 was estimated to be 2.53 t/d and the energy released by the diffuse degassing process in this area should be about 2.38 MW, considering the total amount of condensed water and enthalpy of steam condensation at 100 ºC.

Methane in volcanic gases at Changbaishan Volcano in NE China

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Changbaishan Volcano is located on the boundary between China and North Korea, the 946 CE eruption of which is one of the largest explosive eruptions on earth in the last 2000 years. Hot springs are widely distributed in the volcanic field and cover areas of more than 6000 m^2 in total. We performed gas studies on the three main hot spring areas from 2014 to 2017. The dominate composition of the hot spring gases is CO_2, with compositions of more than 80%. The average compositions of CH_4 in Julong, Jinjiang and Hubin hot springs are 0.21%, 1.84% and 7.40%, respectively. The carbon isotopes (δ13C) of the Julong, Jinjiang and Hubin gases are variable, ranging between -49.7‰ and -34.8‰, between -38.4‰ and -31.6‰ and between -53.6‰ and -49.5‰, respectively. According to these characteristics, we suggest that the carbon isotopes of CO_2 and CH_4 reached re-equilibrium in shallower reservoirs and the CH_4 of Changbaishan Volcano may be derived from the mantle magma.

S01.33 Poster

Use of a drone for measuring gas and aerosol concentrations in quiescent volcanic plumes

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Volcanic plumes are comprised of a complex, evolving mixture of volcanic and atmospheric gases, aerosol particles and ash (1.). Measuring the quantity and ratio of relative components is essential for quantifying likely human, environmental and climatic impacts of the volcanic emissions (2.). Quiescently degassing volcanoes accounted for the majority of global volcanic SO_2 emissions over the last decade (3.). Such persistently high quiescent emissions necessitate close monitoring via ground-based, satellite and aerial measurement techniques.

This project aims to develop a cross-section 'map' of aerosol and gas concentrations in quiescently degassing plumes. This is not possible using ground-based or balloon instrumentation as it requires controlled movement within the plume for in-situ measurements. Conversion of SO_2 gas to sulphate particles and changes in aerosol size distribution with plume age will be investigated. Concentrations of plume components will be examined and combined with wind speed to estimate the flux of volcanic aerosol and gases, key parameters in dispersion modelling.

Here we develop and test an Unmanned Aerial Vehicle (UAV) platform for monitoring inside the plume of quiescently degassing volcanoes. An Alphasense OPC-N2 (Optical Particle Counter) is used for the detection of aerosols in the plume. Alphasense electrochemical SO_2, CO and H_2S gas sensors and a Gascard NG Non-Dispersive Infrared (NDIR) CO_2 sensor will also be used. Initial testing of the UAV platform and instrument packages will occur at geothermal power plants in Iceland. Data from initial testing will be presented along with ground-based data from Masaya Volcano, Nicaragua.

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Dynamics of gas bubbles in crystal-rich magmas: Experimental insights into Strombolian activity

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Prior experimental efforts to understand the dynamics of gas bubbles in magmas have focused on two-phase (liquid-gas) mixtures, in which the stability of a foam in a magma chamber plays a key role in the form of gas venting at the surface. Other studies of gas slugs have focused on the role of coalescence during rise of bubbles with different ascent rates in the conduit. However, magma may be highly crystalline (up to 45 vol. % crystals), which would exert a strong control on rheology and influence bubble coalescence and the style of degassing. We explore the effects of different magmatic crystal contents on open- vent degassing through a series of novel three-phase (liquid-solid-gas) analogue experiments aimed at probing how the dynamics of gas flow through a particle suspension and pack varies with the particle load. Our small-scale experimental setup consists of a long vertical Perspex tube filled with mixtures of glycerol and water of varying viscosity together with cellulose acetate particles to represent crystals. Gas is introduced via a pump at the base of the cylinder and the nature of the flow is investigated for various gas flow rates, particle loading and liquid viscosity. We find that the bubble evolution strongly depends on the particle content: as the particle content increases the bubble regime changes from high frequency of small bubbles to one of periodic gas slugs. Our experiments will allow a better understanding of Strombolian activity involving highly crystalline magmas e.g. Stromboli, Reventador, Erebus, Yasur and Villarica.

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S01.34 - Volcanoes from the space

Volcano monitoring from space using high-cadence Planet cubesats: application to Fuego volcano, Guatemala

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Earth-orbiting satellites can provide unique observations of volcanoes during paroxysmal activity, when ground-based techniques may be too hazardous. However, satellite measurements at high spatial resolution (e.g., Landsat, Sentinel) have low temporal resolution (typically ~1-2 weeks), which limits their use in studies of dynamic phenomena. Here, we assess the potential of a new source of Earth observation data for volcano monitoring: a constellation of over 100 cubesats ('Doves') operated by Planet Labs Inc. The Planet constellation has been deployed since 2014 and provides 4-band (visible to near- infrared) PlanetScope imagery with high spatial resolution (~3 m) at high cadence (~12-72 hours), permitting space-based tracking of volcanic activity with unprecedented detail. In this study we analyze Planet data (e.g., using change detection techniques) for recent paroxysmal eruptions at Fuego volcano, Guatemala. Fuego is frequently active and monitoring the volcano from the ground is challenging due to an inaccessible vent region. Changes in morphology are frequent at Fuego due to its persistent activity, and eruption deposits are often rapidly eroded after emplacement by heavy rains. Fuego has produced several paroxysmal events in 2016-17, providing opportunities to analyze PlanetScope images collected before, during and after these eruptions to characterize any significant changes in vent morphology and map eruption deposits. The 31 January – 1 February 2018 Fuego eruption was particularly well captured in PlanetScope data, and involved a violent strombolian eruption, continuous lava fountains and two lava flows directed SW from the vent. Two pyroclastic density currents (PDCs) also flowed down the east flank, filling two of the seven channels (barrancas) that surround the edifice. We use this paroxysm and other recent events at Fuego to evaluate the utility of PlanetScope data as a tool for volcano monitoring and rapid deposit mapping that could assist volcanic hazard mitigation efforts in Guatemala and elsewhere.

S01.34 Poster

Application of airborne hyperspectral remote sensing for mapping Surface mineral and volcanic products at 2014-2015 Holuhraun lava flow (Iceland) using Sequential Maximum Angle Convex Cone (SMACC) method

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Holuhraun lava flow was the largest effusive eruption in Iceland for 230 years, with an estimated lava bulk volume of ~1.44 km^3 and covering an area of ~84 km^2. The six months long eruption at Holuhraun 2014-2015 generated diverse surface environment. Therefore, the abundant information of airborne hyperspectral imagery above the lava field, calls for the use of time-efficient and accurate methods to unravel them. The hyperspectral data acquisition was acquired five months after the eruption finished, using an airborne FENIX- Hyperspectral sensor that was operated by Natural Environment Research Council Airborne Research Facility (NERC-ARF). The data were atmospheric corrected using the Quick Atmospheric Correction (QUAC) algorithm. Here we use Sequential Maximum Angle Convex Cone (SMACC) method to find spectral endmembers and their abundances throughout the airborne hyperspectral image. In total we acquire six spectral endmembers and abundances (oxidize surface, sulphate mineral, water, basalt, hot material, incandescent lava) that represent pure surface materials in a hyperspectral image. We, thus, analyse the endmembers of the Holuhraun 2014-2015 lava flow characterization and respective abundances. Analysis were qualitatively and quantitatively done using Spectral Angle Mapper (SAM) to assess spectral similarity. The methods offer optimum and fast selection for the volcanic products segregation. However, the ground truth spectra are needed for further analysis.

Keywords: FENIX, Airborne Hyperspectral, SMACC, SAM

S01.34 Poster

Analysis of the surface thermal anomaly of Solfatara volcano by comparison of satellite and ground thermal infrared images

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Solfatara is a volcanic vent inside the Campi Flegrei volcanic area (Pozzuoli - Italy) monitored by INGV surveillance networks systems. In this work we performed a comparison between the surface temperatures of Solfatara area obtained by satellite imagery in the Thermal Infrared (TIR) bandwidth and by infrared thermal scenes of ground cameras network (TIRNet). TIRS from LANDSAT and ASTER provide thermal IR channels to monitor the evolution of the surface temperatures in the Campi Flegrei area. TIRNet has been developed by INGV-Osservatorio Vesuviano as part of the volcanic surveillance networks at Campi Flegrei caldera and it acquires scenes of portion of the Solfatara area characterized by significant thermal anomalies.

First of all, the comparison procedure needs to georeference all the scenes from TIRNet. The results show a good correspondence between the surface temperature values obtained by processing ground and satellite imagery. As the time-series of both TIRNet and satellite data are influenced by seasonal effects, it has been necessary to remove this cyclical component in order to highlight possible spatio-temporal temperature variations due exclusively to endogenous dynamics. The deseasonalizing algorithm which was applied is the STL algorithm (Seasonal Decomposition of Time Series by Loess; Cleveland et al. 1990). It allows to split time-series into three components: seasonality, trend and remainder. The seasonal component was evaluated by processing the continuous TIRNet data and then it was used to correct the satellites discrete data. This procedure allowed to calibrate the surface temperatures of all the satellite imagery dataset and thereby to extend the area of analysis of thermal anomalies to almost all the whole Campi Flegrei caldera. The effectiveness of this methodology gives also the opportunity to remove the seasonality to the satellite scenes acquired before the installation of TIRNet ground network, extending by this way the surface temperatures data time-length.

How well can we measure Etna emission from satellite?

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Sulfur dioxide (SO_2) is an important atmospheric constituent that plays a crucial role in many atmospheric processes. Mt Etna is one of the bigger volcanic sources of SO_2 which can be identified in satellite products during both explosive eruptions and periods of quiescence degassing

The Infrared Atmospheric Sounding Interferometer (IASI) on the METOP satellite can be used to study volcanic emissions of SO_2 using high-spectral resolution measurements from 1000 to 1200 and from 1300 to 1410 cm^{-1} (the 7.3 and 8.7 μm SO_2 bands). The scheme described in Carboni et al. (2012, 2016) utilises these to return both the SO2 amount and altitude data.

We categorize emissions of SO_2 at Etna into two regimes:

1. Quiescent degassing and low-levels of volcanic activity.
2. Volcanic eruptions that inject SO_2 into the troposphere and stratosphere.

For the degassing quiescent periods the IASI retrieval is performed assuming the altitude of Etna's summit craters, rotating each image following the wind direction and averaging them into a monthly mean. These estimates are then compared againstSO_2 SO_2 observed by the ground-based ultraviolet scanning array (FLAME) and the Ozone Monitoring Instrument (OMI) database.

For periods of explosive volcanic activity between 2008 and 2015, the scheme described in Carboni et al. (2012, 2016) has been applied to measure the volcanic SO_2 amount and altitude. Where possible these results have been compared against those from other satellite products (e.g. MODIS, SEVIRI) and against the FLAME network.

Systematic and automatic ground deformation monitoring via space-borne DInSAR techniques

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The large availability of SAR data from several space-borne constellations is contributing to shift the interest of the geohazard community towards the implementation of operational services for the generation of advanced interferometric products (e.g. displacement maps, deformation time series), which can be very useful for risk management and natural hazard monitoring.

In this context, a crucial role is played by the European Copernicus Sentinel-1 (S1) constellation that, with its global acquisition policy, has literally flooded the scientific community with a huge amount of data acquired over large part of the Earth on a regular basis (down to 6-days with both Sentinel-1A and 1B passes). The S1 data are openly and freely accessible, thus fostering their use for the development of automated and systematic tools for Earth surface monitoring, with particular reference to the ground deformation applications.

In this work we present the activities carried out for the development of a CNR-IREA automatic InSAR service based on S1 data. The service consists on the systematic processing of S1 data on selected areas of interest, to generate updated surface displacement time series every time a new S1 acquisition is available. The system exploits the Parallel version of the Small BAseline Subset-InSAR algorithm (P-SBAS) and is automatically triggered by the new acquisition availability. As additional feature, the system is able to retrieve the on-line real-time earthquake information to automatically generate an InSAR co-seismic displacement map once a major earthquake occurs.

The implemented service is already running to monitor the Italian Campi Flegrei and Etna volcanoes for Civil Protection purposes. Moreover, it has also been integrated within the ESA GEP platform and is available for the European Plate Observing System (EPOS) Research Infrastructure community. The proposed system can be extended to include additional processing tools, as those able to model the causative sources of the observed displacements.

MIROVA: Middle Infrared Observation of Volcanic Activity

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MIROVA (www.mirovaweb.it) is an automatic volcanic hot-spot detection system based on the analysis of infrared data acquired by the MODIS sensors. The system is operative in near real time over more than 200 volcanoes, and enable to detect, locate and measure the heat radiated by several types of volcanic source. In this contribution, we briefly describe the system and we give and overview of the use of MIROVA thermal data to monitor and study the emplacement of basaltic and silicic lava flows, the extrusion of lava domes as well as the formation and evolution of lava lakes and high-temperature fumaroles fields. We also show how the data collected at open vent volcano allow to detect changes in the thermal emission that may anticipate, accompany or follow major eruptions. Finally, we present the preliminary results of a combined analysis of space-based thermal and gas emission that improve our capability to decrypt the eruptive behaviors, and to evaluate the associated, evolving volcanic hazards.

S01.34 Talk

A multi-sensor integrated approach for the proximal and distal monitoring of the volcanic eruptions

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Volcanic eruptions are one of the most important sources of natural pollution. They affect environment, climate, public health and represent a severe threat for aviation safety.

The volcanic activity is monitored through satellite and ground-based instruments operating at different spectral ranges, with different spatial resolutions and sensitivities.

In this work we exploit the complementarity between geostationary, polar satellite sensors and ground-based measurements, to improve the proximal and distal monitoring of volcanic eruptions. The method proposed is based on the measurements collected from SEVIRI, an instrument on board the MSG geostationary satellite platform. The typical space–time scale of the geostationary observations in the thermal infrared, are integrated by considering different wider spectral range from visible to microwave. The procedure is able to improve the estimations of the volcanic eruption source parameters (e.g. eruption start and duration, volcanic column top height, mass eruption rate, time averaged discharge rate, total erupted mass, total grain-size distribution) and atmospheric parameters (ash cloud mass loading, mean effective radius, aerosol optical depth and SO_2 mass loading).

The integrated retrieved parameters can be used to feed volcanic ash transport models for reconstructing tephra loading and reducing the uncertainties associated with the far- travelling airborne ash mass simulations.

Development of an integrated and automated tool for InSAR time series processing and near real time displacements monitoring

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Funded by the Belgian Science Policy (BELSPO) and the Luxembourg National Research Fund (FNR), the RESIST project contributes to understanding the source mechanisms that drive volcanic eruptions and landslides in the area extending from the North of Lake Tanganyika to the North of the Virunga Volcanic Province, in Central Africa.
RESIST relies on ground-based instrument networks, field surveys and modern Earth observation techniques.
In this frame, we have developed and adapted our own SAR interferometry software to build a fully automated tool allowing to ingest and combine any SAR sensor acquisition in order to monitor local displacements through multidimensional small baseline subset (MSBAS) technique.
The CSL InSAR Suite (CIS) processor is being extensively and successfully used to study and monitor the ground displacements associated to the Nyiragongo-Nyalumagira highly active volcanoes from multi-sensors InSAR time series. The obtained results are showing a much higher time resolution than those classically obtained with SBAS.
CSL allows handling most of the currently available sensors including Sentinel1. It includes 2 home made phase unwrapping processor in addition to snaphu and allows performing Split Band interferometry.
To reduce processing time, the reading and processing of Sentinel-1 data can be limited to a burst selection encompassing the area of interest, even across swaths. Highly precise orbitographic computation allows performing Sentinel1 data coregistration without requesting Extended Spectral Diversity processing.
Each InSAR processing tools was fine-tuned allowing full automation through scripts to process all modalities (ascending, descending, CSK, K5, TSX, TDX, S1, EnviSAT, RADARSAT, …) from reading differential phase layer generation in geo-projected coordinate system. New modalities may be added as they come to extend time series.
Differential phase layers are then sent to the MSBAS processor to generate or update displacement measurements, allowing to perform near real time monitoring.
Examples on the Nyiragongo volcano (DRC) are shown.

S01.34 Poster

Radar backscatter analysis methods applied to the 2011-2013 Kīlauea lava flows

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Space-based Synthetic Aperture Radar (SAR) amplitudes can be used to detect changes to the Earth's surface caused by volcanic activity. Radar amplitude is primarily controlled by surface roughness, angle of slope with respect to the satellite and the ground's dielectric properties. The emplacement and development of lava flows alters these parameters, making it possible to detect and analyse changes using time series of SAR amplitude images. This provides complementary information to interferometric phase, used to measure deformation and phase coherence, which is also related to the rate of change in the Earth's surface scattering properties.

We explore the potential of intensity-based methods using COSMO-SkyMed data from the 2011-2013 Kīlauea, Hawai'i lava flows to investigate lava flow dynamics, through detecting variations in effusion rate, channel complexity and flow propagation. The Hawai'i volcanoes are extensively monitored and have a high density of past in situ and remote geophysical measurements. Together with semi-continuous lava emplacement, this makes Kīlauea an ideal area to ground-truth the use of SAR intensity-based methods with respect to lava flow development.

We analyse backscatter intensity variations to investigate specific lava flow events that occurred during 2011 to 2013, and compare them to characteristics of Kīlauea's current eruption phase. We selected episodes to include fluctuations in lava lake height, transitions in flow mechanisms and morphology.

Processing SAR imagery includes radiometric calibration to reduce the influence of differences in satellite geometry. We also examine the impact of different speckle reduction methods on volcanic applications. Backscatter changes can be visualised using RGB scaled difference maps or thresholds to define significant levels of change. We explore the application of these approaches to Kīlauea's lava flows and compare our results to other geophysical and field observations. This allows us to link remote sensing observations to lava flow physical and morphological characteristics.

S01.34 Poster

Automatic InSAR processing to monitor volcanic deformations in The Canary Islands

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National Geographic Institute of Spain (IGN) operates a multidisciplinary volcanic monitoring system (VMS) in The Canary Islands which include deformation, seismic, gravimetric, geochemical and geomagnetic techniques. Regarding deformation, GNSS and tiltmeters provide daily and subdaily solutions in certain locations. On the other hand Spaceborne SAR interferometry (InSAR) can monitor deformation process over broader areas, despite its lower temporal frequency, which makes InSAR a good complement to GNSS and tilt measurements.

One important requirement of a volcano monitoring system is the fast data processing and analysis. Sentinel mission allow free and open acquisition of radar images, thanks to Sentinel1 constellation, within 6-12 days and over any place in Europe. Taking this into account, a development of an automatic InSAR processing methodology to reinforce current VMS capabilities is now feasible.

A first stage of this methodology have been developed using mainly SNAP toolboxes and is currently been applied in The Canary Islands. This workflow makes possible the generation of displacement maps for each island only a few hours after the image capture, and without the intervention of an operator. The revisit period for each island and acquisition geometry is 6 days for Tenerife, Gran Canaria, La Palma, La Gomera and El Hierro islands, and 12 days for Fuerteventura and Lanzarote islands (due to Sentinel-1 images availability).

This methodology have been applying during the seismic activity took place in La Palma island on October 2017 and February 2018.

Next steps in the development of the methodology in which we are currently working are the application of different techniques of removing atmospheric signals automatically and the development of an automatic time-series methodology. Moreover, other areas of interest could be easily add to the process allowing the generation of displacement maps all over the country.

Interpreting volcanological processes using NASA space-borne remote sensing imagery

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Volcanic eruptions represent a significant source of atmospheric aerosols and can produce local, regional and global effects. In this work, we exploit the NASA Earth Observing System's Multi-angle Imaging SpectroRadiometer (MISR), MODerate Imaging Spectroradiometer (MODIS) and the Ozone Monitoring Instrument (OMI) data to investigate volcanic emissions generated in Kamchatka, Russia. Kamchatka was selected to develop this technique due to multiple active volcanoes (Shiveluch, Kliuchevskoi, Bezymianny, Tolbachik, Kizimen, Karymsky, Zhupanovsky and Kambalny), displaying both ongoing and intermittent eruptive activity, during the analysis period (2000-2018).

MISR multi-angle imaging was used to derive plume height and dispersion characteristics, and to qualitatively characterize particle microphysical properties of plumes emitted during the analysis period. Additionally, daily observations are incorporated of MODIS thermal anomalies produced by warm, radiating features (e.g. lava flows, lava lakes), and sulfur dioxide (SO_2) concentrations from OMI. The combination of data from MISR, MODIS and OMI provides insight into a variety of processes specific to volcanic activity. Plumes imaged at a spatial resolution of 1.1 km were observed dispersing up to 400 km downwind. MISR particle-type analysis shows evidence of downwind particle evolution in individual plumes including: particle fallout, physical aggregation and chemical evolution (oxidation and/or particle hydration). Additionally, differences in plume particle properties (e.g. type and intensity of light absorption) and overall dispersion characteristics between volcanoes provide clues about the underlying regional geology.

Our eruption dynamics investigation technique can be implemented globally, and is predominately limited by the observation frequency of the MISR instrument (observations every ~2-8 days depending on latitude). Satellite-based techniques, such as those presented here, are particularly valuable in remote locations where extensive monitoring is financially or logistically restricted.

Satellite-based thermal precursors of volcanic eruptions

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A major challenge in natural disaster management revolves around detecting the warning signs that precede volcanic eruptions. Volcanic processes involve the transfer of heat from the Earth interior to the surface, although the thermal footprint preceding eruptions is subtle and its automated detection remains elusive. Here we explore whether the recent explosions and eruptions of Ruapehu (2006 and 2007; New Zealand), Ontake (2007 and 2014; Japan), Redoubt (2009; Alaska), and Puyehue (2011; Chile) volcanoes could have been forecasted through the space-based monitoring of thermal emissions. We address this issue through a new method that captures the diffuse emissions of heat using long-wavelength thermal infrared data from the MODIS instruments onboard the Terra and Aqua satellites (band 31; 10.780 – 11.280 micron). In particular, our method: (a) calculates the thermal emission difference (TED) between the volcanic edifices and the lower altitude surrounding areas; (b) applies a median-of-median algorithm (typically used in seismology) that minimizes the unwanted effects of cloud coverage and geolocation errors; (c) and applies an efficient denoising technique based on wavelet transform filters (previously tested with Montecarlo experiments) that minimizes annual variability and noise. This method allows us to recover long-term (~years) thermal anomalies associated to volcanic phenomena, and reveals that the last 6 eruptions of the target volcanoes were preceded by significant increases of TED. Increases of TED in the years prior to eruptions likely reflect hot gas circulation in the crust and greater diffuse outgassing, since other heat transfer mechanisms are less efficient. The real-time monitoring of diffuse heat emissions from space may therefore help to better forecast eruptions in the future.

S01.34 Talk

Monitoring thermal anomalies in ice covered volcanoes using C-band aircraft ground clearance radar

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Several of Iceland's most active volcanoes have extensive ice cover. As a result many eruptions involve volcano-ice interaction and melting. Moreover, several volcanoes have persistent geothermal activity, that in glacier-covered areas are manifested as depressions in the ice surface, caused by basal melting by the geothermal heat. The term ice cauldron is commonly used for such depressions that range from shallow, crevasse-free depressions to steep-sided, heavily crevassed and deep cauldrons. Variations in geothermal activity can be manifested as varying depth and size of such cauldrons. Since 1999, cauldrons in the surface of the ice-filled caldera of the Katla volcano have been monitored using an aircraft- based system consisting of a C-band ground clearance radar, linked with either KGPS or sub-meter DGPS. The system provides profiles of glacier surfaces with a spatial resolution of 15-20 m and elevation accuracy of 1-3 m. The flight inspection aircraft of Isavia, the civil aviation service of Iceland TF-FMS, is equipped with this system and has for the last 19 years been used to monitor the geothermal areas in Katla, Grímsvötn, Bárdarbunga and Öræfajökull volcanoes, as well as occasionally surveying other glacier-covered regions. This monitoring system has played a key role in many cases of unrest, such as sudden ice cauldron formation and glacier outburst floods from Katla in 2011, the eruptions of Grímsvötn in 1998 and 2004, the caldera subsidence of Bárðarbunga in 2014-15, and in the formation of an ice cauldron in Öræfajökull in late 2017. An early version was used to map ice surface changes associated with the Gjálp eruption in 1996. The surveys from TF-FMS provide quantitative data on cauldron development that can be used used to estimate e.g. rates and volume of caldera subsidence, magnitude of new geothermal activity under ice, and melting during volcanic eruptions.

InSAR characterization of lava flows at Piton de la Fournaise

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At Piton de la Fournaise (La Réunion Island), the monitoring of ground displacements by InSAR is used to quantify evolutions of deep and superficial volcanic systems and to monitor the edifice over space and time. The observed ground displacements are caused by various processes sometimes difficult to discriminate. For example, it has been shown that the Eastern flank of the volcano is affected both by large wavelengths seaward sliding and by localized subsidence related to lava flow compactions and substratum flexure. Our study is a necessary step for a precise and global quantification of the displacements induced by the lava flows in order to separate them from the displacements related to the Eastern flank of the volcano.

First, we have characterized the lava flows emitted from 2010 to 2017, exploiting the InSAR product. Thanks to an acquisition before the lava emplacement and a second one during/after the eruption, the lava pixels have a bad InSAR coherence to compare to the mean coherence of the volcano. We propose to use the coherence to quantify the lava flow area. To achieve this task, we have developed an algorithm based on a statistical analysis of the pixel coherence that allows us to quantify the uncertainties on the lava flow location and area. Then we used those of the post-eruptive interferograms in order to characterize topographic changes related to the lava flow emplacement and then to obtain an estimate of the final lava flow volume and the Up-Down and East-West displacements.

The results that we present are on the July 2015, August 2015 and July 2017 eruptions at Piton de la Fournaise. These examples allow to have a precise quantification of the all displacements linked to the lava flow emplacements and are a first way to remove the lava contributions on the interferograms.

S01.34 Poster

Complex utilization of satellite remote sensing dataset for volcano acitivity monitoring

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Conventional volcanic studies using seismometers, leveling, gravitymeters etc. are still important tools for understanding the volcano activity. At the same time, technical advances of remote sensing allowed to analyze volcano behavior in terms of both spatial coverage and temporal patterns, albeit its distant access. Especially, interpretation of deformation data (e.g. InSAR: Synthetic Aperture Radar Interferometry) and thermal observation (e.g. thermal infrared images) allowed to significantly improve the precursor monitoring of volcanic eruption.
Most usable ones for the research on volcanic eruption precursor are SAR and infrared images. From these two sensors we can produce time-series deformation pattern and surface temperature changes. On the other hand, visible satellite images are limited to monitor volcanoes because light is required for imaging. Therefore, to monitor volcanic activity effectively, we should use various types of remote sensing images.
Even though no active volcano exists on the Korea peninsula, some volcanoes, such as Mt. Baekdu (Changbaishan in China), Sakurajima, Mt. Aso. etc, have possibility to cause damage in South Korea through ash dispersion. Therefore, Korea Meteorological Administration has studied volcano activity using remote sensing techniques such as InSAR, thermal imagery, and visible imagery. In this paper, we introduce KMA's effort and techniques to monitor volcanic activity using remote sensing data.

Multi-sensor remote sensing analysis to monitor active volcanic areas: an application to the 2011-2015 eruptive activity of Mount Etna (Italy)

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In volcanic areas, where it could be difficult to gain access to the most critical zones for carrying out direct surveys, remote sensing proved to have remarkable potentialities to track the evolution of lava flows, as well as to detect slope instability processes induced by volcanic activity. A methodology for observing and quantifying eruptive phenomena was developed by processing, integrating and comparing radar data and optical images acquired from different satellite platforms. The approach also integrates images acquired from in-situ visible and thermal video cameras, processed and orthorectified through a dedicated tool. The proposed methodology was tested by analysing data acquired during the 2011-2015 Etna eruptive activity for mapping the evolution of the lava fields emitted from the New South East Crater. Lava flows evolution maps, derived from the analysis of satellite data, are compared and combined with the maps obtained from the ground based images collected by the permanent ground NEtwork of Thermal and VIsible Sensors located on Mt. Etna (Etna_NETVIS). The combination of different satellite sensors optimizes and enhances the observational capability of standard surveillance activities. The data acquired from ground- based sensor networks allows to downscale the information derived from satellite data and to integrate the satellite datasets in case of incomplete coverage or missing acquisitions. The performed analysis enables to assess the integrated capability of ground-based and satellite sensors to monitor the evolution of fast evolving lava flows propagating along the volcano slopes, and how this activity can contribute to improve hazard assessment evaluations. The developed methodology can be easily applied to quantify and document eruptions from other volcanoes. In particular, first results for Galeras volcano (Colombia) will be showed.

First comparative results from SENTINEL-2 and MODIS-MIROVA volcanic thermal dataseries

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In the satellite thermal remote sensing, the new generation of sensors with high-spatial resolution open the door of a major thermal constraining of volcanic phenomena, with implications for the comprehension of volcanic behaviors and related hazards. Combining the high spatial resolution images with moderate resolution sensors as MODIS, with a high revisit frequency, can greatly increase both monitoring capabilities and volcanic applications. Here we present some preliminary results about the comparison between thermal dataseries derived from SENTINEL-2 (Level 1C) and MODIS images, the latter processed by the MIROVA system, in the 2016-2018 timespan. We applied an integration of the HOTMAP algorithm (1), based on empirical thresholds and ratios between bands 8a-11-12 in the SWIR region, with a 20-meter spatial resolution. The algorithm is applied to different volcanic activities, defining an empirical Thermal Index (TI) as a sum of reflectances, which represents a proxy of the heat source temperature. We compared the thermal trends and the number of pixels alerted from SENTINEL-2 with the MIROVA Volcanic Radiative Power (in MW) datasets. The data presented show interesting comparable trends between the two imagery suites. The Thermal Index turns out to be suitable to track the thermal variations of heat sources, thus providing unexplored insights about volcanic system behaviors and eruptive patterns. Moreover, the use of high-spatial resolution images allows to localize precisely the thermal anomalies and detail morphometric features of heat volcanic sources, such as area and thermal distribution. These promising results indicate how the comparison of MODIS-MIROVA and SENTINEL-2 thermal dataseries constitutes a first step for a future application in multi-sensor hot spot detection system, with increased monitoring capabilities and useful for communities which relate with active volcanoes.

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Developing baseline thresholds for satellite detected infrared emissions at persistently active volcanoes

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Monitoring of volcanoes is routinely undertaken using satellite infrared imaging and done so at a multitude of spatial and temporal scales to reflect the diverse manifestations of volcanic activity. High temporal resolutions allow for near-real time detection, whereas higher spatial resolution provide a more detailed perspective, but on one given sensor there is often a trade-off between the two. Systems that use high temporal sensors to trigger high spatial sensors are available, yet they do not use robust baselines to determine whether the radiances are evidence of a significant event. Persistently active volcanoes such as Kīlauea or Erta ‘Ale can remain active for decades with little to no repose period, and often produce consistent radiances whilst posing no significant hazard or change in eruptive conditions. However, significant radiance escalations from baseline activity could represent changes in eruptive regime and be considered significant events warranting further investigation. This study utilises rank order and maximum likelihood statistics alongside data from the MODVOLC detection algorithm to define a threshold over which activity would be considered statistically significant thus worthy of triggering higher spatial resolution sensors. When the algorithm was run in hindsight using data from Kīlauea and Erta ‘Ale from 2000-2017, events such as the opening of the Halema’uma’u crater at Kīlauea and the 2017 fissure eruption at Erta ‘Ale were captured, which would have allowed for automated and timely triggering of a high spatial resolution sensor. Developing thresholds at these volcanoes have also highlighted heighten activity at the crater prior to flank eruptions, most notably in the case of the 2017 flank eruption of Erta ‘Ale. By developing these statistically robust baselines, these provide an automated and effective way to monitor persistently active volcanoes.

Lava lake level changes measured by times series of SAR amplitude: a proxy for pressure changes in the magmatic system at active volcanoes

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We measure the rise of the crater floor and the lava lake level fluctuations from the module of hundreds of SAR images acquired by RADARSAT, COSMO-SkyMed, SENTIEL-1 and Envisat. The height changes are obtained from the length of the shadow casted by surrounding rims. We set an automatic method for detecting illumination/shadow transitions using a grid-search strategy among an extensive dictionary of synthetics 1-D transects. We discuss the uncertainties and validate the results with high resolution DEMs obtain from UAV photogrammetry and SplitBand Radar Interferometry.

This analysis is applied to the Nyiragongo volcano (DR Congo), which hosts a ~260m wide persistent lava lake nested in a 1.2km wide crater. Recurrent lava overflows inundate the crater, which, after solidification, make the floor to rise up to several dozens of meters per year.

After its drainage in 2002, the crater filled up on ~400m thickness until 2008. Till 2012, the activity remained reduced (level fluctuations of various amplitude and time scales within the pit), then, after a large volume eruption at Nyamulagira volcano (located 13km away), the level progressively lowered, reaching ~70m below the crater floor. It remained at low level until the end of 2015. Early in 2016 a new vent opened within the crater, which intermittently emits important lava flows that blanket the crater. In November 2016, the lake level dropped of a hundred meters in a few hours.

We compare these measures with other parameters (seismicity, degassing, ground deformation and visual observations). We infer that these lava lake level changes can be used as a proxy for the pressure changes in the magmatic system.

The shadow measurement method can be applied to some of the other rare volcanoes hosting a lava lake, such as Kīlauea or Erta Ale.

Multisource inversion of ground deformation sources: the case of Sakurajima volcano, Japan

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Ground deformation in volcanic and geothermal areas often show complex spatial and temporal patterns due to the presence of multiple sources having different geometries and behavior. Typical examples are the presence of multiple magmatic reservoirs or the coexistence of magmatic and hydrothermal reservoirs and possible slip along fault surfaces.

The retrieval of source models in these contexts requires complex modeling tools and/or cumbersome inverse methods to solve simultaneously for the parameters of different sources. An alternative solution can be separating the ground deformation related to the different sources before the inversion of the data. Independent Component Analysis (ICA) has shown to be an excellent mean to perform such a separation. On the other hand the inversion of individual sources, having a simpler spatial and temporal behavior, makes easier the use of advanced inversion techniques as well.

In this work we present some example application of the source separation using ICA, and the subsequent inversion of individual sources using a non-linear inverse method based on a finite-element forward modeling approach.

We applied this novel method to a SBAS DInSAR datasets acquired by ascending and descending orbits on Sakurajima volcano using the ALOS L-Band sensor. The ICA analysis showed the presence of a clear deep source, located in the Kagoshima bay, as well as a minor source located beneath Sakurajima volcano. We determined the parameters of both sources showing the spatial and temporal correlation between them.

Development of the Detection Technique for Ash Deposition Area Using NIR channel

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The deposition of volcanic ash may induce damages in urban area and transportation facilities. The volcanic ash can spread out over hundreds of kilometers in case of large volcanic eruption. In the traditional method, ash diffusion area was estimated by human activities such as direct measurement and hearsay evidence. However, they are inefficient and time-consuming. In order to respond to volcanic hazard, it is necessary to estimate efficiently the deposition area of volcanic ash. The remote sensing technique can provide a system for effectively monitoring the active volcanoes as well as volcanic eruptions. A goal of this study is to compare actual volcanic deposition and satellite images of the volcanic eruption case. We apply the remote sensing approach using satellite imageries, which are taken on the geostationary satellites platform, to detect areas of volcanic ash deposition. We utilized NIR (Near-Infrared) channels 7 and 8 of GOCI (Geostationary Ocean Color Imager) images for Mt. Aso eruption in 16:40 (UTC) on October 7, 2016. To estimate deposited area quantitatively, we applied change detection techniques. Two methods were used to detect areas that had changed. First, Principal Component Analysis and a series of morphological filtering were used. Filtering was applied to divide the geometric area of volcanic ash deposition. Secondary, statistical threshold method and morphological filtering were applied. Lastly, based on the Japan Meteorological Agency (JMA) report, it was compared to the area of volcanic ash deposition observed at the field site. From the results, we could extract volcanic ash deposition area about 380km2. The results of the study showed that the combined statistical threshold method and morphological filtering results were most consistent with the JMA report area at 84%. Our results exhibited that satellite imagery is one of the powerful tools for surface change mapping in case of large volcanic eruption.

S01.34 Poster

Exploring the use of IASI retrievals for monitoring volcanic SO_2 emissions

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Satellite remote sensing is a widely used method for the detection and quantification of sulphur dioxide emissions from volcanic eruptions. Emissions into the troposphere, such as those from smaller explosive eruptions or non-eruptive degassing, are often measured with ultraviolet sensors. However, there are advantages to using infrared instruments, for example, they are able to make measurements at night and during high latitude winters. Previous applications of retrievals developed for the Infrared Atmospheric Sounding Interferometer (IASI) have demonstrated that these can be successfully applied to large eruptions, but there is little literature available on how these can be applied to smaller SO_2 emissions. This study applied a 'fast' linear retrieval across the globe for an eight-year time period. The results were dominated by emissions from large scale eruptions, but elevated signals can also be identified from smaller eruptions and industrial centres, suggesting the technique has promise for detecting lower level emissions. The speed of this technique facilitates its use for near real time monitoring and for identifying interesting signals for further study with a full iterative retrieval. Ecuador and Kamchatka were chosen for further study with the more computationally expensive iterative retrieval, which is able to quantify SO_2 mass loading. At Tungurahua these results were compared against the Ozone Monitoring Instrument (OMI) and ground-based flux measurements. While the magnitudes differed, all three exhibited the same trend, demonstrating that the IASI iterative retrieval is capable of capturing relative changes in activity at Tungurahua. The IASI and OMI trends also agreed well in Kamchatka, where OMI, and other UV sensors, are unable to operate for three to four month each year due to the lack of sunlight in winter months. Therefore, these results suggest that IASI could be used to complement other instruments for evaluating changes in volcanic activity.

MOUNTS: a Sentinel-powered monitoring system for volcano monitoring

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The continuously growing constellation of Sentinel satellites provides a constant stream of freely available imagery, which makes routine volcano monitoring possible. Importantly, the diversity of sensors on-board the spacecrafts provide the potential for a comprehensive monitoring of volcanic hazards. In particular, the synergetic use of radar (Sentinel-1), optical / near-infrared (Sentinel-2), and upcoming ultraviolet (Sentinel-5P) payloads, are particularly promising for surveillance of volcano surface deformation, heat radiation, and aerosol emission at high spatial and temporal resolution. MOUNTS (*Monitoring Unrest from Space*) is a monitoring platform currently in development, which intends to tackle this challenge. The system currently manages automatic download, processing, and web- publishing of Sentinel-1 and Sentinel-2 products at selected active volcanoes. The volcanic activity is easily visualized through the systematic display of images (i.e., radar amplitude, interferogram, coherence, and optical-infrared composition), and time series (i.e., area affected by surface change, surface deformation, and high heat flux). We take as a case example the eruption of Erta Ale (Ethiopia), ongoing since 2017, and show how volcanic unrest is detected on MOUNTS and lava flow emplacement is tracked. Moreover, we show how radar coherence is used to detect changes in the activity of the summit craters, both before and after the opening of the new eruptive vent, and we discuss its implications on the feeding system. Methodology and analysis of the thermal activity is done in synergy with the operating system MIROVA (*Middle InfraRed Observation of Volcanic Activity*), from which MOUNTS is strongly inspired.

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S01.36 - Hazard assessment of pyroclastic density currents and lahars current capabilities and new strategies for comprehensive uncertainty quantification

Assessing the inundation and potential impacts of eruption-derived lahars at Mount Shasta

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Mount Shasta is the largest active volcano in California and hosts five glaciers and large volumes of perennial ice and snow. It has experienced at least 15 Holocene eruptions since the formation of the Shastina cone (between 9,700 and 9,400 years ago). While the volcano is known for producing small seasonal debris flows related to glacial outflow (events in 1930s, 1997, 2014…) to date, there has been no examination of the potential size, flow path and impacts of eruption-derived lahars. With its large volume of snow, firn and glacial ice, Shasta holds an ample reservoir of water for spawning lahars. This study uses geologically-informed locations for future eruption sites and styles and present estimates of snow and ice volumes on Shasta with LAHARZ modelling of lahar inundation limits to produce an eruption-derived lahar hazard assessment for the volcano. In addition, we apply GIS analysis of critical infrastructure and local resources/etc. to determine the most likely impacts of such lahars. Combining these analyses provides useful scenarios for emergency planners and land managers who must prepare for the eventuality of volcanic hazards.

Modeling infrasonic sources related to pyroclastic density currents

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Pyroclastic Density Currents (PDCs) are among the most hazardous products of volcanic activity. These gravity driven flows dominated by the fluid-particles interaction are quite complex to model and understanding the key controls their dynamics remains a major challenge. To date seismic and infrasonic monitoring techniques focuses mainly on detection and location purposes having important implications in the timely assessment of volcanic hazard.

We present a new integrated approach that by mean of computational modeling aim to find theoretical and empirical relation between the geophysical signal record and the dynamical properties of the flow. In particular, for a dilute PDC the upper and turbulent part of the flow is well developed and coupled with the atmosphere and thus is very effective in generating infrasound.

We use the ASHEE model to perform a sensitivity analysis and to describe the dynamic evolution of the gas-particle density current. The relationship with the origin of the acoustic wavefield is explored by varying both numerical and initial conditions in a stratified atmosphere.

Comparing synthetic signal with real infrasound of PDCs activity recorded on the field we find a strong correlation between the frequency content of the infrasonic signal and the dimensions of the density current. Our study may have strong implication in terms of hazard assessment. Infrasonic signals could be then used to remotely estimate physical properties of PDCs dynamics providing also data useful to constrain experiments and numerical modeling.

S01.36 Poster

Title: Modeling of the lahars from the volcanic complex Nevados de Chillán through the software RAMMS

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The volcanic complex Nevados de Chillán is located in the Andes Mountain Range, about 80 km from Chillán city, Chile. The volcanic complex has many historic records of lahars from the last two centuries, and large lahar deposits can be found in its surroundings, thus becoming relevant to estimate the magnitude and reach of newer events. Particularly, this work is about modeling of lahars from channels Estero Renegado and Río Diguillin in the SSW side from the volcanic complex. The methodology consists in lahar models created using RAMMS (Rapid Mass Movement Simulation) software, calibrating the different frictional parameters.

In this study we proposed volumes between 500.000 m^3 and 9.000.000 m^3. The smaller volumes (500.000-1.000.000 m^3) reached distances up to 9.5 km, with average wave height of 0.5 m and average velocity of 5.2 m/s. On the other hand, the bigger volumes (3.000.000-9.000.000 m^3) reached distances up to 32 km, with average wave height of 8.46 m and an average velocity of 9.48 m/s.

In general, the map that was generated in this study is useful as a first approximation of lahar dynamic behavior. For this reason, it assesses the mitigation measures that could be needed. For example, the safe places along the riverbed can be determined by the wave height value, and the travel times and cinematic energy of the flow can be estimated by the velocity values.

S01.36 Poster

Spatial distribution of superficial lahar generation

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Rain-triggered lahars are generated by erosion and landslides. However, its denudational characteristic in proximal facies is still poorly understood because data acquisition and *in- situ* observation are extremely difficult. The objective of this research emphasized the analysis of spatial distribution of superficial lahar generation. Physical simulation using flume and artificial rainfall is recorded by front and side cameras. Eight scenarios are carried on by taking into consideration the origin of materials, presence of volcanic ashes on surface, and rainfall intensities. There is no scaled reproduction to avoid misinterpretation of geometric, cinematic and dynamic behavior of solid fractions of lahars. The results show that the spatial distribution of superficial lahar generation is affected by three level of denudational process (rapid, progressive, and slow). The topographic evolutions consist of erosion, stable and depositional areas. Rapid topographic evolution by a massive landslide dominate the spatial distribution of erosion area. Depositional areas spreads below the erosion areas, while stable areas are very limited. The spatial distribution of superficial lahar generation is also influenced by rainfall pattern, infiltration rate and crusting formation. The findings of this research would be important to strengthen the existed lahar numerical models.

S01.36 Poster

Closing the gap: Cutting edge hazard assessments or operational hazard maps

Eliza Calder

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The IAVCEI Commission on Volcanic Hazard and Risk has been undertaking a review of volcanic hazard maps. The review has exposed the diversity and richness of approaches utilized globally in the development of volcanic hazard maps. However the review has also exposed stark differences in the methods and development of hazard assessments as undertaken in the literature, and those in use and employed in the great majority of operational hazard maps around the world. Simply put, for a few well studied volcanoes elaborate, probabilistic approaches are used which consider several hazards, yet for the majority of volcanoes around the world, this level of complexity in the hazard maps is not provided, and potentially not of interest to local stakeholders. In particular the methods used for flow hazards, because of the complexities involved in modeling flows over topography, are often highly simplified with respect to what is possible through todays modeling approaches. This presentation will discuss the apparent gap between what is possible, and what in practice is done. What are the key issues limiting how hazard assessments for flow phenomena are undertaken and included on hazard maps? To what extent is it desirable to encourage the use of more elaborate methods? To what extent can the academic community help to advance robust and operational hazard maps? And to what extent does the academic community need to listen to what the stakeholders really need? The aim of this presentation is to stimulate discussion on this topic.

S01.36 Talk

Benchmarking and validation of numerical models of Pyroclastic Density Currents

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Numerical simulation represents one of the basic tools used to improve our understanding of the dynamics of pyroclastic density currents (PDCs), and to predict the impact of future pyroclastic eruption scenarios on the natural and anthropic environment. This is required for hazard and risk assessment, and for design of risk mitigation measures. However, the predictive capability of numerical models is currently limited by: 1) incomplete knowledge of the physical processes taking place during eruptions; 2) insufficient numerical model resolution and difficulty of estimating the related numerical error; 3) large epistemic uncertainty associated to initial and boundary conditions. This work is part of a collaborative study focusing on developing a conceptual physical/sedimentological model of PDCs, and a consensual validation and benchmarking procedure to assess the performance of numerical models used to simulate PDCs. The general approach to validation is based on an iterative process of integrating data (from field, monitoring, remote sensing and laboratory), with theoretical and numerical models. In this process, synthetic benchmarks are designed to evaluate, through inter-comparison studies, model-related uncertainties associated to initial and boundary conditions, physical approximations, and numerical discretization and solution algorithms. Complementary to this, experimental benchmark data serve as a quantitative basis to test and assess numerical models.
Preliminary studies compare the performance of various numerical modeling approaches used to simulate the movement of both dilute and concentrated PDCs generated by the break of a dam on a slope. While this represents a simplified prototype of granular and particle-laden pyroclastic currents, this integrated effort is fundamental in order to achieve three overarching goals: 1) developing a general physical/sedimentological model applicable to all types of PDCs; 2) consensually evaluate the accuracy of numerical models in representing PDC-related phenomena, and the uncertainty on the results; and 3) drive future research on PDC dynamics and hazard assessment.

A multidisciplinary study on lahars associated to remobilization of pyroclastic deposits at Vesuvius

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Volcanic mudflows generated by the remobilization of pyroclastic deposits material, commonly known as lahars, pose a high threat to population and infrastructure in the circumvesuvian Plains and in the adjacent Apennine valleys. The deposits most affected by heavy rain mobilization are both fallout and pyroclastic flows, mainly related to recent plinian and sub-plinian eruptions of Vesuvius.

The assessment of the hazard associated with lahar must consider several aspects that include i) the identification of potential areas of origin, ii) heavy or persistent rain events able to generate deposit mobilization, iii) the extension and the characteristics of the potential flow, iv) the ability to modify the flow properties along the path related to water content, erosion and solid load deposition (which can alter the topography), v) the frequency of such events in the past.

We present the results of a multidisciplinary effort to tackle these points for the Vesuvian area. Field studies have shown that areas involved in the deposition of lahar associated with past eruptions are much wider than those directly affected by the deposition of primary products of the eruptions. Field and laboratory investigations allowed, for selected cases, the characterization of the source and the invasion areas, the lithological and sedimentological properties of the mobilized deposits and their interactions with the pre-existing topography.

Particular attention has been posed to the syneruptive lahars of the 472 AD eruption, characterized by the greatest areal distribution in the northern plain and Apennine valleys. Field and laboratory data analysis were used to calibrate and define the source area for an ad hoc numerical model based on the shallow layer approach. The model has been first validated with analytical solutions, then used to perform a sensitivity study and produce maps of the areas of possible invasion of lahar in the circumvesuvian area.

Testing a one-dimensional dilute pyroclastic density model against scaled laboratory experiments

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Laboratory experiments can provide fundamental insights into the dynamics of pyroclastic density currents (PDCs), help to validate numerical models, and demonstrate links between deposits and transport processes. Here we examine dilute PDC dynamics by creating density currents in an 8.5 x 6.1 x 2.6 m tank and by heating and turbulently suspending talc powder (20 um) in air. We scaled the experiments such that the currents were dynamically similar to natural PDCs with respect to Froude number, densimetric and thermal Richardson numbers, and particle Stokes and Settling numbers. Reynolds numbers were less than those of natural PDCs, but large enough such that the currents were fully turbulent. We placed obstacles in the path of some of the flows and illuminated 2- dimensional planes within the flows with laser sheets. We measured average sedimentation rate, distance travelled with time, and current height. We compared our experimental measurements to predictions from a 1-dimensional model of a dilute, compressible density current that entrains air and sediments particles. We found that the numerical model matches experimental results – thereby supporting the use of a 1-dimensional model for estimating PDC travel distance and entrainment rates. Finally, we observed that laboratory density currents can propagate laterally after impact with tall barriers. We found that the lateral propagation speed of density currents (90 degrees from their initial flow direction) matches predictions from our 1-dimensional model. Comparisons between laboratory experiments and our 1-dimensional model allow us to validate our model, estimate entrainment rates, and appreciate that PDCs can propagate laterally against barriers at predictable speeds because similar processes govern forward and lateral dilute PDC propagation.

S01.36 Poster

Hazard Footprint from Partial Exposure of Pyroclastic Density Currents on Mt Ruapehu, New Zealand

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Mt Ruapehu, an andesite-dacite stratovolcano, is one of New Zealand's most active volcanoes, last erupting in 2007. There have been few studies investigating the pyroclastic density current (PDC) hazard for Mt Ruapehu, despite it being a popular tourist attraction. Due to the unpredictability of this hazard, it is crucial to be aware of past events in order to produce an effective plan for future PDCs.

Comprehensive field-mapping over 3 months formed the basis for this study by identifying potential PDCs from partial exposures. A confidence-based pyroclastic identification chart developed by Cowlyn (2016) was used to quantitatively support interpretations based on diagnostic textures of PDCs. Grain size distribution, vesicularity, geochemical, and thin section analyses of samples have been used to correlate deposits and infer the eruption style. The magnitude and volume of flows have been approximated using a DEM and estimated flow paths.

Approximately 35 PDCs have been identified on Mt Ruapehu, adding to the 12 previously characterised by Cowlyn (2016). Most of these flows were formed during sub-plinian or vulcanian eruptions, evidenced by low vesicularity of the clasts. The majority of PDCs are identified with "moderate confidence" based on the pyroclastic identification chart.
Poor preservation in the rock record due to past glaciations, erosion, and poor consolidation has led to significant uncertainty when identifying PDCs, and estimating their frequency and magnitude. This is increased by similarities in textural properties between different volcanic flows. Multiple analytical techniques in the field and laboratory have been used in an attempt to reduce these uncertainties.

This study presents a map of potential previous PDC flow paths and an updated account of PDC occurrence for Mt Ruapehu. Increasing the awareness of past PDCs can help inform hazard management and provides a foundation for subsequent studies to investigate future PDC scenarios on Mt Ruapehu.

Real time numerical simulation of a volcanic mudflow and other sediment movements by cellular automaton at Mt Fuji, Japan

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Mt. Fuji is the largest duplicated volcano on the Japanese archipelago, and has remained quiet for more than 300 years since the eruption of Hoei in 1707 AD.

At the vast mountain foot of Mt. Fuji many people's living and economic activities are carried out, and there are infrastructure/lifelines including important transportation networks that greatly influence the living base and Japan's economic activities.

As sediment movements accompanying volcanic eruption, there are debris flow after ash fall, snow melting type volcanic mud flow and lava flow, etc. There are also sediment movement disasters such as heavy rainfall and slash avalanche.

We will show the methods and the results for real time simulation of these sediment movement phenomena using Cellular Automaton (CA) and Multi Agent System (MAS).

Estimating the hazard from volcanogenic floods and lahars at Öræfajökull volcano, Iceland

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Flooding resulting from rapid melting of ice by magma-ice interaction is a hazard on many volcanoes with ice cover on their upper slopes. These floods are the most common volcanic hazard in Iceland, where half of the active volcanoes are glaciated to considerable degree. The most dangerous ice-covered volcanoes are Katla, Eyjafjallajökull and Öræfajökull as they are located on the south coast, close to inhabited areas. The upper slopes of Öræfajökull, Iceland's highest volcano, are covered by 50–500 m thick ice. Two eruptions have occurred at Öræfajökull since the settlement of Iceland in the 9th century: The major rhyolitic plinian eruption of 1362 that devastated the neighbouring region, and a VEI 4 intermediate composition eruption in 1727. Both caused extensive ice melting and large floods that inundated parts of the inhabited lowlands, an area that is now a very popular tourist destination.
A comprehensive study was carried out to estimate the size, development and severity of floods caused by future eruptions of Öræfajökull. The study involved a systematic estimation of melting potential of eruptions while routing of floods was done using the Samos model, initially developed for snow avalanches. The results indicate that eruptions on the volcano flanks can lead to very swift and destructive floods of 1,000–10,000 m^3/s peak discharge, large eruptions within the ice-filled caldera can cause floods of order 100,000 m^3/s, while pyroclastic flows in plinian eruptions may cause floods that seem to fall mostly within the range 1,000–15,000 m^3/s. Importantly, the time between the onset of eruption until a flood reaches the lowlands can be only 15–25 minutes. These results demonstrate that evacuation will need to happen before the outbreak of eruption, with early warning having to rely on real-time seismic and other precursor monitoring.

Preliminary report on a ground-hugging flow observed during Kusatsu-Shirane 2018 eruption

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We will present a preliminary result of the movie analyses and in-situ survey of ash-cloud-hit ropeways to discuss the motion of a ground-hugging flow generated from ash clouds observed during the 2018 eruption of Kusatsu-Shirane volcano located in central Japan. A small-scale phreatic eruption occurred at Moto-Shirane, which is the southern peak of Kusatsu-Shirane volcano, at about 10 a.m. on 23 January 2018. The volcanic vent was located at a few hundred meters away from a popular ski area, and as a result, many skiers and some ropeways were hit by volcanic ash and ballistics; one person was killed and eleven injured. We carried out the analyses of the movies that had been recorded during the eruption and captured the ground-hugging flow spread along the foot of the volcano. We also conducted in-situ survey of the gondola lifts of the ropeway hit by the ground-hugging flow. The survey clarifies that a significant volume of volcanic ash has adhered to some windows of gondola lifts depending on their orientation. This indicates the ground-hugging flow was wet and confined to topographic depressions. In addition to that, the first distress call reported that some skiers had hit by snow avalanche. These facts imply that the ground- hugging flow is possibly a kind of dilute pyroclastic surges enhanced by re-suspended snow particles deposited on the ski area; i.e., the flow may be a hybrid between a pyroclastic surge and a snow avalanche.

VolcFlow: a promising tool for volcanic hazard and risk assessment

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Pyroclastic currents are some of the most devastating phenomena that may happen during a volcanic eruption. Evaluating the societal impact of pyroclastic currents needs accurate tools to predict their future emplacements: damaged areas, time for evacuation, expected risks related to the type of currents. For some years we have developed a numerical code, VolcFlow, for the simulation of volcanic flows: debris avalanches, lava flows, lahars and associated tsunamis.

A new version of VolcFlow has been developed for pyroclastic currents, coupling two fluids: the concentrated and the dilute parts, together with their interactions. Because of the complexity of pyroclastic currents, our approach is to identify their physics by testing several rheological laws until the field measurements are reproduced.

We will present three well studied pyroclastic currents: Soufriere Hills (Montserrat, 1997), Tungurahua (2006, Ecuador) and Merapi (2010, Indonesia). We show that, for the first time, a numerical model is able to reproduce the deposits characteristics (extensions, thicknesses, velocities) of both the concentrated and the dilute parts. The model is also able to simulate surge-derived concentrated flows that can cause destructions out of the expected damaged area, as observed in Montserrat. A weakness of the model is that some laws are empirical and still not understood. A strength is that the same type of laws reproduces the 3 eruptions studied. Before being used as an operational tool, the model must be tested with other accurate field cases, data accuracy being now the limiting factor. However, VolcFlow already seems to be a promising tool for volcanic hazard and risk assessment.

S01.36 Poster

Assessing high-temperature hazards associated with block-and-ash flows at Mt. Taranaki, New Zealand

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Dome growth and destruction is ubiquitous at many stratovolcanoes around the world and has led to several major historical catastrophes. The main hazard is from hot and high- speed, block-and-ash flows (BAFs), a type of pyroclastic density current formed from exploded or collapsed lava domes descending volcano flanks. The temperatures of BAFs varies, depending on the source conditions, spanning between very hot actively growing domes, to cooled dome margins, or older dome remnants disrupted by new dome growth. Here we used paleomagnetic methods to assess the thermal hazard of BAFs at a typical stratovolcano, by understanding the emplacement temperatures of deposits at varying distances from source. The latest AD1800-1830 dome collapses show emplacement temperatures ranging from ~350°C to over 500°C, in units emplaced within 5 km, indicating a wide thermal gradient existed in this dome during its collapse. Different emplacement temperatures in deposits within separate river catchments, indicates an early collapse of mostly cooler carapace material, followed by a larger-scale collapse of the much hotter dome interior. At ~10-15 km a series of BAF deposits from larger eruptions 200-1000 yrs BP were mostly emplaced >500°C, indicating a series of large-hot domes that collapsed soon after emplacement. In the most extreme example, a similar pyroclastic density current from this volcano was emplaced ~10ka BP, at between 250 and 500°C out to >24 km from source. These results show that extreme thermal hazard persists for considerable distances from stratovolcanoes and should be considered out to at least 25 km from source.

How hot an ash-cloud surge can be? Reflectance analysis on charred trees during the 10-11 July 2015 Volcán de Colima dome-collapse eruption (Mexico)

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Temperature estimation of the ash-cloud surges developed during the 10-11 July 2015 dome collapse at Volcán de Colima, Mexico, was performed for the first time using reflectance analysis and microtomography image processing of pine wood charred fragments. The application and combination of these two independent and well-established methods to volcanic environment, constitutes a pioneering attempt for dilute pyroclastic density currents (PDCs) indirect temperature estimation. A total of 32 wood fragments were collected from charred pine trees still standing after the emplacement of dome-collapse induced PDCs along the Montegrande ravine. Wood fragments at different heights along tree trunks were selected in order to detect temperature variation, not only from proximal to distal area, but also within the ash cloud. The results obtained from charred wood Reflectance analysis highlighted temperature variation from 345°C-464°C in valley confined area to 307 °C in open distal fan area, indicating a strong drop in temperature with the change in topographic confinement conditions. Further Reflectance investigation on 4 selected pine trees at different locations along the Montegrande valley, indicate increase in temperature (average of 35-40°C) from tree base to top. Microtomography image analysis of the same charred samples, revealed an increase in microporosity of wood texture parallel with intensification in Reflectance degree, confirming a charring temperature strengthening upwards. The results of vertical and horizontal temperature variation have been discussed as the sum of ash-cloud surge dynamics and its interaction with the underrunning dense granular flow, air entrainment, and thermal flow behaviour of dilute PDCs. These results have important implication in hazards assessment of small, valley–confined PDCs. The overrunning ash cloud, representing a risk for a wider area, can surmount topographic barriers and reach further distances, but its extension and temperature are strongly dependent from the underlying concentrated PDC, without which, it will quickly lost strength.

S01.36 Talk

Probabilistic hazard from pyroclastic density currents in the Neapolitan area (Southern Italy)

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The metropolitan area of Napoli (Italy) is located in between two explosive active volcanoes: Somma-Vesuvius and Campi Flegrei. Pyroclastic density currents from these volcanoes may reach the city center, as witnessed by the Late Quaternary stratigraphic record. Here, we compute a novel multi-source probabilistic volcanic hazard assessment of pyroclastic density current invasion, over the city of Napoli and its surroundings in the next 50 years, by combining the probability of pyroclastic density current invasion from each volcano, assuming that they erupt independently.

We model pyroclastic density current invasion with the Energy Cone model accounting for flows of very different (but realistic) mobility, and use the Bayesian Event Tree for Volcanic Hazard (BET_VH) to incorporate other volcano-specific information such as the probability of eruption and of different eruption sizes, and the spatial variability in vent opening probability. Worthy of note, the method provides a complete description of probabilistic volcanic hazard assessment, i.e., it yields percentile maps displaying the epistemic uncertainty associated with our best hazard estimation, that describes the aleatory variability.

We introduce two important novelties in terms of epistemic uncertainty assessment. First, given that the probability density functions of the model parameters of the Energy Cone are unknown, we propose an ensemble of different hazard assessments based on different assumptions on such probability density functions. In particular, the ensemble merges two plausible distributions for the collapse height, within the gas-thrust region of the eruption column: we model this uncertain variable by means of an exponential (low heights are far more likely) and a uniform distribution (all heights are equiprobable).

Finally, we apply an innovative model-based and spatially-varying quantification of the epistemic uncertainty in the BET_VH model. This quantification accounts for variations in the simulated frequency of invasion under different theoretical assumptions on the link between the Energy Cone parameters.

S01.36 Talk

A time-distance reconstruction of the Campanian Ignimbrite pyroclastic current based on lithofacies architecture

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Large ignimbrites are the product of high-temperature pyroclastic density currents (PDCs) spreading over huge regions. Understanding the behaviour of these volcanic events is critical to assess the hazard posed to millions of peoples living near volcanoes producing this type of activity. Here we present a detailed examination of the medial (from 30 to 80 km from the source area) ignimbrite sequence of the Campanian Ignimbrite eruption (Campanian Ignimbrite s.s., CI), a caldera-forming Plinian event, occurred 39 ka ago, whose PDC spread over a huge area from Campi Flegrei (Italy). Ignimbrite deposits have a mass of $1.74*10^{14}$ kg and a tephra volume of 54 km^3 (25 km^3 DRE). We describe CI lithofacies and their vertical and lateral variations. The eruption started with a fluctuating Plinian phase that collapsed irreversibly spreading a pyroclastic density current over a rugged region. Vertical facies variations reflect a temporal evolution of depositional mechanisms, from traction- to granular- or fluid escape-dominated, that records unsteady conditions and contrast with persistent lateral facies reflecting an overall uniform spatial behaviour of the current. Our lithofacies investigation illustrates how the CI PDC evolved in time and space and the role of internal (eruptive and transport mechanisms) and external (topography, surficial water and rain) factors in governing its behaviour. Our study may have important implications for assessing the hazards related to the reactivation of the Campi Flegrei caldera with a large ignimbrite-forming Plinian event, like the Campanian Ignimbrite eruption, on the densely populated Campania region.

Volcanic risk frontiers: probabilistic hazard curves and maps of dense pyroclastic density currents at Somma- Vesuvius (Italy)

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Pyroclastic density currents (PDCs) are one of the most hazardous phenomena associated with volcanic eruptions worldwide. They are hot flowing mixtures of gas and pyroclasts that can cause widespread loss of life and structural damage around the erupting volcano. Volcanic hazard assessment that includes quantification of aleatory and epistemic uncertainty is a necessary step towards calculating volcanic risk of PDCs in an accurate and complete manner.

We develop a three-stage procedure to quantify such uncertainties for dense PDCs. First, the TITAN2D model is parameterized to simulate the PDC phenomenology at the target volcano. Second, TITAN2D is coupled with Polynomial Chaos Quadrature (PCQ) to propagate aleatory uncertainty from model parameters to hazard-intensity measures (flow depth and speed). Third, the TITAN2D-PCQ analysis is merged with the Bayesian Event Tree for Volcanic Hazard to include other volcano-specific uncertainty and evaluations of epistemic uncertainty.

A comprehensive collection of probabilistic hazard curves and maps for PDC flow depth and speed around the volcano is obtained through this methodology and its application is illustrated at Somma-Vesuvius (Italy). Our results indicate that, given an eruption from the current central crater, exceedance probabilities can be 40-70% for the first 2-3 km around the vent, for flow depths of 1 m and flow speeds of 2 m/s (considering aleatory uncertainty only). Dense PDCs faster than 30 m/s may occur, over areas about 100 km² around the vent, in 1 out of 10 eruptions. This type of probabilistic hazard products represent a crucial step towards quantitative volcanic risk of dense PDCs worldwide.

S01.36 Poster

Numerical modeling of BAFs for different eruptive scenarios of Tacaná Volcanic Complex, Chiapas, México

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The Tacaná Volcanic Complex (TVC) located in the state of Chiapas, is a chain of four main structures NE-SW oriented, named from oldest to youngest: Chichuj, Tacaná, Las Ardillas dome, and San Antonio volcano. The complex serves as the geographic boundary between Mexico and Guatemala. TVC began its construction during Late Pleistocene and has been continuously active up to modern times. During the past 50 ka, the complex has produced at least five voluminous block-and-ash flows (BAFs) that have occurred ~38, 28, 16, 15, and 2 ka. The deposits emplaced by these flows have reached up to 13 km from the vent. The last event (2 ka) named Mixcum produced at San Antonio volcano generated the largest BAFs and post-eruptive lahars that flooded the ceremonial site of Izapa leading to its abandonment (30 B.C.-80 D.C.). Therefore, in case of renewed activity of the TVC it could pose a serious threat to surrounding populations. In this work, we present the results of the first comprehensive study based on the numerical modeling of BAFs for three different eruptive scenarios of the TVC by using the Titan2d code. The scenarios were defined based on the volume and extent of the BAFs deposits mapped and its resemblance to recent BAFs developed at Volcán de Colima, which have been extensively described. The simulated scenarios are: (Low = 2015 Colima Volcano BAF), (Medium = 15 ka BAF) and (High = 2 ka Mixcum BAF). We used a DEM of 12.5 m resolution and varying the input volumes, the coordinates of the source points and the basal friction angle. Here, we show a preliminary analysis of the zones that could be affected and that will serve to integrate the hazard map of the TVC.

The effects of topographic uncertainty on lahar flow dynamics: modelling uncertain topographic data and strategies to improve quantitative lahar hazard assessments

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Lahars and dense pyroclastic flows are strongly controlled by the topography over which they flow. Predictive models of these flows for hazard assessment must incorporate topographic data which is usually represented as a digital topographic map (DTM). There are uncertainties inherent in the DTM due to for example, finite resolution for the data set, measurement error and temporal changes in elevation. Unlike uncertainties related to model parameters and source conditions, the uncertainty in topography is seldom assessed when quantifying uncertainties.

We present a method for incorporating topographic uncertainty into quantitative uncertainty analysis and demonstrate the approach with application to our recently developed dynamic lahar model, LaharFlow. DTM data from the NASA Shuttle Radar Topography Mission (SRTM) is freely available and has a (near) global coverage, so is widely used in hazard models. Previous characterization of the error in the SRTM data allows us to statistically model the uncertainties in the SRTM data as a Gaussian Random Field. The topographic uncertainty is propagated through the lahar model and combined to create a 'probabilistic routing map'. We demonstrate the methodology through application to lahar hazard prediction at Tungurahua volcano, Ecuador. Frequent lahars and secondary lahars have occurred during Tungurahua's recent eruptive episode (1999-present), presenting major hazards to populations and infrastructure around the volcano.

We discuss strategies to reduce topographic uncertainty through field measurement combined with statistical and numerical modelling. We show that point-data for elevations (e.g. from differential GPS survey) can be used to locally reduce the uncertainty. Wide-area topographic surveys by UAV is becoming an affordable method of acquiring high-resolution DTM. We discuss the use of high resolution topographic data in flow hazard modelling and present the computational methodologies employed in LaharFlow to facilitate lahar hazard modelling in urban environments using UAV-acquired topographic data.

S01.36 Talk

LaharFlow – a web-based tool for modelling lahar dynamics

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Lahars are extremely dangerous volcanic flows with impacts on populations and infrastructure extending up to 100s km from the volcano. Lahars occur during eruption and can lahar activity can persist for long times after eruption. The diverse mechanisms leading to lahars makes forecasting difficult. Physical models that describe lahar dynamics are useful tools in managing lahar hazards, allowing quantitative hazard assessments to be performed. In addition to predicting flow routing and inundation, physical models can provide quantitative predictions of flow variables that are valuable for assessing impacts on infrastructure (such as depth, velocity, dynamic pressures etc), as well as arrival times of lahars.

Here we present an overview of our new model of lahar dynamics, which we call LaharFlow, that we have developed explicitly to be used as a tool in hazard assessment. As such, our model includes only the dominant physical processes and adopts bold parameterizations. We adopt a shallow-water framework, and model the transport of a mixture of water with entrained solid material. The flow of the mixture is resisted by a basal stress whose form evolves with the composition of the flow. Erosion of the bed and deposition of the solid material alter the local topography that feeds back into the mobility of the flow.

To facilitate the use LaharFlow in hazard assessments, we have developed a web-based interface, providing user-friendly remote access to the LaharFlow implementation that employs robust numerical methods on a high-performance computing architecture. We demonstrate the LaharFlow web-interface and discuss the use of model outputs.

Evaluation of an ancient and giant pyroclastic flow hazard, 1.2 Ma Ongatiti Ingimbrite (New Zealand)

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The Mangakino Volcanic Centre (MVC) is the oldest rhyolitic volcanic centre in the Taupo Volcanic Zone (TVZ) in the North Island, New Zealand. The MVC eruptive products include several ignimbrites and one of the major rhyolitic ignimbrites is the Ongatiti Ignimbrite. We determine the topographic controls on distribution of the ignimbrite.

Field observations were combined with GIS data, and a digital elevation model (DEM). The ignimbrite covered hills and infilled valleys and reached elevations of approximately 900 m above sea level (asl) in proximal regions. In medial areas it has filled valleys and reached elevations of around 150-300 m asl; however, the distal equivalents (Oparau Tephra) were emplaced of elevations of <50 m asl.

The current study shows that the Ongatiti Ignimbrite has been emplaced by a super- eruption and its volcanic explosivity index (VEI) would be 7. The ignimbrite was a landscape-modifying event on the scale of at least the western North Island. Internal deposit temperatures were high enough to cause welding for up to about 80 km from the source volcano; beyond that, and more than 90 km from the source to the north-west, the pyroclastic flow deposited a relatively cooler non-welded tephra.

The GIS maps reveals that up to around 40 km from the MVC, the ignimbrite covered surrounded hills and valleys, but beyond those distances, the pyroclastic flow significantly traveled only through the valleys.

Assessing the topography of the North Island’s modern landscape shows that the areas around the younger calderas are mostly dominated by relatively low-lying lands with only moderate relief. This means there are few large natural barriers to control powerful pyroclastic flows and so they could travel and bury a vast area of the North Island catastrophically. Our findings can be helpful to estimate the hazardous areas, which will be significantly affected by a large eruption in the island.

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S01.38 - The contribution of experimental and numerical investigations of eruptive processes for improving hazard assessment at volcanoes

Development and validation of MagmaFOAM for the simulation of magmatic systems

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Numerical simulations have been shown to play a fundamental role in the prediction and understanding of the generation, ascent and eruption of magma. The recent extraordinary progress in computer performances and improvements in numerical modeling allow us to simulate multiphase-multicomponent systems in mechanical and thermodynamic disequilibrium. Here we present MagmaFOAM, a model based on the open source library OpenFOAM that resolves the fluid dynamics of melt-gas systems. The model includes thermo-mechanical non equilibrium phase coupling and phase change, and implements state of the art multiple volatile solubility models and constitutive equations with real thermodynamic and transport properties. For the validation we consider high temperature magma (chaotic) mixing experiments as well as multiphase shock tube simulations for conduit dynamics. Benchmark simulations and comparison with experimental data illustrate the capability and potential of MagmaFOAM to account for the complex physical and chemical processes and dynamics in a wide range of conditions pertaining to natural magmas.

S01.38 Poster

Death by a thousand perils - spontaneous oscillations in pyroclastic surges control their hazard impact and sedimentation dynamics

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Dilute pyroclastic density currents (or surges) are amongst the most frequent and dangerous processes associated with explosive volcanism. Too violent to probe directly, the infamous perils of surges, associated with their high velocities and temperatures, variable ash-load and dynamic pressures, can only be indirectly assessed in the eruption aftermath, but a direct view inside these flows remains missing.

Here we characterize the spatial and temporal evolution of the velocity, density, grain-size and thermal structure of hot dilute PDCs through dynamically and kinematically scaled large-scale experiments. The resulting insights into dilute PDCs demonstrate that surges spontaneously develop strong low-frequency downstream- and high-frequency downwards- propagating wave-like oscillations of their velocity and density fields.

The low-frequency fluctuations in velocity and flow density generate a succession of peaks in dynamic pressure (up to 1kPa in experiments, several tens of kPa in nature) that endure throughout the entire flow passage. As a consequence, and somewhat similar to earthquake damage in strong aftershock sequences, we suggest that the mechanical damage of surges is associated with repeated impacts of pressure pulses over several tens of seconds to minutes. This contrasts with a postulated single pressure peak during passage of the flow head. A turbulence analysis shows that the discovered low-frequency oscillations are related to the passage of the largest surge eddies, and that their characteristic time and length scales can be predicted.

The high-frequency oscillations result from regular sedimentation waves in the inner (velocity) layer of dilute PDCs. In high-speed movies, these are seen to feed a concentrated bedload layer of variable shifting sandwave, migrating dune and antidunes, as well as rolling and saltating sediment transport. A broad range of high frequencies in the turbulence spectra that characterises these sedimentation waves results from the successive marginalisation and later detachment of partially gas-coupled to gas-decoupled particles from large eddies.

Experimental Study of vertical partial block effects on dilute pyroclastic density currents

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The effects of lateral partial blocks on gravity driven currents were experimentally studied by lock-exchange method. Saline and particle driven gravity currents passed through vertical-partial blocks with 1/4, 1/2 and 3/4 of the tank width, respectively. The kinematic characters, front acceleration/deceleration modes and deposition patterns of flows were investigated.

Lateral partial block exerted a lag-deceleration influence on compositional gravity currents. The current fronts slowed down after a distance after the partial block. The non-dimension current length (L) and time (T) have relationships of $t^{0.771}$, $t^{0.700}$ and $t^{0.623}$ with buffer/tank-wide ratio of 1/4, 1/2 and 3/4, respectively.

Lateral partial blocks showed complex effects on particle driven gravity currents. Experiments showed that the 1/4 lateral partial block exerted an acceleration of current front speed and an increasing of sedimentation at certain distance on particle driven currents. The 1/2 lateral partial blocks decelerated front speed within ~ 100 T, then accelerated after ~100 T, and decreased total particle sediments of the dilute experimental currents after lateral blocks. The 3/4 lateral partial blocks decelerated flow front speed and decreased the total particle sediments after them.

These results highlight some processes in particle transportation and deposition through valley and city construction useful for the understanding of natural PDCs, and give out an explanation for behaviors of pyroclastic flows in Unzen volcano (Japan), which erupted on June 3, 1991.

Key words: Dilute pyroclastic density currents, Particle-driven gravity currents, Lateral partial block, Experimental simulation

Rates of volcanic ash production in pyroclastic density currents

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Dynamics and sedimentation of pyroclastic density currents (PDC) are strongly controlled by the amount of ash transported in the current, which continuously varies during transport for the concurrent effects of deposition at the flow boundary, lofting by gas coupling, and syn-transport production by clast-clast interaction. Quantitative assessment of ash production during transport is difficult to approach, and different methods have been used by several authors in the recent years. We present here the results of experiments of clast- clast interaction on different types of pyroclastic material from Vesuvius (highly vesicular pumice vs. mildly vesicular scoria), performed in order to illustrate the progressive change of bulk grain size population with travelled distance and dependence of absolute ash production on original grain size and componentry of the material. Bulk samples collected from the Avellino Pumice and AD 472 eruptions were charged into the steel rotating cylinder of a Los Angeles test machine. After treating at fixed times, samples were analyzed for bulk grain size, and shape parameters of selected clast sizes were measured before the reintroduction of samples in the machine. Results are discussed in terms of treatment time (a proxy for travelled distance) and changing of external morphology with particles size and experiment duration. After initial breakage of the coarser grained clasts, abrasion predominates, creating and stabilizing fixed, fine-grained classes possibly correlated with average bubble size and vesicularity. Shape parameters (solidity, convexity and factor form) of clasts of different size also evolve with time (or travelled distance). Rates of ash production are finally calculated for different lithologies in terms of relative variation for each grain size per travelled distance, and experimental data compared with data on natural samples of selected PDC deposits collected at different distances from the vent.

Impact of dissolved fluorine on surface tension of hydrous rhyolite

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Recently Gardner et al. (2018) examined experimentally the impact of dissolved fluorine on the number of bubbles nucleated in water-rich rhyolite. The experimental results surprisingly show that, all else being equal, samples with greater concentrations of fluorine produce much higher values of bubble number density. The slight differences in melt compositions, water diffusivity, or melt viscosity cannot explain the observed differences in the bubble number density. According to the classical nucleation theory, the net change in free energy upon forming a single nucleus is proportional to the cube of surface tension, thus a small decrease in surface tension can lower the surface energy of a bubble nucleus and can thus produce substantial increase in bubble nucleation rate. Here I used the gradient theory model to investigate the effect of fluorine on the surface tension of rhyolite. Gradient theory calculates the surface tension taking into account the excess of Free Energy across the liquid-gas interface. To apply this model, the thermodynamic properties of water and rhyolite has to be calculated and a density profile across the interface has to be assumed. In accordance with the experimental evidence of decompression experiments, I find that surface tension decreases with the addiction of few percents of fluorine. The thermodynamical model provides the physical reason of that. The low molar mass of fluorine, compared to the other oxides, reduces the molecular weight of rhyolite that, in turn, controls the so called “influence parameter” of the melt, hence the surface tension. In conclusion, dissolved fluorine may have a deep impact on the supersaturation needed to nucleate bubble determining substantial differences in bubble nucleation kinetics during eruptions.

S01.38 Poster

Crystallization of dacitic rocks of the Paraná Magmatic Province: A comparative approach based on natural and experimental products

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The Rio Grande do Sul region presents some of the best continuous exposures of the volcanism of the Paraná Magmatic Province (131-134 Ma). Mapping of silicic volcanic sequences in this area shows the existence of three main cycles of volcanic activity which generated a large volume of magma and eruptive products in a short period of time (1-2 Ma). The most representative of these units, in terms of volume, homogeneity of erupted products and sample preservation, is the Caxias do Sul dacite (CS). This sequence is characterized by high liquidus temperatures (~1,000ºC), low H_2O (1.5-2%), slightly oxidized character (~QFM + 1/2) and viscosities between 104 to 106 Pa s. Although many studies have characterized. the geochemistry and petrology of volcanic products, it is still unclear the eruptive style and the pre-eruptive conditions of the CS magma. A comparative approach was used to establish the temperature and H_2O conditions which controlled the ascent, eruption and emplacement dynamics of the magma. The experiments were performed by using homogeneous crystal-free glass at different T(900-1000°C) and H_2O (2-4wt.%) content in the low and upper limit for the storage conditions of these magma (150-400 MPa) with two solid media devices. Run products (pyroxene, plagioclase and ti- magnetite) and glass chemistry have been compared with the natural samples. The results seem to agree with previous interpretations of the high eruptive temperature and low H_2O of CS magmas.

S01.38 Poster

Olivine compositional changes in primitive skarn environments: A reassessment of divalent cation partitioning models to quantify the effect of carbonate assimilation

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The geochemical evolution of olivine from primitive skarn environments has been studied by atmospheric pressure experiments carried out at 1,250, 1,200, and 1,150 °C under QFM oxygen buffering conditions. The used starting materials were three synthetic basalts (i.e., $^{melt}Mg\#_{78}$, $^{melt}Mg\#_{75}$, and $^{melt}Mg\#_{72}$) doped with variable amounts of $CaCO_3$, in order to reproduce the natural concentration levels of CaO-rich magmas interacting with the skarn rock shells. Results from decarbonation experiments evidence that the crystallization of Fo- CaO-rich, NiO-poor olivines is more favored at high *T* when primitive basaltic magmas assimilate increasing amounts of carbonate materials. The number of large size Ca cations entering olivine crystal lattice is proportional to the amount of Ca-O-Si bonds available in the melt. Due to differences between Fe^{2+} and Mg cation radii, the Ca-Fe^{2+} substitutions into M2 crystallographic site are more facilitated than Ca-Mg ones, thus enhancing the Fo component in olivine. The partitioning behavior of Ni, Mg, Fe^{2+}, Mn, and Ca between olivine and melt has been also investigated to better understand cation redistribution mechanisms at the magma-carbonate reaction zone. Under the effect of $CaCO_3$ assimilation, the partitioning of divalent cations can be parameterized as a function of *T*, bulk composition (i.e., CaO and MgO contents in both olivine and melt) and melt structure (i.e., NBO/T). In turn, cation exchange reactions are primarily controlled by the strong depolymerizing effect of $CaCO_3$ assimilation that increases the number of structural sites critically important to accommodating network-modifying cations in the melt phase.

The integration of fieldwork, experiments and modelling towards the next generation of volcanic hazard quantification tools

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Integrating fieldwork, experiments and numerical models is a challenging, though preferable approach for understanding the physics of complex phenomena like volcanic eruptions. Fieldwork and the analysis of samples in the laboratory help keeping volcanologists linked to the products of volcanic processes, which models have to reproduce. Experiments allow verifying (or contradicting) hypotheses on how volcanic processes work, and their outcomes are particularly relevant to the volcanological community when they are properly scaled and make use of real volcanic materials. Models (often numerical) are a necessary tool for predicting and quantifying the hazard and impact of dangerous volcanic processes and, in the ideal case, are linked to the reality provided by the geological record and make use of the most up to date knowledge obtained from experiments in the form of constitutive equations.

In this talk, a successful example of the application of this approach is presented. Laboratory experiments on the shape and terminal velocity of real volcanic particles were carried out to obtain a new globally-convergent shape-dependent drag law. Measurements from large-scale experiments, on the other hand, allowed obtaining a new sedimentological model for calculating the sedimentation rate from particle-laden turbulent flows. Both experimental models have been implemented in PYFLOW_2.1, a numerical model for calculating the impact parameters of pyroclastic density currents based on field data. The model has been applied to quantify the impact parameters of pyroclastic density currents at Vesuvius and Campi Flegrei starting from the collected field data.

S01.38 Talk

The influence of particle shape on the aerodynamics of volcanic particles: a new drag law and application to ash dispersal models

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The aerodynamic drag of volcanic particles is strongly influenced by their irregular shape. In fact, volcanic ash and lapilli particles not only are generally far from perfect spheres, but their surface is rough with irregularities at various scales. In turn, the aerodynamic drag controls how solid particles are coupled to fluid carrier phase (e.g. atmospheric winds, pyroclastic flows) and eventually settle at their terminal velocity. Here we present a new shape-dependent drag law obtained from terminal velocity experiments of real volcanic ash and lapilli particles carried out over a wide range of Reynolds numbers (0.03 – 10,000), meaning that it can be applied to the complete spectrum of multiphase flow regimes characterizing eruptive processes, from pyroclastic density currents to the advection and sedimentation of fine ash into the atmosphere. The law is globally convergent, hence it allow predicting the drag coefficient and terminal velocity of solid particles outside the Reynolds number range of the experimental dataset. Additionally, the new law works in the whole range of variation of particle shapes, from highly irregular particles to perfect sphere. We also present results from the implementation of the new drag law into FALL3D and NAME, the ash dispersal models of INGV and UK Met Office, respectively. Results show that, with the new drag law, the models predict longer travel distances and residence times of irregular particles compared to almost spherical ones, as expected. A comparison with the application of Ganser's model is also presented and discussed, which shows that the two models are comparable in part of the fluid dynamic range, but significantly different in other parts, namely at very low and very high Reynolds number. For the ash dispersal applications, this implies that the two models predict different concentrations and travel distances of fine ash particles.

S01.38 Poster

From pyroclasts to lava flow: rheology of a clastogenic lava

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On the 18th May 2016 an eruptive episode characterized by a high intensity lava fountaining occurred on Mount Etna. Following the filling of the summit craters by the pyroclasts ejected, a clastogenic lava flow spilled out from the western rim of the crater area, setting up on the western flank of the volcano. To describe the rheological behaviour of this clastogenic lava flow, we performed a series of high-temperature (1050 to 1100 °C), uniaxial deformation experiments (strain rate $10^{-4}s^{-1}$) on selected natural samples (i.e., crystal- and vesicle-bearing) collected at different distance from the vent. We collected loose scoriae samples from the summit area, and a transect of lava samples representing the channel and the lateral levees where the lava overspilled from the summit crater threshold. The lava flow was also sampled at its distal front where both flow core and autobreccia clasts were sampled. Textural analyses, indicate similar crystal content, but very different vesicle content, with maximum values for pyroclasts (56%) and varying from the inner part (18%) to the upper part (25%), reaching a minimum value in the intermediate portion (10%) of the lava flow.

Rheological results show that at 1050°C the samples behave in a brittle manner under the experimental deformation regime, independently from their textural features and the portion of the lava flow in which they were collected. In contrast, with minor T increase (50°C), while samples with high vesicle content maintain their brittle behaviour, in denser samples ductile deformation dominates.

Combined textural and rheological data confirm field observation of the 2016 clastogenic lava flow: a marked decreasing in vesicle content from the pyroclasts to the overflowing zone due to sintering and compaction promoted lava viscous flow. Subsequently, a downflow mean porosity increase favoured brittle behaviour and autobreccia formation.

Towards A Structural Model for the Viscosity of Geological Melts

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The viscosity of silicate melts is the most important physical property governing transport and eruption of magma. This macroscopic property is controlled by composition and temperature but ultimately is a reflection of the structural organization of the melt operating at the microscale. At present, there is no explicit relationship connecting viscosity to silicate melt structure and vice versa. Here, we use a single Raman spectroscopic parameter indicative of melt structure to accurately forecast the viscosity of natural, multicomponent silicate melts. We provide, for the first time, an explicit, albeit empirical, linkage between the Raman parameter, taken as the ratio of low and high frequency vibrational bands from the silicate glass (i.e. Raman Ratio), and coefficients in Vogel- Fulcher-Tammann function for the temperature dependence of melt viscosity. The proposed relationship provides a means of predicting melt viscosity from spectroscopic measurements on glasses preserved on Earth and other planets and has significant implications for understanding the control of melt structure on viscosity.

S01.38 Poster

Combining numerical and experimental modeling to constrain the surge formation mechanism

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Pyroclastic density currents are complex flows often generated during large volcanic eruptions. Despite numerous studies since the last fifty years, their physical behaviour is still debated. The commonly accepted model predicted a flow in two parts: the basal flow, rich in particles and blocks, overridden by the dilute current, a turbulent suspension of ashes. The interactions and mass exchanges between these two parts are not fully understood.

We investigate the formation and evolution of the dilute current by coupling a numerical and an experimental model. We have developed a new version of the numerical model *VolcFlow* that simulates both components of a pyroclastic density current (the basal and the overriding dilute parts). The mass transfer between the two currents has been obtained from wind tunnel experiments and by comparing numerical model with real deposits. However, they are still empirical. To better understand these exchanges, we have developed an experimental model that reproduces a dilute current in air from a dense granular bed. The granular bed can be heated, sheared by air and vibrated to simulate the displacement of the dense part. We have measured the properties of the dilute current (concentration, deposit thickness,...) generated and correlate them with the properties of the dense part.

The experiment exhibits a mechanism of dilute flow formation by forced incorporation of air into the dense part by vibrations. The air is aspirated into the granular bed during dilatations, and expulsed during the contractions. A part of the particles are then sustained by the turbulent expulsed air and forms a mixture of gas and particle that transforms into a dilute current. Extrapolation of this mechanism to the pyroclastic density currents gives an explanation of the dilute flow formation and significantly improve the accuracy of the model. The hazard mapping using *VolcFlow* will be consequently greatly improved.

Influence of extrusion rate and conduit flow mechanics on magma rheology and the growth style of lava domes: Insights from particle-dynamics modeling

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Lava domes are structures that grow by the extrusion of viscous silicic or intermediate composition magma from a central volcanic conduit. Repeated cycles of growth are often punctuated by collapse, as the structure becomes oversized for the strength of the composite magma, which stiffens and strengthens at its surface. These processes have important implications for hazard assessment and mitigation during volcanic crises. We develop a 2-D particle-dynamics model, following the evolution of fractured lava, with solidification driven by degassing induced crystallization of magma. Extrusion rate and magma rheology together with crystallization temperature and volatile content govern the distribution of strength in the composite structure. We explore different lava-dome growth styles ranging from endogenous growth of a ductile dome core to the exogenous extrusion of a degassed lava plug producing a lava spine. Our model links conduit flow dynamics with growth of the lava dome, fueled by an open-system magma chamber undergoing continuous replenishment. Reduced effusive flow rates promotes degassing-induced crystallization; the shape and extent of the ductile core and the overall structure of the dome are strongly controlled by infusion rate. Material stiffness and strength are key model parameters that govern non-Newtonian magma rheology and the morphological character and stability of the dome. An increase in stiffness and strength of injected magma causes a transition in the style of dome growth, from endogenous expansion of a ductile core, to intruding material capable of punching through the overlying lava, resulting in the development of a spine, or possibly inducing dome collapse. Model results are similar to dome growth dynamics observed at Soufriere Hills Volcano, Montserrat, indicating a strong correlation between extrusion rate and dome morphologies similar to those observed at Mount St Helens and Merapi, demonstrating that lava domes can sag and spread during and following extrusion pulses.

S01.38 Poster

The characteristics and consequences of turbulence in dilute pyroclastic density currents

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Dilute fully turbulent pyroclastic density currents (PDCs or pyroclastic surges) are omnipresent and highly dangerous hazards on almost every active volcano worldwide. Of particular concern to hazard scientists and decision makers is the generation of substantial dynamic pressure, which cause variably degrees of mechanical damage to man-made and natural structures. This range in dynamic pressure has been estimated to range from less than one kilopascal (which may be survivable) to pressure in access of one hundred kilopascals (capable to swiftly erase strong steel-reinforced concrete bunkers). Currently, our ability to model and forecast the space- and time-variant distribution of dynamic pressure inside pyroclastic surges is limited because little is known about the dynamic evolution of vertical velocity and density profiles in hot highly turbulent real-world flows.

Here we present a complete dataset from hot, fully turbulent experimental pyroclastic surges, which have been synthesized at the large-scale eruption simulator facility PELE in New Zealand. Time-variant vertical profiles of flow velocity, temperature, particle concentration and grain-size distribution are analysed along the 35 m long flow. Together they define the dynamic pressure field, which we study from the deposit upwards through the wall-boundary layer and the outer jet region. The flows are fully turbulent with Reynolds numbers up to 10^6, characterised by strong spatial and temporal variations in eddy structure and gas-particle coupling. We discuss the turbulence structure and its relevance for the distribution of dynamic pressure inside surges.

Guided by our attempt to define an international benchmark for numerical surge hazard models, we further seek solutions to separate the velocity and concentration data into two parts: self-similar mean profiles, and turbulent fluctuations of both parameters. In analogy to turbulent volcanic plumes, we suggest new self-similar, time-dependent profiles of mean velocity and concentration, as well as functions describing the time-variant turbulence intensity.

S01.38 Poster

Effects of componentry, size and initial depth on particle acceleration within volcanic conduits

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During an explosive volcanic eruption, the decompression of a multiphase mixture in the conduit and its expansion in the atmosphere causes the acceleration of both fragmented magma and eroded/entrapped dense lithic particles. The initial acceleration and depth of he particles within the conduit, as well as the coupling between particles and the gas during the acceleration phase, play a key role on the eruptive plume dynamics, and on the ballistic ejection behavior (e.g. maximum range of a projectile).

Loose material collected from the fall deposit of Pomici Principali eruption (Campi Flegrei) was separated into two main componentry (pumices and dense clasts), and used for a series of decompression experiments aimed to investigate these controlling parameters. Experiments included mixtures with different proportion and sizes of pumices and dense clasts, as well as pumice-dense-pumice layered structures. Samples were slowly pressurized up to 10MPa using argon gas and then rapidly decompressed to ambient pressure. A transparent setup enabled to monitor the conduit processes with a high-speed camera. Microsecond detail of these experiments allowed us to measure the gas-particles velocity from a large number of particles, and to compare the acceleration behavior depending on componentry and particle size of the initial sample, as well as on particle positions within the conduit.

Preliminary results suggest that within the conduit the presence of smaller-sized pumices may increases mixture acceleration, while increased amount of dense clasts does not significantly enhance/reduce the overall mixture acceleration. Moreover, for the investigated conditions, the acceleration of shallower particles may be one order of magnitude higher than for deeply seated particles, on first order independently of clast nature and sizes. The method and results presented may help improve the quantification of initial particles acceleration within volcanic conduit to be used for modelling and hazard assessment, e.g for Vulcanian eruptions.

Modeling the crystallization and emplacement conditions of a basaltic trachyandesitic sill at Mt. Etna volcano

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This study documents the compositional variations of phenocrysts from a basaltic trachyandesitic sill emplaced in the Valle del Bove at Mt. Etna volcano (Sicily, Italy). The physicochemical conditions driving the crystallization of minerals have been reconstructed by modeling major and trace element analyses of clinopyroxene, feldspar (plagioclase and K-feldspar), and titanomagnetite. Clinopyroxene is the liquidus phase, recording decompression and cooling paths variable from 200 to 0.1 MPa and from 1050 to 940 °C, respectively. On the other hand, plagioclase and K-feldspar cosaturate the melt in a temperature interval of 1000-870 °C. Cation substitutions in clinopyroxene (Mg-Fe) and feldspar (Ca-Na) indicate that the ascent of magma is accompanied by H_2O exsolution up to 2 wt.%. This translates to a degassing-induced undercooling of 80 °C from the deeper parts of the plumbing system to the surface. The titanomagnetite compositional changes reflect oxygen buffering conditions variable from NNO-0.5 to NNO+0.8, possibly due to significant H_2O liberation and degassing at the time of emplacement. A fractional crystallization model for REE and HFSE has been adopted to quantitatively assess the role played by clinopyroxene and feldspar fractionation on the trace element pattern of the basaltic trachyandesitic sill. Assuming a primitive Etnean basalt as parental magma, REE and HFSE concentrations in the sill bulk rock are succesfully reproduced by prevalent clinopyroxene fractionation (55%) at depth, followed by minor fedspar segregation (14%) at shallow crustal levels.

S01.38 Poster

Constraining thermo-rheological properties of lava: from lab and field experiments to applications for modeling

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Lava flows are multiphase fluids travelling downslope whose velocities and final lengths depend on a number of internal and external factors. The key internal parameter is the rheology of the lava itself. Rheology is directly linked the fluid temperature and its chemical and physical properties, i.e., composition, redox state, volatile content, and shape and size of bubbles and crystals. During flow downslope, the lava rheology continuously changes due to cooling, degassing and crystallization. This dynamic process has a direct influence on lava flow emplacement because it controls velocity and leads to cessation of flow when the rheological parameters are such that they impede further forward motion. A good quantification of rheology is therefore needed to model lava flow behaviour in active systems and also to retrieve dynamics of past eruptions. Here, we present and discuss laboratory viscosity measurements that use re-melted lava at super- and sub-liquidus temperatures. These are then compared with syn-eruptuve *in situ* field measurements performed by inserting a viscometer into the lava while it was flowing. Although such field experiments are notoriously difficult to perform they are the only way to quantify lava rheology in its natural state. When fully-integrated with sample characterization they also allow quantification of three-phase lava viscosity, and validation of theoretical and empirical rheological models. Using PyFLOWGO to test all possible thermorheological scenarios, we find that when appropriately selected and initialized rheological properties are applied, actual flow properties are well reproduced. We thus show that dynamic cooling experiments in conjunction with field measurements are needed to fully understand and model lava emplacement conditions. Collecting several field measurements down a single flow system is the most promising approach to quantify evolving lava rheology in time and space and will lead to proper benchmarking for lava flow modeling.

S01.38 Talk

Storage region controls on dike propagation and the location of future eruptions

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Magmatic dikes are known to trigger volcanic eruptions. When they ascend from depth, they can either make contact with a magma storage region, miss and breach the surface or be emplaced underground. We investigate how the pressure state of a reservoir can control dike propagation, using analogue modeling techniques. We show that an over-pressurized reservoir orients the stresses in the crust in a way that dikes propagate radially. If the reservoir is in an under-pressurized state, dikes are forced into a tangential orientation. This has important implications for hazard management, in that the orientation of a dike has a degree of control on the direction in which it propagates. In this way, a highly pressurized storage region tends to attract dikes, which can make a summit eruption more-likely. Conversely, a highly depressurized region deflects dikes away, which may lead to a flank eruption or to dike emplacement. It is therefore important to understand the pressure state of a volcano's magma storage region, which can help us predict how an ascending dike will behave and where they may initiate an eruption.

A comprehensive approach for the investigation of ash aggregation in volcanic plumes

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Particle aggregation is a topic of interest for several scientific disciplines. It arises when the surrounding environmental is favorable for large collision rates among particles and not negligible sticking processes are present on their surfaces. The key role of aggregation on volcanic ash sedimentation has been emphasized during the 2010 Eyjafjallajokull eruption in Iceland, when most of the airspace in Europe was closed for several days and in situ observations revealed the presence of ash aggregation. Ash aggregation generally leads to an increase of the terminal velocity and a variation of the residence time of particles in the atmosphere. Therefore, neglecting ash aggregation could potentially lead to an overestimation of ash concentration in the far field and an underestimation of ash load in proximal areas.

The most common approach in the volcanology community has been based on the application of empirical or semi-empirical relationships to redistribute part of the initial mass fraction into predetermined final classes of particles. In our work we propose an alternative approach, where the mathematical limitations of previous models have been addressed and the physics of the processes better quantified.

We provide a comprehensive methodology to treat the problem of ash aggregation in volcanic plumes. The final numerical scheme is capable to describe the evolution of aggregates tracking their evolution in two or more internal variable. A complete set of new collisional frequencies in a turbulent plume is also provided. A particular attention has been posed in describing the mechanisms of sticking among volcanic ash. Two main mechanisms of dissipation of relative kinetic energies are considered: wet aggregation, due to the dissipation of a water layer on the surface of the objects; dry aggregation, due to the dissipation of the adhesive viscoelastic forces. Several examples are discussed together with an application to real eruptions.

S01.38 Poster

Solid-state sintering contributes to cyclical explosive activity at dome- producing volcanoes

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In the crystal-rich volcanic systems that produce lava domes and spines, the primary outgassing feature is the cylindrical shear zone that surrounds the rising lava. When initially formed, these shear zones are made up of pulverized crystal-rich glass-poor lava, and are high porosity, high permeability regions. However, shear zones encasing erupted dome lavas at surface comprise low porosity, low permeability, lithified cataclasites. The densification and lithification of the granular material in the shear zones results from solid- state sintering: atomic diffusion between adjacent crystalline particles causes the particles to fuse together, transforming the unconsolidated crystalline material in to dense composites. As such solid-state sintering contributes to the healing of shear zones in crystal- rich volcanic systems, and the shut down of outgassing pathways.

We present results from high temperature (*T*), high pressure (*P*) hot isostatic pressing (HIP) experiments designed to explore the timescales of solid-state sintering at conditions expected within the volcanic conduit (700-900°C; 40, 70 MPa). Samples of unconsolidated crystalline dacite powders used in these experiments were transformed into dense, low porosity, solids within 60 hours. The permeability of the composites decreases by more than an order of magnitude (1.4×10^{-14} to $9.9 \times 10^{-16} m^2$) with decreasing porosity (0.30 to 0.13). We present a time (*t*) dependent equation for densification by solid state sintering where ρ^* and ρ_i^* are the modeled and initial relative densities, respectively, and *a*, *b*and *c*are fit parameters.These HIP experiments, and models built from the results, show that solid-state sintering operates over a timescale of days at the conditions found in volcanic conduits. By modeling the time-dependent loss of porosity and permeability as a result of solid-state sintering, we can begin to predict the recurrence interval between the cyclic explosive events often documented at dome- and spine-producing volcanoes.

FOAMGLAS®: An ideal proxy for natural magmatic foams

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The presence of bubbles within silicate melts changes the bulk viscosity, the most important property governing transport and eruption of magma. Here,we describe FOAMGLAS®, a closed-cell glass insulation produced by Owens Corning Corporation that can be used to rigorously study bubble-rich melts in the laboratory. It has a high porosity (>90%), no microlites or crystals present, contains gas-filled bubbles, and is impermeable (its permeability is below the resolution of our permeameter, $<<10^{-18}m^2$). It can be cut, cored and heated to above its glass transition temperature (Tg) without macroscopic or microscopic fracturing, and can be used as a proxy for natural crystal-free foams (e.g. rhyolitic magmas).

To demonstrate its utility we present the results of high temperature (>Tg) compression experiments. The measured bulk viscosity is 2.5 orders of magnitude less than the melt viscosity at the experimental temperature but, critically, is 1.5-3 orders of magnitude greater than that predicted by existing models. The difference between the measured and modeled viscosity can be attributed to the pressurized gas in the bubbles, which resists deformation in a way that is not accounted for in existing models. Furthermore we see the mechanism for time-dependent strain accommodation (volume loss vs. bulging) changes during deformation: When applied strain is ~0.4, bulging takes over from volume loss as the dominant mechanism for taking up strain. The opposite trend is observed during the deformation of melts populated with pores that contain gas that does not become pressurized as a result of compression (i.e. open-cell foams). These results highlight the influence of a compressible gas within bubbles on the viscosity and deformation behaviour of a bubbly melt. FOAMGLAS® can be used to distinguish between the rheology of closed- and open-cell melts, which should be considered when modelling the rheology of natural crystal-free magmas.

Pores vs. bubbles: a rheological study

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The presence of pores strongly controls the rheological behaviour of magma and thus influences all volcanic processes (pre-syn and post-eruptive). Nevertheless, the effects of porosity on the rheology of magma are not well characterised, and a general parameterization is not available yet.

Here we present a new set of experiments designed to investigate the rheology of porous melts at high temperature (750-800 °C), low strain rates (10^{-6}-10^{-7} s^{-1}) and variable porosity (10-50% vol.). Experiments were performed at 1 atm using TMA. The starting materials are 5 x 5 mm cores of natural rhyolitic obsidian from Krafla, Iceland (vesicle and crystal-free) initially containing 0.11(4) wt% dissolved H_2O.
Two steps compose the experimental procedure: 1) synthesis of bubble-bearing materials by heating and expansion due to foaming; 2) cooling down to different target T (750-800 °C) and deformation of the foamed samples. During the first step, cores are heated above the Tg (900-1050° C) and held for set amounts of time (10–24 h); the change in volume of the foamed samples increases because H_2O vapour-filled bubbles nucleate and expand.
In the second step, two different experimental strategies are employed

1) *Single-stage*: samples are deformed directly after foaming. A constant load (150 g) is applied by silica or alumina probes to the core, and the cores deform isothermally for 5-20 hours.

2) *Double-stage*: deformation of synthesised occurs after the quench of pore-bearing cores.

In both cases, the variation in length (displacement) and volume (porosity) is continuously recorded and used to calculate the viscosity of the foamed cores using Gent's equations.

Preliminary results suggest that single-stage measurements have lower effect of bubbles on the bulk viscosity, compared to double-stage measurements. We suggest that the different behaviour may be related to the nature of the pores and/or the different microstructure of the experimental materials.

Pyroclasts cooling through infrared thermography: the Agnano Monte Spina and Pollena cases of study

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To better understand the temperature dynamics affecting pyroclasts during an explosive eruption, a suite of laboratory experiments was carried out with a thermal camera FLIR T 1030 on selected pyroclasts of variable porosity, dimension and composition. Investigated samples include pumices and scoriae from the 4.1 ka Agnano Monte Spina (AMS, Campi Flegrei, alkali-trachyte) and 472 CE Pollena (PO, Vesuvio, tephritic phonolites) eruptions. Samples with fixed shapes (cubes with sides of 1,5 cm and 0,9 cm) range in porosity (φ) from 53-63% (PO) to 82-88% (AMS). Pyroclasts were heated up to 800°C and temperature variation was recorded during cooling in air with a thermal camera and with two thermocouples placed inside the sample and next to its surface (used as external calibration temperatures).

Thermal loss was studied by combining temperature measurements from centre, corner, vertex positions and surface mean T of the clasts. Temperature-time plots indicate that differently from the usually adopted single exponential equation that defines the standard law of exponential decadence for cooling, T-t plots seem to be better reproduced by a double exponential equation (1):

$$T=(T_i - T_s)e^{(C1*t)}+T_s e^{(C2*t)} \quad (1)$$

where Ti is the initial temperature, Ts is the temperature of separation between regions with different decay trends defined by different coefficients C_1 and C_2 (in s^{-1}; C_1, $C_2 < 0$ and $C_1 > C_2$). The two members of the equation represent two distinct regions of the cooling curve.
Cooling behavior of investigated scoriae and pumices is strongly affected by clast dimension and porosity. In general, cooling efficiency increases with decreasing size and increasing porosity of the clasts. Moreover, the influence of dimension seems to be more important for low porosity clasts, compared to high porosity ones where higher air entrainment allows more efficient cooling.

S01.38 Poster

An experimental approach to investigate seismo-acoustic markers of degassing patterns

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The analysis of geophysical patterns enables tracking the surface effects of sub-surface volcanic processes with great detail and provides a fundamental tool for the surveillance of active volcanoes. The full exploitation of geophysical data (in particular seismic and infrasonic) requires the capability of linking quantitatively fluid dynamics and degassing processes at depth with signals recorded at the surface. Nonetheless, the outcomes of the attempts made so far are still considered very uncertain because of volcanoes inaccessibility to direct observation on fundamental parameters such as plumbing system geometry and magma properties. This issue can be solved by integrating field measurements with laboratory experiments. To this extent, we developed a novel experimental device aimed to mimick volcano degassing processes with different regimes and gas flow rates, and allowing for the investigation of the related seismo-acoustic emissions. The implemented device permitted us to (i) precisely fix and control fundamental parameters such as the geometry of the structure where the two-phase analogue mixture flows, the gas flow rate (5-180x10^{-3} l/s), and the fluid viscosity (10-1000 Pas); (ii) measure micro-seismic signals in fixed locations of the analog conduit by means of an array of laboratory sensors (including one microphone, two piezo-film sensors and one accelerometer); (iii) directly observe the degassing pattern through the optically clear analog magma and define the degassing regime producing the seismo-acoustic radiations.

Shock-tube investigation on jet development and pyroclast acceleration during transient explosive eruptions

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There is gap in the study of the life cycle of pyroclasts from explosive volcanic eruptions. Many studies have addressed the modes of pyroclasts formation; i.e., the fragmentation of magma. An equally large number of studies has focused on the emplacement of pyroclasts, i.e., the different means and dynamics of their atmospheric transport and sedimentation. There is a disproportionately small number of studies that specifically focus on what happens to pyroclasts between magma fragmentation and ejection from the vent. Here, we approach the problem of pyroclast ejection using analogue modeling in a shock-tube apparatus and simple shock-tube modeling theory. In particular, we focus on the acceleration of pyroclasts by rapid decompression and on their ejection in an eruption jet, in broad analogy with the dynamics of transient explosive eruptions. We use a transparent shock-tube and compressed air to accelerate natural pyroclasts of different grain size and eject them into the atmosphere. Both the acceleration and ejection phases have been documented using high-speed video imaging, and the acceleration in the shock-tube has been also occasionally documented using piezo sensors. Several configurations of the shock- tube (e.g., gas volume, pressure, pyroclast size, height of the pyroclasts below the tube exit) have been tested, and some results have been compared against simple 1-D shock-tube numerical modeling. The results illustrate how the acceleration phase of pyroclasts in the conduit, function of the initial shock-tube conditions, reflects in the space-time distribution of their ejection velocity at the tube exit. A comparison with the same distribution measured during volcanic eruptions open the way for potential, new inferences on the processes controlling the dynamics of pyroclasts in shallow conduits and at the vent during transient explosive eruptions.

Thermal regime of column collapses and controls on initial temperature of pyroclastic density currents

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The temperature of pyroclastic density currents (PDCs) is one of the main hazards for communities and infrastructures surrounding volcanoes. PDC deposits are known to vary from extensively welded to completely nonwelded with emplacement temperatures close to ambient. The reasons for such great diversity are debated in terms of eruptive versus transport and emplacement processes. Here we present three-dimensional numerical simulations to understand the influence of different column collapse regimes on the thermal character of PDCs. We show that the initial temperature of PDCs depends linearly on the amount of mass involved into the collapsing phase, with a maximum decrease of 45% of the starting magmatic temperature in the case of an incipient column collapse, owing to the more efficient entrainment of air through the jet structure. Our results provide evidence for explaining the large thermal variability of PDCs, and suggest that their depositional temperatures could be used as a reliable marker of past column collapse intensities that are important for the hazard assessment of volcanic regions.

S01.38 Talk

Clinopyroxene sector zoning revisited: magma mixing vs. kinetic effects

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Clinopyroxene is a common early phase in mafic to intermediate magmas and its texture and composition readily respond to the physicochemical changes of the melt feeding the crystal growth. In this context, the variable concentration of cations incorporated in the concentric zoning of clinopyroxene can help to elucidate magma dynamics in the plumbing systems beneath active volcanoes. However, the chemistry of clinopyroxene is also highly sensitive to crystallisation kinetics, and is known to develop sector zoning. In such cases, the fidelity of compositional changes as recorders of magma history is dubious and the interplay between kinetic and thermodynamic controls remains poorly understood.

Here we explore sector zoning with electron microprobe and laser ablation micro-chemical maps of clinopyroxene crystals from Mount Etna (Sicily, Italy). Elemental maps afford the possibility to revisit sector zoning from a spatially controlled perspective. The most striking observation is a clear decoupling of elements into sectors vs. concentric zones within single crystals. Most notably, Al-Ti enrichments and Si-Mg depletions in the prism sectors relative to the basal (hourglass) sectors correlate with enrichments in REE and HFSE due to cation exchanges driven by kinetic effects. In contrast, transition metals (Cr, Sc, Ni) show little partitioning into sectors and strong enrichments in concentric zones following resorbed surfaces, interpreted as evidence of mafic recharge and magma mixing. Our results document that kinetic partitioning has minor effects on the compositional variations of cations with low charge relative to the ideal charge/radius of the structural site they occupy in the lattice. We suggest that this might be due to a lower efficiency in charge balance mechanisms compared to highly charged cations. Therefore, low charge compatible metals might be considered trustworthy recorders of mafic intrusion even in sector zoned crystals.

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S01.40 - Advanced Processing Techniques for Geophysical Signals Recorded at Active Volcanoes

Dynamics of Vulcano Island (Tyrrhenian Sea, Italy) investigated by long-term (40 years) geophysical data

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Vulcano Island is a composite volcanic edifice located in the south-central sector of the Aeolian Archipelago (Tyrrhenian Sea, Italy). Historic activity has been characterized by frequent transitions from phreatomagmatic to minor magmatic activity. The last eruption in 1888-90 saw powerful explosive pulses and this eruption defines what we call 'vulcanian' also for other volcanoes. Since then, volcanic activity has been in the form of fumarolic emanations of variable intensity and temperature, mainly concentrated at "La Fossa" crater.

We investigated Vulcano dynamics through ca. 40 years of ground deformation and seismicity data collected by the discrete and continuous INGV monitoring networks. We considered levelling, GPS, EDM, seismic and tilt data. EDM and levelling measurements began in the middle of the 1970s; since the late 1990s, the EDM benchmarks have been measured using GPS.

We analysed data on time-space scales, distinguishing the dynamics of different sectors of Vulcano (Piano, Vulcanello, La Fossa cone and Caldera) and three periods (1974-1984, 1984-1999, 1999-2013). We also show how the regional tectonic stress plays an important role in the transition of the volcanic system from a phase of stability to one of unrest, inducing the heating and expansion of shallow hydrothermal fluids.

Lastly, we performed a data inversion, identifying for the 1999-2013 period, the action of a regional tectonic tabular source coupled with a deflating magmatic one located under Vulcanello at 4-5 km a.s.l.

Automatic detection of Long Period events based on the advanced subband analysis algorithm SALPED

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Volcanic seismology studies the dynamics of active magmatic systems through the analysis of specific seismic signals such as Long and Very Long Period events and Volcanic Tremor. The Long Period (LP) events are of particular interest to understand physical processes within a volcano, playing an important role in determining the internal volcano dynamics. Understanding origin and periodicity of LP events can be crucial, as they commonly precede and accompany volcanic eruptions. Monitoring LP activity helps us to understand the unrest state of the volcano, and could forecast volcanic crisis through early-warning monitoring systems. Aimed to these purposes, we applied the SALPED algorithm in order to perform an automatic detection of LP events in continuous seismic records. Using this algorithm, the continuous raw signals from the seismometer are first filtered into three frequency bands separating lower, central, and upper frequency components. These new signals are then processed in parallel to extract subband envelopes and create a characteristic function that enhances LP features. We used as a dataset, the seismic signals recorded on Mt. Etna Volcano during the 2010 summer. Performing this analysis, we found different LP families, and the difference in the waveform shape between the families could be caused by a different source position and/or source mechanism. We observed that these families were not recorded continuously throughout the period under study, due probably to the volcanic activities occurred during august 2010. The proposed approach will open interesting perspective toward utilization of this algorithm to find seismic signals that are relevant to monitor volcanoes and forecast their activity through the analysis of existing big seismic data records.
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S01.40 Talk

Application of Machine Learning Techniques to distinguish and classify Low Frequency events during the 2015 Cotopaxi Volcano reawakening

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Understanding and reporting transitions between volcanic unrest and eruptive activity is one of the most important and critical tasks performed by volcano monitoring agencies. Transition periods are usually recognized by changes in geophysical and geochemical parameters such as deformation, seismicity, infrasound, and degassing. When the rate of seismic events rises in an accelerated fashion, it could indicate the possible beginning of an eruption. In this study we used seismic data to evaluate the transition period from unrest into eruptive activity during the 2015 reawakening of Cotopaxi volcano (Ecuador). We studied this transition by identifying possible key families of low (or very low) frequency events, which occurred shortly before and during the reawakening.

During May of 2015, a notable increase on the rate of seismic events was detected in Cotopaxi Volcano, which put into alert the local monitoring institution - Instituto Geofísico de la Escuela Politécnica Nacional (IGEPN). A change in the rate and size of seismic events also occurred, with the later appearance of tremor in June 2015, preceding the explosive activity that initiated on August 14, 2015. We used recordings from the permanent broadband seismic network at Cotopaxi from May 2015 to December 2015, a period which comprises a couple of months before and during the volcano's reawakening, to detect seismic events with low frequency content. We applied computational techniques to identify possible families of "particularly shaped" events. These techniques included some classic unsupervised classification algorithms such as k-means and hierarchical clustering based on diverse similarity measures such as frequency vector comparisons, waveform correlation/correntropy and dynamic time warping. Finally, it was possible to identify precise types of events with particular shapes -although their occurrence was sporadic during the studied period- and initial efforts were made to interpret the relation between their forms and the possible sources that originated them.

Analogue and Numerical modelling of double-piston piecemeal calderas

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Analogue experimentation has been proven to be important for revealing out the structural and morphologic evolution of volcanic edifices. Both inflation and/or collapse scenarios shed light on the structural evolution of calderas. It has been shown that the shape and the depth of the magma chamber may affect the caldera morphology and collapse styles. We have carried out several sandbox experiments simulating inflation followed by an edifice collapse where the growth of the magma chamber has a significant lateral inflation component. With repeating experiments we were able to create funnel type, nested and blocky/piecemeal collapse caldera models. Topographic evolution of the models was monitored by high- precision surface elevation models created by Multiview Stereo-Photogrammetry (SfM-MVS) at certain stages of the experiment. Series of top-view photographs acquired during experiments were also used for particle tracking analysis. X-ray Tomography and X-ray Micro Computed Tomography (Micro-CT) of fixated collapsed analogue models were used to investigate the post-collapse internal structures in 3D digital medium. Finally, mimicking real dimensions, dynamics and parameters, we numerically tested our results using finite element method. Our results show that, during tumescence, the lateral expansion of magma chamber analogue causes an inequivalent deformation on the roof block where two differently deformed domains are separated by a tensional structural limit traversing the edifice. The following collapse event forms a double-piston piecemeal caldera where those differently deformed domains collapse as separate blocks and at different subsidence depths. Previously documented structural elements of calderas: outward dipping reverse and inward dipping normal boundary fault couple, radial faulting during tumescence and circumferential faulting during collapse have also been observed.

S01.40 Poster

Using Exploratory Data Analysis in Volcano Seismic Signals

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Analyzing seismic activity in volcanic scenarios is a very challenging task. Shallowness of the source mechanisms, lower magnitudes, near-source effects and rough topography complicate the identification of volcano-seismic events. Automatic detection and classification of high frequency and low frequency events complements the work of human experts through automatic signal processing and artificial intelligence, allowing the systematic processing of very large amounts of data recorded. As a result, knowledge about the inside of the volcano and its evolution increases.
The concept of Exploratory Data Analysis (EDA) was introduced in the 20th century by Jonh Tukey. The main goal is to find information in data aimed at generating hypotheses. This concept is especially useful when the Data Scientist analyzes complex data with a high dimensionality. Essentially EDA is an approach for searching patterns in the data with an open mind; EDA helps to answer questions as how to determinate the most suitable machine learning algorithms and also how to select the best feature vector for a particular data set. Mainly EDA uses graphical tools to represent the data.
In this work we propose the application of the EDA approach to a set of volcano-seismic events (mainly high frequency and low frequency events) registered in different volcanoes (Campi Flegrei, Colima, Deception, Peteroa and Monserrat) aimed at finding the similarities and differences in the signals recorded in that set of volcanoes, and also finding a representative set of features for describing these events.

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S01.40 Poster

Dike propagation energy balance from deformation modeling and seismic release

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Magma is transported in the crust mainly by dike intrusions. In volcanic areas, dikes can ascend vertically and also move horizontally through lateral propagation, eventually feeding flank eruptions. Understanding dike mechanics is a key to forecasting the expected propagation and associated hazard. A poorly understood aspect is the relation between dike- induced deformation and the energy released during its propagation, e.g. by seismicity. We pinpointed a simple equation that can be used as a proxy of the expected mechanical energy released by a propagating dike. For several intrusions around the world (Afar, Japan, Mt. Etna), we relate such mechanical energy to the seismic moment released by the induced earthquakes. We obtain an empirical law that quantifies the expected seismic energy released before arrest. The proposed approach may be helpful to predict the total seismic moment that will be released by an intrusion and thus to forecast the time of dike arrest.

S01.40 Poster

Integration of InSAR time series and GNSS data for reconstructing the 3D ground deformation of Etna in the last 4 years

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Sentinel-1A and 1B data are routinely used for monitoring ground deformation on Etna, with the maximum detail in space and now with an acceptable detail also in time (revisiting time of 6 days, using ascending and descending orbits). This allows the detailed time series of LOS displacements to be calculated for each pixel of the monitored area. GNSS surveys are also carried out on the volcano periodically, depending on the ongoing activity on the whole network (about 80 benchmarks) or on part of it, to integrate the information coming from the permanent GNSS monitoring system. GNSS data are always integrated with the InSAR ones by the SISTEM algorithm to calculate the 3D displacement field with the spatial detail and resolution of the InSAR images, also for constraining the INSAR time series. Here, we show the integrates maps and time series of the ground deformation of Mt. Etna from the end of 2014 up to now, evidencing the general inflation of the volcano, locally interrupted by brief deflation episodes, mainly located on the upper part of the edifice.

S01.40 Poster

Automatic Classification of Volcano- Seismic Events with Convolutional Neural Networks

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Energy exchange between volcanoes and the environment produces a myriad of seismic anomalies. These sources interact in a heterogeneous and absorptive media, with strong attenuation and path effects that alter the intrinsic attributes of the recorded signals. Furthermore, natural distortion effects can be misleading during source identification from recorded seismograms. In order to provide accurate monitoring, especially in volcano observatories where large databases are being generated continuously, robustness under adverse conditions becomes even more imperative than ever. Convolutional Neural Networks (CNNs) arise as potential monitoring systems that can be deployed to classify seismic data at scale, enhance current early-warning systems and build extensive seismic catalogues. By employing successive layers of convolutions, high-level features are computed from raw data and further mapped into a high-dimensional space which provides a better representation of the input data distribution.

In this research, we present a concise description of CNNs and explain how they can be used in volcano-seismic monitoring. We further evaluate classification performance on seven different seismic events registered at “Volcán de Fuego” (Colima, México). Attained results demonstrate that CNNs are powerful models to classify a wide range of volcano- seismic signals, with good generalization capabilities. Furthermore, frequency attributes contain useful discriminative information for the CNN, as higher layers of the network can combine high-level features computed for each frequency. Being at the intersection of deep learning and geophysics, the proposed work enables future studies of how CNNs can be used in volcano monitoring to characterize volcano-seismic events.

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Contributions from seismic interferometry to the knowledge of Andean volcanoes: the cases of Planchon- Peteroa (Argentina-Chile) and Cuicocha (Ecuador)

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Several of the main reasons for which understanding and forecasting volcanoes were historically hardly achieved are incomplete knowledge of volcano dynamics, subsurface structures, and timescale variations of internal processes. This work shows the application of three methodologies based on seismic interferometry (SI) to seismic data recorded around two poorly-understood Andean volcanoes, i.e., Peteroa and Cuicocha volcanoes.

Peteroa, the current active volcano of the Planchon-Peteroa Volcanic Complex, is located along the Argentina-Chile boundary. Peteroa has had approximately twenty eruptive events (with VEI<4), the latest occurring in 2010 and 2011. We used seismic data recorded in 2012 by nine seismic stations (six in Argentina and three in Chile). Using seismic events located close to the stations, we applied SI based on autocorrelations to estimate the depth of the main subsurface structures below each of these stations down to ~4 km depth. We also used the recorded ambient seismic noise to perform a tomography using retrieved ballistic surface waves on the eastern flank of Peteroa, and to provide S-wave velocity profiles down to ~400 m depth.

The Cuicocha is the only active volcano of the Cotacachi-Cuicocha Volcanic Complex (Ecuador). At present, one of the main hazards of the Cuicocha is the development of potentially destructive lahars, provided the amount of water contained in its crater lake. We used seismic data recorded by four seismic stations located within 7 km from the volcano. Using SI, we monitored the seismic-velocity changes that occurred between May 2011 and January 2016, which we then correlated to their likely physical sources.

Our results contribute to the knowledge and understanding of Peteroa and Cuicocha volcanoes. This information is expected to be used by studies preceding risk analysis and hazard-assessment investigations. Our results also reinforce that SI could be a powerful tool for automated volcano monitoring, thus aiding forecasts.

S01.40 Poster

The VULCAN.ears project: an Esperanto for the volcano-seismic event recognition as a portable tool for real-time monitoring and eruption forecasting

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The increase of the seismic activity of volcanoes is still the most reliable precursor used for Eruption Forecasting and Early Warning Systems (EWSs). In order to discriminate precursory seismic patterns it is necessary a) to detect relevant events and b) to assign them to classes according to their physical origin, in a process called labeling or classification. While volcano monitoring (VM) centers and EWSs demand real-time operation, manual classification carried out by experts is a time-consuming and not always reliable task, often resulting in the impossibility to properly analyze the seismic evolution during crises.

The aim of the EU-funded *VULCAN.ears* project (*Volcano-seismic Unsupervised Labelling and ClAssificatioN Embedded in A Real-time Scenario*) is to build an automatic Volcano Seismic Recognition (VSR) system designed to detect and classify signals in unsupervised scenarios (without having any prior knowledge of the signals to recognize), and portable enough to be easily integrated into any monitoring system. The system is based on state-of- the-art VSR technologies, using a structured modeling via Hidden Markov Models (HMMs) and a parallel approach (Parallel System Architecture, PSA-VSR) composed of specialized channels, each designed to recognize events of a single class from continuous data streams.

- Relevant advances have been achieved towards real-time, unsupervised VSR:
- Design of a GUI front-end (*geoStudio*) to easily integrate the automatic VSR into VM centers and EWSs.
- Efficient description of events via robust feature selection in PSA-VSR systems, increasing the recognition class accuracy by more than 40% compared to usual serial VSR (SSA-VSR).
- Joint databases built from several volcanoes allow the building of general models able to classify events from other volcanoes.
- The automatic classification of volcano-seismic events improves the success of prediction approaches, such as the material Failure Forecast Method, when applied to the most relevant event class(es).

S01.40 Talk

Surface Deformation and Source Model at Semisopochnoi Volcano from InSAR and Seismic Analysis During the 2014 and 2015 Seismic Swarms

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Semisopochnoi volcano in the western Aleutian Islands has been in a state of quiescence for over a century, but in the summer of 2014 and early spring of 2015 two microseismic swarms were recorded on Semisopochnoi and neighboring islands. Neither swarm resulted in any evidence of an eruption. This study employs differential SAR techniques using TerraSAR-X images to observe surface deformation from 2011-2015. The interferograms provide evidence of island wide radial inflation, totaling ~25 cm over two years. Multiple source geometries are used in the inversion of this deformation data to define the best fit parameters as a spheroid with a major axis of ~3.5 km and minor axes of ~1.5 km under the central caldera of Semisopochnoi. In 2014 an influx of 0.041 km^3 of magma caused deformation of ~17 cm. This magma was stored at depths of ~7.3 km, until, in 2015 an additional 0.024 km^3 was added, reaching depths as shallow as 5.7 km. In conjunction with this definition of inflation source parameters, the recorded seismic events are relocated using differential travel times. These relocated events outline a linear seismic void within a larger group of shallow (<10 km) seismicity. This aseismic region aligns with the centroid of the deformation model. A conceptual model of a spheroidal magma storage at a depth of ~7 km is interpreted to be below a linear feature of partial mush that receives additional magma, heat, and pressure as the main storage experiences an influx of material from depth.

S01.40 Poster

New evidences on the structure of Popocatepelt volcano using aeromagnetic data

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Popocatepelt is one of the most active volcanoes in Mexico and located in the central part of the Trans-Mexican Neovolcanic Belt. Because of its proximity of Mexico City this strato- volcano with an eruptive history of thousands of years and recent activity since the 90s. Since the area is heavily populated it represents high risk.

The volcano has been studied geologically and the activityia being monitored but, relatively few geophysical studies have been carried out. The use of potential fields is very useful in obtaining information about the structure of volcanic edifices and tectonics. We present the first results of the analysis and processing performed on an aeromagnetic survey carried out in 1977, with a height flight at 5000 m. The reference geomagnetic field (IGRF) had been removed. In this presentation, numerical techniques were applied to process and analyze the aeromagnetic data.

The analysis of an aeromagnetic survey supported by geological data sheds new light on the structure of the Popocatepetl volcano and surroundings in the central sector of the Mexican Volcanic Belt.

Among several structures, the alignment of NE-SW vents which intersects the crater is clearly defined.

S01.40 Poster

Mt. Etna feeding system: a new 3D image constrained by earthquakes distribution and 3D modelling analysis in a customizable GIS

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Imaging the interior of a volcano is crucial step to model its dynamics and develop an efficient eruption forecasting strategy. High-resolution seismic image models of the interior of the volcanoes, usually based on tomographic methods, make possible to image the shape and locate possible lava ascending paths, shallow magma chambers and areas of flank collapse. Here, we model the lava ascending path and feeding systems of Mt. Etna (Sicily, Italy) using the Marching Cubes algorithm (MC), usually applied to medical visualization and 3D modelling, combined with 16 years of earthquake localization data.
The analysis in the framework of a novel volcano-oriented GIS environment (VolGIS) offers the possibility to develop numerical tridimensional model improving the interpretation thanks to both the high visualization resolution and the known exact geolocalization.
The results show a high-resolution 3D model of the feeding system of Mt. Etna, interpreted as a ductile realm surrounded by a fragile one.
In particular, the model: (1) highlights the plumbing system in a depth span between 1 km and 6 km b.s.l., increasing the detail of structures previous imaged by deep seismic tomography; (2) suggest new evidence behind the eastern flank instability; and (3) it is compatible with published models of the conduit structure. We infer that the Marching Cubes algorithm, applied to those volcanoes with high seismicity, may improve considerably the ability of the user to obtain a preliminary imaging of the main feeding system reducing time cost and helping interpretation on common seismic tomography.

Under Pressure:
How does Crustal Rheology Influence the Interpretation of Volcanic Unrest?

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Worldwide, there are numerous caldera systems undergoing active deformation, including Campi Flegrei, Rabaul and the Taupo Volcanic Zone. Recently observed non-eruptive inflation and deflation episodes raise the fundamental question of whether this deformation represents individual phases of an active magmatic system undergoing unrest or, instead, are driven by a combination of post-eruptive and tectonic processes. Here, our investigations are concentrated on the Taupo Volcanic Zone, a region dominated by a significant thermal regime, a product of an extensive, rifting-induced magmatic plumbing system.

Whilst episodes of deformation are readily identifiable within geodetic timeseries, the underlying processes facilitating this deformation are more enigmatic. From these signals, the ultimate aim is to infer source characteristics, namely the size, overpressure and, potentially, the magma fluxes involved. Traditionally, these parameters are estimated, using simple, elastic models. Recent geodetic models employ viscoelastic rheologies, accounting for the elevated crustal temperatures and thermal regimes typically induced by long-lived magmatic systems. These studies highlight a tendency for elastic models to significantly overestimate the volume of magma or overpressure involved in an episode of unrest.

Our research presents a novel comparison of viscoelastic representations. We construct a series of models to investigate the relationship between best-fit source parameters and the resultant deformation timeseries for the Maxwell, Kelvin-Voigt and Standard Linear Solid viscoelastic configurations. By utilising a model with uniform, geologically-reasonable parameters and reversible pressure conditions, we observe that the choice of viscoelastic rheology can amplify the surface deformation of elastic models by up to a factor of 8. Further to this, we demonstrate that a Standard Linear Solid viscoelastic model can suitably reproduce a reversible deformation timeseries, classically attributed to elastic rheologies and unrealistic overpressures. Ultimately, our results emphasise how different crustal rheologies influence the interpretation of source pressure, and hence the classification and significance, of unrest episodes.

S01.40 Talk

Decoupling the volcano infrasound source from the crater acoustic response

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Volcano infrasound is an important component of multi-disciplinary volcano geophysics and has proven utility for tracking eruptive activity and quantifying eruption dynamics. Unfortunately, a major limitation in our interpretation of volcano infrasound is that it is critically affected by the morphology of the volcanic crater, which can transform potentially simple source-time functions occurring within the crater into a signal that is substantially more complex. If infrasound waveforms are to be used to recover important physical parameters about an eruption source, then a robust understanding of the acoustic response of the crater is required. In many cases, and especially for large deep craters, the acoustic response function acts as a severe filter. For example, at Cotopaxi Volcano (Ecuador) infrasound 'tornillos' with an impulsive onset and peaked spectra at 0.2 Hz decaying for more than 90 s are part of the source response due to the crater's steep-walled, deep crater.

We analyze broadband infrasound data from open-vent volcanoes with a wide variety of crater geometries and jointly calculate their crater acoustic response using 1-D (axisymmetric) and 3-D morphologies derived from structure-from-motion digital terrain models. We analyze both explosion and lava lake infrasound from Villarrica (Chile), Stromboli (Italy), and Nyiragongo (Democratic Republic of the Congo) to demonstrate a broad spectrum of volcano infrasound, whose attributes are heavily influenced by crater shape. We demonstrate how some differences between simulations and recorded explosion are influenced by source-time functions, which may range from brief and impulsive to complicated or extended in time. Numerical modeling shows that each volcanic crater has a unique impulse response and that deconvolving this acoustic response is vital for estimating important eruption parameters including the size of volcanic explosions.

Observation and preliminary analysis of drumbeat seismicity at Turrialba volcano, Costa Rica

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Many source models have been proposed to explain the large variety of seismo-volcanic events observed before and during eruptions. However the mechanism of most volcanic earthquakes is not yet well understood. In particular, the differences and relationships between the physical processes associated with VT, LP, and hybrid events and volcanic tremor are not well defined. The observation and analysis of drumbeat seismicity, which has common features with the types of event mentioned above, can contribute to the understanding of volcanic systems and associated seismic activity.

After 150 years of quiescence, Turrialba volcano presented increasing fumarolic activity since 1996 and produced some phreatic eruptions in 2010. After that and until now, the strato-volcano produced intermittent ash emissions and small explosions. Its seismic activity includes mainly LP and VLP events and episodes of volcanic tremor. Three short sequences of drumbeat activity have been recorded in 2013, 2017, and 2018. The clearest episode occurred on 27 January, 2018 from 03:00 to 05:45 TU. It was composed of about 600 small earthquakes with remarkably similar waveforms but with varying amplitudes. Most inter- event intervals lasted 6 to 10 seconds and their values slightly increased in average during the episode. The spectral energy of these events was concentrated in the range 2-14 Hz. No significant changes in the surface eruptive activity was observed during the drumbeat sequences. We will present here the first results of the analysis of this phenomenon.

S01.40 Poster

Investigating large-scale change in seismic time-series data using machine learning analysis

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Understanding changes in activity is a key aim of volcano monitoring. Transitions between eruptive and non-eruptive volcanic behaviour are often marked by change-points in a dataset. However, identifying change-points in this ever-various observational time series (such as seismicity, geodesy and gas measurements) can be problematic. Moreover, the waning stages of volcanic activity are often harder to observe, as the gradient of change can be more gradual. It can also be difficult to distinguish a break in eruption from the end of eruption.

Machine learning algorithms can be used to recognise the timing of changes in large and noisy datasets. Moreover, machine learning approaches have been demonstrated in the field of healthcare to recognise patterns in data which traditional analytical methods are unable to detect. Application of these approaches in volcanology is currently an emerging field. Machine learning therefore represents an important tool for identifying when the pattern of seismic activity critically changes at the onset and end of volcanic activity.

We apply machine learning methods - including support vector machine and logistic regression - to seismic time-series datasets which span multiple eruptive periods. These datasets contrast persistently restless behaviour at Telica volcano in Nicaragua and the sporadically explosive activity at Nevado del Ruiz volcano in Colombia. We use eruption classifications from the Global Volcanism Program to develop supervised learning models, and observe the timing of changes in the datasets, relative to the changes recorded in global catalogues based on observational definitions, with a focus on identifying the end of volcanic eruptions.

S01.40 Poster

Automatic P- and S- phase picking: an insight to Planchón-Peteroa volcano-tectonic earthquakes.

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The correct picking of the P and S phase arrival for volcano-tectonic earthquakes provides useful insight to the inside of the volcano. These seismic events are induced by the interaction between magma injection (or withdrawal) and the host rock related to the plumbing system of the volcano. Due to the nature of these events, their phase detection is more challenging than in the case of tectonic earthquakes. In particular, the S phase recognition is very tricky because this phase is often weak and emergent, overlapped with the preceding P coda and mixed with S to P conversions.

In this work we present a P- and S- phase picking analysis performed on a representative set of volcano-tectonic earthquakes acquired from the Planchon-Peteroa Volcanic Complex (PPVC), during 2012 time interval after the occurrence of important phreato-magmatic activities. The analysis has been performed using state-of-the-art automatic picking algorithms. P- phase has been picked using an automatic algorithm based on adaptive multiband processing and noise reduction techniques. Based on the automatic P- onset detection, S- phase has been picked using an automatic algorithm based on a windowed analysis of spectral dissimilarities in the time interval when S-phase is expected. Through this advantage data processing, interesting results on the sources position of the PPVC volcano-tectonic signals have been obtained, and we are confident that the employment of the algorithm presented in this work can contribute to improve our ability to successfully forecast the evolution of the eruptive activity at PPVC that is the second most dangerous volcano in Argentina.

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S01.40 Poster

Statistical Analysis of Infrasound Signals and Eruption Forecasting at Reventador Volcano (Ecuador)

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Infrasound monitoring is one of the most effective tools for tracking explosive volcanic activity. Infrasound has been increasingly used for scientific study and for eruption monitoring during the last few decades. Long time span infrasound data collection has led to robust records of explosion occurrence and eruptive cycles, which is particularly well suited for statistical analysis. Here, we demonstrate that long-term chronologies derived from infrasound corroborate seismic and video data and provide insights into the activity of Reventador volcano (Ecuador).

Since early 2015, infrasound data have been collected by two infrasound arrays located on the northeast and southeast flanks of Reventador at about 8 km from its summit. Coherence analysis is used to accurately detect volcanic infrasound and identify eruptions, quantify their duration and intensity, and derive repose intervals (time between eruptions). Over the multi-year record we detect about 95 events per day with mean duration of 18 s. We find that repose intervals fit Weibull distributions (rather than log-logistic distributions) suggesting that Reventador's degassing follows a classic failure model. Further, we recognize and characterize two different periods of activity that follow distinct Weibull distributions with mean repose intervals of 15.6 and 8.2 minutes. The first period is from January 2015 until early August 2015 when Reventador activity is dominated by explosive behavior and then transitions into a second period with a combined effusive and explosive behavior and the opening of a new vent. This transition between the two modes of activity helps us to better understand how the shape and scale parameters on a Weibull distribution are related to the increased magma supply evident during the second period.

On the relevance of microgravity measurements in the detection of active, shallow magmatic systems

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Many volcanic systems are characterized by the existence of one or more shallow, relatively small reservoirs periodically receiving batches of less chemically evolved, volatile-rich magma from larger and deeper reservoirs. Unfortunately, detecting the presence of such shallow magmatic bodies is not necessarily simple and straightforward, mainly because they can be smaller than the resolution allowed by geophysical inspection techniques. We show here, through numerical simulations of the transient dynamics of magma recharge, convection and mixing in multiple magma chamber systems, as well as simulation of the associated geophysical signals as they would be recorded at the surface, that ground displacement measurements alone may completely miss the detection of the shallow magmatic system, highlighting instead only the deep magmatic system. By contrast, microgravity changes are mostly sensitive to the shallow system where mass displacements and expansion of volatiles are more effective. We propose, therefore, that the vertical separation between the inverted source from ground displacement and microgravity signals is diagnostic of a composite, multi-chamber magmatic system undergoing periodic convection and mixing dynamics; and that the association of ground displacement and microgravity measurements is a powerful tool to detect the existence of relatively small magma bodies intruded at shallow depth and periodically refilled by magma with deeper provenance.

S01.40 Poster

Towards remote estimation of volcanic plume source parameters from regional infrasound arrays

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Infrasound has been used to estimate source parameters like eruption time, number of explosions, duration, and plume height using location stations. This technique has rarely been used at distances over 10s of km, and this project aims to explore the potential for using regional infrasound to retrieve the same parameters. Two case studies are used: one with local infrasound using established methods, and one at regional distances combining these methods with atmospheric modeling of the infrasound propagation. In May 2018 there were two eruptions at Marapi volcano in Sumatra in Indonesia, which were recorded with the local infrasound network. The second and larger eruption occurred during daylight hours and into a relatively clear sky making other measurements of plume height and visual confirmation of eruption time possible. This event can be characterized with multiple datasets which can be compared to the infrasound results. In 2014 Sangean Api erupted after a long period of quiescence, and this eruption was clearly recorded on several of the International Monitoring System (IMS) infrasound arrays in the region at thousands of kilometers distance. Remote sensing of the eruption plume has also been studied and the known plume height can be compared to a plume height derived from the regional infrasound using a combination of the methods used at a local network, with atmospheric modeling. With a high fraction of cloud cover in SE Asia, infrasound could be a valuable addition to the operational tools currently in use to augment satellite and local networks.

Advanced time-series processing techniques of thermal infrared images acquired by the permanent IR surveillance network of INGV - Osservatorio Vesuviano at Campi Flegrei and Vesuvius (Italy)

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The permanent Thermal InfraRed surveillance Network (TIRNet) of INGV - Osservatorio Vesuviano acquires at night time IR scenes of diffuse degassing areas in Campi Flegrei caldera and at the Vesuvius crater (Italy). The IR images are daily processed by the automated system of IR analysis (ASIRA) and the results are displayed in the Surveillance Room of Osservatorio Vesuviano.

The first development of ASIRA (Automated System of InfraRed Analysis) software was aimed to characterize the spatio-temporal evolution of the thermal features in the monitored areas giving also basic automated procedure. Since this first versions some of the peculiar steps were implemented such as a quality selection of IR scenes and the accurate co- registration of the IR scenes of the whole image time-series.

In the last years the processing methods have become more sophisticated and ASIRA (at version 4.2) now is based on a complex automated processing chain conceived to deepen the knowledge of the surface temperatures field evolution of studied diffuse degassing areas.

In ASIRA 4.2 the spatial alignment of the scenes was enhanced by applying the SIFTflow Matlab algorithm. Moreover, a significant improvement in the seasonal component removal was realized by applying the STL algorithm (Seasonal Decomposition of Time Series by Loess), developed in R statistical computing language, which splits the time-series of the raw temperature values of every pixel into three components: the trend, the seasonality and the remainder. By removing seasonality to every pixel, it is possible to estimate the global radiated thermal flux affecting an area and to produce maps of yearly rate of temperature change of the IR scene

These type of elaborations make better use of the high information content of IR image data time-series providing useful information toward refining physical and conceptual models, as well as improving surveillance of active volcanoes.

S01.40 Poster

Tracking rockfalls and landslides in real- time at Stromboli volcano

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Flank instability is one of the early phenomena often associated to ground deformation preceding volcanic eruption. In general, this is triggering an increase in the rockfalls and landslides occurrence which in case of volcanic islands it could potentially trigger tsunami waves. The most recent occurred during 2002 eruption of Stromboli volcano, when a tsunami wave was triggered by a partial collapse of the Sciara del Fuoco NW flank. Hence, the detection of rockfalls and landslides on a volcano represents an issue for any monitoring system and could be identified by their seismic signature. We developed an automatic landslides detection algorithm based on a multi-frequency analysis and waveform pattern recognition, which is capable of extracting signals associated with rockfalls and landslides out of the signals associated to volcanic and tectonic process. The method was applied to the last two effusive eruptions occurred at Stromboli in 2007 and 2014 and shows a strong correlation between rockfalls episodes and volcanic activity. Gravitational instability increases during the pre-eruptive phase until the effusive onset, and suddenly stopped when the lava flow gets started. This behavior, compared with other geophysical data, appear to be linked with the progressive deformation of the volcano edifice, and give us a further element to investigate the physical processes under the eruptive phases at Stromboli volcano. The comparison of the results of our algorithm with a dedicated visible-camera, shows that the algorithm is detecting in real-time and automatically most of the landslides with less than 4% of false positive alerts. Finally, we show how the developed system could be efficiently inserted in a multiparametric monitoring network, and it may provide a key tool to support a prompt risk assessment and a tsunami early-warning system, that could be vital in active volcanic island.

S01.40 Poster

Optimizing detection capabilities of remote infrasound network in Southeast Asia in a context of timely automated volcano early warning

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Volcanic eruptions are a threat to nearby communities but also to air traffic, especially in Southeast Asia where 70% of the global volcanic hazard is. Prior work has focused on accurately assessing the detection capability of the infrasound network in the region. The method we developed allows us to predict the attenuation and the minimum detectable source amplitude with a confidence index taking into account the uncertainties related to propagation and atmospheric models.

By simulating the performances of the infrasound network in Southeast Asia, it is then possible to define the optimal configuration of the network to monitor a specific area of the region, during a given period. First, we quantify the contribution of adding one station to the existing infrasound network. Then, we propose a method to retrieve the best location where to add at least one station. We discuss either we should complement the network one station at a time, or simultaneously. Furthermore, we include in our research method the probability of eruption, as we don't want to optimize the infrasound network to better monitor all the volcanoes in Southeast Asia, but instead we want to focus on the monitoring of volcanoes with a high probability of eruption.

This optimization work will help us to decide a strategic location to add a station to the existing infrasound network. In a context of volcano early warning, such work will help us to automatically send alerts on shorter timescales and thus prevent eruption disaster, especially on air traffic.

S01.40 Poster

Sea-level oscillations and Ground Displacements by means of Tide Gauge Network: Neapolitan volcanic area case study

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Osservatorio Vesuviano (OV), branch of Istituto Nazionale di Geofisica e Vulcanologia, is in charge of the surveillance monitoring of the Campanian volcanic areas (Southern Italy). OV manages an integrated monitoring system at Neapolitan Volcanic area, where three active volcanoes (Somma-Vesuvio, Campi Flegrei caldera and Ischia Island) are located.

This work is a contribution to the integrated evaluation of the ground deformations in volcanic area starting from Tide Gauge measurements, the first kind of signal recorded continuously in Neapolitan volcanic area to assess vertical ground displacements.

We investigate the water-level oscillations collected at the tide gauges located in Gulfs of Pozzuoli and Naples spanning the period from May 1999 to December 2017, over 18 years. Harmonic analysis has been performed on yearly time series, with sampling of 1 hour, considering the seven major tidal constituents, four major semidiurnal (M2, S2, N2, K2) and three major diurnal (K1, O1, P1).

The residual respect to the astronomical tide contains information about meteorological component, eustatic variation, ground deformation and noise. The residual sea level variation, for each site, can be represented by two terms: sea level background and local sea level variations due to noise, site effects and ground deformation. Removing, by deconvolution, the differential behaviour of the sea-level respect to a reference station, provide an estimation of the ground level variation. The results have been compared with the results of levelling and GPS analysis. Beyond the study of the ground displacements, we also evaluate the response of the two basins, Gulf of Naples and Gulf of Pozzuoli, through the amplitudes of the tidal components obtained at each station of the network. Concluding, we discuss the obtained results taking in account the conceptual models present in literature.

Recurrent Neural Networks as Automatic Volcano-Seismic Recognition Systems in real-time

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Based on the pioneering studies conducted in the first half of the 20th century, the volcanic seismology has emerged, as one of the basic pillars for prediction and forecasting volcanic risk. Volcanic activity and its interactions with the environment give rise to a range of physical processes (such as fracturing rocks, escape of pressurized gases or ground deformation) that can be monitored. As a result, seismographs can register a wide range of volcano-seismic signals that reflect the nature and underlying physics of the source process. However, in order to improve our knowledge about the state of the volcano, to analyze the incoming information in real time and to identify the active sources of emission involves a strenuous and time-consuming effort.
In this research, we propose a new classification framework to detect and classify real time sequences of volcano-seismic records based on Recurrent Neural Networks. We aim to determine the robustness of these architectures as classifiers and we explore their relative generalization properties despite the change in geophysical properties across eruptive periods. We evaluate classification performance on five different seismic events registered at Deception Island (Antarctica) for different seismic campaigns. Attained results expands the possibilities of RNN for real-time monitoring of volcanic activity, even if seismic sources change over time.
Work supported by Research Project TEC2015-814 68752 (MINECO/FEDER), by European Unions Horizon 2020 Research and innovation programme under the Marie Sklodowska-Curie grant agreement No 798480.

S01.40 Talk

Deformation time-series integrated with multidisciplinary data to constrain source processes: Evidence of magma recharge at Colli Albani, the volcanic district at the gates of Rome (Italy)

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Colli Albani (CA), Italy, is amvolcanic district located 20 km SE of Rome (3 M inhabitants) and lastly erupted 36 ka ago. Since the modern volcanic activity at Colli Albani seems not particularly intense, scientists have interpreted this volcano to be quiescent. Therefore, unlike other Italian volcanoes, the area has not undergone extensive monitoring. However, a seismic swarm during 1989-1990 has been related to a local uplift of ca. 30 cm since the 1950's along the western side of the volcano, giving rise to a debate about its possible interpretation in terms of unrest. We investigate the deformation processes at CA from the analysis of about 20 years of InSAR data (1992-2010). Time-series show long-term, constant rate, uplift of its western and southern flanks, and intra-caldera subsidence. This deformation setting cannot be related to a single cause, but reflects the interaction between different and spatially independent dynamic processes. Gas geochemistry (He, CO_2 and their isotopic ratios) data was analysed in order to obtain information on the nature of the sources. The changes in the isotopic composition of the discharging CO_2 and helium indicates that the CA dynamics is the result of decoupling between magma intrusion along pre-existing tectonic faults and the inner caldera. In order to design a comprehensive geophysical model inclusive of all the above reported peculiarities, we consider potential sources related to magma/fluid migration or accumulation processes at depth through the main tectonic structures active at CA, by means of a numerical model. In summary, we demonstrate that despite the present-day phase of caldera deflation, the magmatic system at CA is in a rejuvenation stage and new, articulated dike-like magma storage zones are slowly forming below the western and southern flanks, with direct consequences for the volcanic hazard assessment at Rome.

Linking volcano infrasound observations with source processes: comparing analytical models with computational fluid dynamics simulations

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Volcanic activity frequently generates low frequency acoustic waves in the atmosphere, typically below the audible frequency range and hence termed infrasound. Volcano infrasound observations have proven to be useful for remote monitoring of volcanoes and can provide insight to eruption physics.

Woulff and McGetchin (1976) considered acoustic recordings from fumaroles at Volcan Acatenango, Guatemala. They developed analytical expressions, based upon multi-pole expansions e.g., monopole, dipole, quadrupole sources, linking the observed acoustic power to the exit velocity at the volcanic vent. These relationships have been widely adopted by the volcano infrasound community and are commonly used to estimate eruption properties, such as erupted volume and plume height. However, considerable debate remains about which source description is the most appropriate in various eruption scenarios. In addition, there is a growing realization that shock waves and other near-source nonlinear effects may strongly influence the observed infrasound and hence bias estimates of eruption properties that are calculated assuming linear acoustic wave propagation. Furthermore, entrainment of atmospheric air into the erupted material may introduce complexity that is not accounted for by the analytical models.

Here, we discuss how computational fluid dynamics (CFD) aero-acoustic simulations can be used to investigate the applicability of the various multi-pole source models to different scenarios of eruptive activity. We focus on short-period eruptions (vulcanian or strombolian- style). We consider the effect of mass discharge rate, source overpressure and depressurization time scale on the observed infrasound signal and on the agreement between the linear acoustic analytical models and the nonlinear CFD simulations that can account for shock wave propagation.

S01.40 Talk

Automated alarms at the Alaska Volcano Observatory

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Many volcano observatories around the world are not staffed continuously. As a result, automated alarms based on geophysical and remote sensing data play a critical role in the rapid detection and characterization of eruptions. This is particularly true for volcanoes lacking local instrumentation or eruptions with limited precursory activity. Here we outline the framework for alarming and alerting developed at the Alaska Volcano Observatory (AVO) and demonstrate its utility during the 2016–2017 eruption of Bogoslof, an un-instrumented volcano in the Bering Sea. All AVO-based alarms are written in Python and were developed internally by AVO research staff. Alarms are centrally managed on a dedicated alarms server, which handles alarms scheduling, data processing and message dissemination. Alerts are delivered via text message to recipients determined by a centrally managed distribution list, as well as to AVO's internal chat tool for observatory-wide access and situational awareness. Triggered alarms also generate images of recent data, which are included in the alert message to contextualize information and facilitate rapid confirmation of volcanic activity. AVO uses Icinga, an open-source network monitoring application, to monitor the individual alarm modules themselves and, effectively, alarm the alarms. Upon completion and regardless of detection, each alarm algorithm sends a heartbeat message to Icinga, which resides on a separate computer system and will itself send alerts via a separate messaging system if heartbeats are missed. Currently this framework applies to seismic, infrasound and lightning alarms, but AVO also receives remote sensing alerts from the National Oceanic (NOAA-NESDIS/CIMSS). A future goal is to assimilate such alerts into AVO’s system and contextualize them with local geophysical data. Together with infrasound and lightning, these alarms provide regional coverage for unexpected or remote activity, and the modular implementation allows AVO to quickly augment them with additional alarm algorithms during ongoing eruption responses.

S01.40 Poster

Integrating time-dependent data at Mount St. Helens (2004-2008) using physics-based conduit models

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Traditional kinematic inversions of deformation data from GPS and InSAR reveal some fundamental information about the magma chamber, but offer limited insight into the physical processes governing magma flow. Previous work by Anderson and Segall [2013] developed a physics-based model of magma ascent in dome-forming eruptions, and employed this model in geodetic inversions to improve constraints on ambiguous parameters, including initial water content and magma chamber volume. We have extended this 1D conduit model to include equilibrium crystallization, as well as vertical and lateral gas escape. Excess pressure in the magma chamber drives Newtonian flow until viscous resistance to flow exceeds rate-dependent frictional strength on the conduit wall, at which point viscous flow naturally transitions to plug flow. Crystallization and gas escape are critical for effusive eruptions because they strongly affect viscosity and thus plug formation depth. We first investigated steady-state solutions and applied the model in a Bayesian inversion incorporating diverse time-independent data from the 2004-2008 Mount St. Helens eruption, including 1) dome rock porosity estimated from hand samples, 2) extrusion rate from photogrammetry, 3) plug depth from the maximum depth of drumbeat earthquakes, and 4) crystallization pressure from petrologic data. We subsequently advanced the model beyond steady state to study transient effects in a 1D chamber-conduit system. As eruption velocity decreases, gas escape becomes more important particularly at shallow depth, which greatly retards flow and could explain how an eruption might end. These conduit processes influence the magma chamber depressurization rate and thus the surface deformation change through time. Since the physics-based model simulates the entire magma ascent process from chamber to surface, we can further extend model results to compare with other time-dependent data, including extrusion flux and gas emissions. Future work will apply this physics-based model in Bayesian inversions to rigorously constrain magmatic system parameters.

S01.40 Talk

Geodetic image of a low viscosity zone beneath the Kutcharo caldera, eastern Hokkaido, Japan

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In order to correlate geodetically observed volcano deformation with magmatic activity the presence of a magma has usually been considered as a deformation source. From rheological point of view, however, a magma chamber and its influenced peripheral rocks should be capturable as a zone that has rheologically less strength. It is therefore interesting to reveal the presence of a rheologically weak domain, and its spatial extent, beneath volcanic active region. In this study, we employ a 3-D finite element model, that an uppermost elastic layer is underlain by a viscoelastic layer, in order to examine the response of the linear Maxwell viscoelastic crust to the emplacement of a sill in the uppermost crust, for which a first-ordered spatial viscosity variation, i.e., a rectangular parallelepiped low viscosity zone (LVZ), is introduced into relatively high viscosity crust. The InSAR data in the Kutcharo caldera, eastern Hokkaido, Japan, is analysed in terms of predicted viscoelastic behaviour, particularly paying our attention to the LOS displacement change at the deformation centre. LVZ is found to have a spatially invariable viscosity of ~4-5x10^17 Pa s, and to be present immediately below a 5km elastic layer down to the middle to lower viscoelastic crust, with a horizontal extent of ~ 10 km or more. Such a LVZ model confirms the overall deformation field to be reasonably well explained. We consider LVZ as the representation of magmatic influence, providing an important mechanical aspect on geophysically imaged crustal structure beneath the caldera. Our results suggest that the presence of a magma is detectable from the surface deformation after a magmatic emplacement into the uppermost crust, in which the deformation rate reflects the degree of magmatic influence.

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S01.42 - The role of the GEO-GSNL initiative and of Integrated research infrastructures in improving the knowledge of volcano dynamics and hazard

TSDSystem: the multidisciplinary INGV- OE database

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The multiparametric approach by joint monitoring of volcanological, geophysical and geochemical data is the winning strategy to detect and investigate volcanic unrest phases and forecast the eruptions. The increasing interest devoted to the study of volcanological phenomena led the constitution of different research organizations and observatories, also relative to the same volcanoes, acquiring large amounts of data from sensor networks, which needs to be properly organized to be shared and used in volcano research and monitoring. To face these requirements, we developed a framework called TSDSystem (Time Series Database System), representing the official database of INGV - Osservatorio Etneo. Such a framework allows acquiring time series from different data sources, standardizing them within a relational database. Standardization provides the ability to perform operations, such as query and visualization, of many measures synchronizing them by using a common time scale. Each data source refers to one or multiple stations and to a particular geospatial location, whose information is stored in a separated database, the TSDSystem "spatial extension", which collects spatial data in a common GIS for data sharing and visualization. To manage data, we perform a smart partitioning table strategy that keeps the percentage of data stored in each database table balanced.
The proposed architecture follows a multiple layer paradigm (Loaders layer, Business Logic layer and Database layer), allowing the following features/services:

- Reading data coming from different data sources;
- RESTful web service implementation for submitting and querying data;
- Multiparametric station management;
- Multiparametric time series data synchronization;
- Real-time and near real-time data visualization using web application;
- Geospatial data retrieving using WMS, WFS and WCS;
- "Master View" application for sharing data between different TSDSystem instances;
- Data policy management;
- Early warning module.

Ten years of the National Network for Volcano Surveillance in Chile: achievements and challenges

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The National Volcano Surveillance Network in Chile was created in 2009 after the unexpected rhyolitic eruption of the Chaitén volcano, in Southern Chile. At that time the volcano was not monitored and little was known about its past geologic activity, although an important town in the Chilean Patagonia was located at only 10 km from the volcano. As a consequence of the rapid hazard assessments done by Sernageomin, national authorities decided within days to a full evacuation of the residents near the volcano. The eruption finished at the beginning of 2010.

After the eruption of Chaitén, the Geological Survey of Chile (Sernageomin) created the National Network for Volcanic Surveillance, which is monitoring the most active volcanoes in the country (45 in total). Along with the network set up, geological studies have been done in order to develop geological studies and the publication of volcano hazard and geological maps. In the last decades, several volcanic eruptions have occurred in the Andean Central and Southern Volcanic Zones, which have affected regions in both Chile and Argentina.

One of the main goals of this network is the establishment of an effective communication of the monitoring status and the geology of the active volcanoes in Chile oriented to both decision-makers and local residents. This is done through periodic reports in the web and social media as well as outreach activities such as “Ferias Volcánicas” in places where communities are more exposed to volcanism. These activities, along with the experience gained in the last decade, will be addressed in this contribution.

S01.42 Talk

Virunga Supersite: implementation status, preliminary results and future challenges

Charles M. Balagizi[1] and Virunga Supersite supporting scientists and agencies

Goma Volcano Observatory, Democratic Republic of Congo

The Virunga is the first Supersite established on the African continent. This supersite was approved at the CEOS Plenary 31 (October 19th-20th, 2017) following the positive evaluation of a proposal put forward by the Goma Volcano Observatory (GVO) and that was sponsored by a large number of top-level scientists and agencies. The Virunga Supersite covers a large area that includes the Virunga volcanoes and Lake Kivu zones, which are Multi-Geohazards and densely populated regions (home for ~3 million inhabitants). The first results include: (1) the Copernicus successfully activated risk analyses with a focus on volcanic hazard, and produced Very Highly accurate DEM to simulate lava flow pathways for future eruptions management; (2) field data were acquired for Risk and Recovery mapping of Virunga volcanoes; (3) the CEOS supports the Virunga Supersite with COSMO-Skymed and Pleiades data free of charge; and (4) the first thorough natural hazards assessment in the Virunga and Lake Kivu region. The future changes are mainly with regards to (1) GVO's resources and capacities for EO data continuous analysis for volcano monitoring, and (2) ground based data acquisition and analysis. Contacts are being made for solving the first issue in the short term through international collaboration, however in the mid-term the GVO needs to become independent by acquiring the necessary training, skills and experience. A project has been written in collaboration with Virunga Supersite Core Team, and it aims at seeking funds to support the achievement of the following objectives of the Virunga Supersite: natural hazard, vulnerability and risk assessment; setting up a multisensory real time monitoring network, capacity building of local scientists, and carry out research activities to allow the understanding of the volcanic and lake systems. These are expected to increase the early warning capacity of the GVO.

Observing Volcano Deformation with Ecuadorian Volcano Supersite SAR Imagery and Future Applications

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Since initiation three years ago the Ecuadorian Volcano Supersite, as approved by the Geohazard Supersite and Natural Laboratory Initiative (GSNL) has provided InSAR time series for analysis which has aided in monitoring 5 Ecuadorian volcanoes. Specifically imagery from the satellite systems Sentinel-1 of the European Space Agency, TerraSAR-X of the German Aerospace Agency and COSMO-SkyMed of the Italian Space Agency were taken over consecutive time periods and corroborated unrest and ground displacements at Cayambe, Chiles, Cotopaxi, Guagua Pichincha and Revantador volcanoes. In 2015 unrest/eruptions at Cotopaxi were preceded by both horizontal and vertical displacements detected by InSAR time series that coincided with GPS measurements on the flanks. We hypothesize that the 7.8 M*w* subduction zone earthquake at coastal Pedernales in April, 2016 may also have accentuated/provoked the onset of more rapid inflationary patterns observed at Cayambe, Chiles and Guagua Pichincha volcanoes, possibly due to increased dilatational strain from this large seismic event by perturbing the important hydrothermal system under each volcano. The LOS displacement velocities at these volcanoes were 3-4 cm/yr during 2016 to early 2018.

Future plans for using InSAR imagery in Ecuador are to complement deformation monitoring of active or suspected volcanoes and calderas; detect fault movement along reverse faults, such as those under the Quito area and along the regional Puna-Pallatanga- Pisayambo-Chingual transpressive structure. Lastly, to detect ground surface subsidence caused by ground water pumping beneath Quito and Cayambe urban areas. The imagery provided by the Ecuadorian Supersite has been important for monitoring purposes and also the results, when creatively projected, have been an important aide in conveying local geodynamic context to the populace and authorities. With more than 30 potentially active volcanoes, the Supersite imagery can and will have many applications around some of the volcanic centers where overall GPS coverage is sparse.

S01.42 Poster

European Catalogue of Volcanoes (ECV) created in the EUROVOLC project and designed after the Catalogue of Icelandic Volcanoes (CIV)

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European volcano observatories aim at building up a unique coherent pan-European catalogue of active volcanoes and volcanic areas, open to the public, through the H2020 funded EUROVOLC project. In the first version, information from different volcanic observatories on key volcanoes and their related hazards will be made available, providing detailed information for both the public and stakeholders regarding e.g. hazards in proximal and distal areas, on ground and in the air. The volcanoes Etna, Vesuvius, Santorini, Teide, Catalan Volcanic Fields, Fogo, Sete Cidades, Piton de la Fournaise and Soufriere of Guadeloupe will be included in the first run showing the amount of information that could be available for all volcanoes listed in later versions of the ECV. The catalogue will contain background information on each volcano and its main eruptions using a homogeneous terminology, scale of measurements of eruption features and level of knowledge of its past phenomena.

The Catalogue of Icelandic Volcanoes (CIV) serves as a template for the European Catalogue. It is an official source of information about volcanoes in Iceland and an open- access web resource serving both the public and decision makers (http://icelandicvolcanoes.is). Contributions in CIV are classified in three types: 1) text and graphic information (e.g. maps) on geological aspects and eruption history of all active volcanic systems and sub-chapters on current alert level and activity status for each volcanic system, 2) real-time data from monitoring systems, updated automatically with information from the IMO monitoring network, and 3) a data portal containing scientific data on all Icelandic eruptions since 2010, designed to make volcanological data open and easy to access.

The ECV is a collaboration of European volcano observatories and universities in Iceland (IMO, UI), Italy (INGV), Spain (CSIC, IGN), Portugal (CIVISA), France (IPGP, UCA), United Kingdom (NERC, Meet Office) and Greece (IGME).

The evolution of the Geohazard Supersites network

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The GEO Geohazard Supersites and Natural Laboratories initiative (GSNL) has grown in the last 5 years to include ten Supersites and one Natural Laboratory, spread over three continents.

New proposals are submitted every year, demonstrating the interest of the scientific community in this initiative. When GSNL was started, such interest was mostly focused on the possibility to have free and open access to large quantities of satellite data, and in some cases also to in situ data.

During the last few years the success of the open data policies implemented by ESA, NASA, as well as the EC and several other countries worldwide, have prompted an evolution of GSNL from the promotion of open data to promotion of open science, as a more innovative and effective way to improve geohazard research and its societal benefits.

While open science is a general term, in essence it implies not only the sharing of data and observations but also of the scientific knowledge which makes the data usable and even the resources needed to exploit them. The full exploitation of open science needs to be supported by technological tools and policies. The former exist or are being developed, also within the initiative itself, while the latter require the implementation of actions and decisions from the scientific community, the publishers and the funding agencies.

The GSNL community is now discussing how to evolve from the use of a data-centric approach to promote geohazard research, to one centered on open science and knowledge sharing. The development of this new vision and the possible way forward will be discussed at the conference.

S01.42 Talk

Petrology Workspace & Database

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Petrological investigations require large amounts of data that range from the specimens' geographic location to detailed geochemical analyses. The different levels of information and the lack of standardization in data archives can pose significant challenges for collaboration between scientists and sustainability of the projects. We present a new interactive Petrology Workspace & Database (PWD; https://eos-volcano-petrology.firebaseapp.com/home) that aims to create a platform for data archiving, visualization and sharing. Where users can interactively input, organize and explore data from the workspace. Furthermore, the PWD data management system allows for compilation of multi-level datasets that hierarchically links different data files. For example, a crystal backscattered electron image can be linked to an X-Ray compositional map or to a file containing compositional analyses. The system will display the location of the analyses on the image and selected data plots that show compositional variations along the traverse. The samples are link to geographic locations, and in the case of volcanic rocks, they are also associated to specific volcanoes and eruptions. This allows data hierarchy within the PWD and facilitates data query, which is done from an interactive map that displays volcano locations around the world. The system can be also used for other types of rocks and petrological projects. The PWD supports different levels of authorization and access control. A project shared among collaborators can only be modified and/organized by authorized users. Moreover, project data package can be downloaded for offline data exchange. A standalone version of this platform is also available.

The Icelandic Volcanoes Supersite: The role of interferometric analysis of synthetic aperture radar images for mitigating effects of volcanic hazards and understanding volcanic processes in Iceland

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The Icelandic Volcanoes Supersite was established as a permanent supersite in 2013 within the GEO Geohazard Supersites and Natural Laboratory initiative (GSNL). Results have been communicated actively to the Iceland Civil Protection, most recently on new unrest at Öræfajökull volcano, where e.g. re-tasking of COSMO-SkyMed satellites has allowed formation of one-day interferograms to constrain ice flow in an area of elevated subglacial geothermal activity. Recent scientific results include a series of studies on the gradual collapse at Bárðarbunga volcano 2014-2015 and the associated eruption and rifting activity. The most important satellite data used by the science teams in past years are from COSMO- SkyMed and TerraSAR-X satellites (several hundred images from each). Use of Sentinel-1 data is rapidly expanding at present. A challenge for the science teams has been the end of the European FUTUREVOLC project in early 2016. That project provided direct funding to work with the supersite data, but after its end the science teams have used alternate sources to carry out research and monitoring. Considerable efforts have been devoted to study geothermal processes, both natural and also the effects of geothermal utilization. The icelandicvolcanoes.is website operated by the Icelandic Meteorological Office provides access to online catalogue of Icelandic volcanoes, an important resource with information on geology and eruptive history of Icelandic volcanoes, as well as alert levels of volcanoes and activity status based on seismic activity. In-situ data is found at web sites and through contacts with individual scientists. The Icelandic Volcanoes Supersite initiative has fulfilled the overall aim of GSNL to improve geophysical scientific research and geohazard assessment in support of Disaster Risk Reduction, through an Open Science approach.

S01.42 Talk

EVER-EST project platform support to scientific investigation on Etna Supersite: Volcanic Plume Retrieval applied to the 03-09 December 2015 Etna eruption

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Volcanic eruptions can have a significant impact on environment, climate, human health and air traffic, through the emission of large quantities of gas and solid particles into the atmosphere. The VPR (Volcanic Plume Retrieval) procedure has been developed for the retrieval of volcanic cloud ash, ice and SO_2 parameters, using MODIS sensor data on board the polar NASA Aqua/Terra satellites.

EVER-EST is a Virtual Research Environment developed between 2015 and 2018 within an H2020 project. The focus of the VRE is to enhance the ability of Earth Science researchers to share knowledge using an Open Science approach. Using the VRE, scientists are able to collaborate with colleagues located in different parts of the world, to remotely access and share data and results, to carry out training sessions and discussions, to compare different results and models. The researchers have the opportunity to reuse data and, above all, algorithms developed by others scientists using the Research Object concept (www.rohub.org). The VRE was developed according to requirements from the scientific community of the GEO-GSNL (Geohazard Supersites and National Laboratories) initiative, and it has been demonstrated for the European volcanic Supersites, i.e., Campi Flegrei/Vesuvius, Mount Etna and Icelandic Volcanoes Supersites.

In this work, we show how the VPR procedure has been implemented into the VRE platform and how it can be shared and re-used by the community for different volcanic contexts. We will show the application of VPR on all the MODIS images collected during one of the biggest lava fountains occurred at the Etna volcano after 2011, the 3 - 9 December 2015 eruption.

Providing Global Volcanism Program data through webservices and linking with volcano numbers

Edward Venzke

Global Volcanism Program, Smithsonian Institution

Data provided through webservices from the Smithsonian's Global Volcanism Program (GVP) Volcanoes of the World database became available for external use in late 2016 using Geoserver software. Layers were created in support of the "Eruptions, Earthquakes & Emissions" web application, which uses a world map and globe to display eruptions and earthquakes since 1960, and satellite-detected volcanic sulfur-dioxide plumes since 1978. Data layers are currently available for Holocene volcanoes, Pleistocene volcanoes, and Holocene eruptions. Eruptions data includes both unique volcano numbers and eruption identifiers. The provision of future layers will likely include eruptive episodes and events.

Webservices data are being used by the EarthChem-supported Deep Earth Carbon Degassing (DECADE) portal to populate volcano-specific pages combining basic volcano data, Holocene eruptions, and SO_2 emissions from GVP, along with content from the EarthChem, SESAR (System for Earth Sample Registration), and MaGa (Mapping Gas Emissions) databases. Collaborations for custom layers are in progress with WOVOdat and Google Earth, and public use is encouraged.

The International Association for Volcanology and Chemistry of Earth's Interior (IAVCEI) and the World Organization of Volcano Observatories (WOVO) have sanctioned GVP to assign volcano names and numbers. Standardization reduces ambiguity regarding names and locations of volcanoes that may have non-unique or multiple names. The original numbers were based on the 1950's for the IAVCEI Catalog of Active Volcanoes of the World (CAVW), with the system gradually being modified and individual numbers changing over time as new research required additions or other updates. The system was significantly revised in 2013, resulting in the numbers becoming permanent and compatible with modern computing systems.

GVP encourages anyone with Quaternary volcanology data to include volcano numbers. Many websites already use these numbers in URL variables, making volcano-specific links convenient in both directions, and creating opportunities for future integration projects.

S01.42 Talk

EUROVOLC - A European Network of Observatories and Research Infrastructures for Volcanology

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A new Horizon2020 Infrastructure project, EUROVOLC was recently established by a large group of Earth and atmospheric scientists from 9 European countries, represented by 18 partners comprising research and monitoring institutions, civil protection and companies from the IT and geothermal industries. The project is built around four main themes: Community building, sub-surface processes, volcano-atmosphere interaction, and volcanic crisis preparedness and risk management. The project's main goals are to: (*i*) network the European volcanological community and its data; (*ii*) enhance knowledge transfer between Volcano Observatories (VO) and Volcano Research Institutions (VRI) and foster development of new, integrated, multidisciplinary volcanological observing systems; (*iii*) strengthen interaction and communication between the community and its stakeholders and define new strategies for best practices and harmonization in communication between scientists and society; (*iv*) advance and optimize research activities to assure the best possible European response before, during and after volcanic crises.

EUROVOLC will open access to multidisciplinary volcanological data from the European VOs and VRIs and adopt existing data and metadata standards. Through Trans-national and Virtual access activities access will opened to the VO and VRI infrastructures themselves and to their software and services to strengthen the European volcanological research area. The project will exploit and build-upon results and services from previous projects, like the European volcanological supersites, FUTUREVOLC and MED-SUV and will interact closely with and utilize the Volcanological Thematic Core Service of The European Plate Observing System, EPOS to distribute and service the data which will be networked in the project.

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S02.02 - Volcanic impacts to society using field, modelling and laboratory approaches to inform disaster risk and resilience assessments and mitigation

Multi-volcanic hazard impact assessment for residential buildings in the Auckland Volcanic Field

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The city of Auckland rests on the Auckland Volcanic Field (AVF), which contains at least 53 volcanic centres. The AVF has been active for the past 200 000 years with the most recent eruption, Rangitoto, occurring approximately 500 years ago.

Volcanic eruptions are multi-hazard events which have the potential to cause widespread and catastrophic damage and disruption. Research has been conducted on volcanic hazards but, the impact of interacting volcanic hazards, which could potentially cause greater damage than any single hazard, has only recently been explored.

Assessing habitability of residential buildings, post-eruption, is a critical gap for building impact assessments. Habitability can be compromised through direct volcanic impact, loss of essential services during and after eruption, and through exacerbation of existing damage when mitigation actions are delayed. Observational assessments post-eruption and witness accounts give evidence that well-constructed buildings can withstand the impacts of hazards associated with volcanic eruption. Therefore, buildings that withstand volcanic eruptions can be cleaned and used to re-house residents which will improve community resilience and reduce the likelihood of a habitability crisis.

A theoretical framework will be developed to investigate the possible orders and impacts of multi-volcanic hazards. This framework will be developed using AVF eruption scenarios and review of literature. Empirical experimentation will be conducted to verify the theoretical framework by assessing the interaction of tephra fall and volcanic ballistic impacts. Experimentation will be conducted using laboratories at the University of Canterbury to assess the impact of tephra on timber framed roofing sections. The intent is to establish the fragility of New Zealand building systems to multi-volcanic hazards and to use this information to inform council and emergency responders of areas and buildings likely to survive an eruption and also to inform the improvement of residential building construction for the future.

S02.02 Poster

Understanding volcanic risk in Turkey for improved emergency response and disaster risk reduction

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Geological and historical records of the ten active volcanoes in Turkey indicate potential for major explosive eruptions in several of them. Over 4 million people live within 30 km of an active volcano and over 15 million live within 100 km. The last major volcanic disaster in Turkey occurred in 1840 from Mount Agrı, when an estimated 1,900 people lost their lives. In an assessment of global distribution of volcanic risk for the UNISDR Global Assessment Report 2015, Turkey ranked 14th in volcanic threat out of 95 volcanically active countries, reflecting high population exposure. Our Project (TURKVOLC) seeks to increase resilience in Turkey by developing a programme of volcano monitoring and hazard assessment to inform volcanic emergency management plans and disaster risk reduction. We present our preliminary data from field studies, geochronological and petrological analysis, and hazard modelling to assess volcanic risk for the central Anatolian volcanoes Mt. Hasan and Mt. Erciyes. Assessment of Erciyes volcano is a high priority with at least two early Holocene M>5 explosive rhyolitic eruptions; it is also close to one of Turkey's most populous cities (Kayseri). The ice and snow covered Mt. Erciyes known for its ski resorts also poses lahar hazards. Both Erciyes and Mt.Hasan volcanoes are characterised by young block and ash flow fans which extend from the summit regions to distances of over 20 km. Both also erupted large magnitude (likely M>7) Pleistocene ignimbrites. Thus volcanic risks from Mt. Hasan and Erciyes volcanoes are high, and increasing due to population and city growth. We are developing hazards maps for the two volcanoes using probablistic and scenario- based modelling of lahars, pyroclastic flows and tephra fall, based on likely scenarios informed by geological and geochronological data. We have installed GPS networks on Mt. Hasan and Mt. Erciyes and plan to install seismic networks.

Recent eruptive history of Mount Hasan and Mount Erciyes stratovolcanoes, Central Anatolia

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Two major stratovolcanoes, Mt. Hasan (3253 m) and Mt. Erciyes (3917 m), pose significant volcanic hazards for Central Anatolia, Turkey. Kayseri in particular, extending from Mt. Erciyes to an area of peripheral lava domes to the north of the volcano, is exposed to hazards from lava dome and pyroclastic eruptions as well as lahars. Both volcanoes erupted during the Holocene, based on archaeological inferences and limited radiometric dating. To establish firmer constraints on the eruptive chronostratigraphy, we have carried out detailed geochronological analyses, which include the first Holocene ages for pyroclastic deposits from Mt. Erciyes. Because of the low-K compositions in Mt. Hasan and Mt. Erciyes rocks, we applied U-Th and (U-Th)/He zircon geochronology, which yields crystallization and eruption ages, respectively. Because we combine both methods for the same crystals, this method (zircon double-dating, or ZDD) provides internal consistency checks for the ages, and thus a very reliable record of the magmatic history of volcanoes throughout the late Pleistocene and Holocene.

Initial results indicate nearly coeval dome eruptions in the northern and southern periphery of Mt. Erciyes' main edifice during the Early Holocene. These dome-forming events are associated with pyroclastic fall deposits. The youngest eruptive activity of Mt. Hasan, by contrast, is effusive lava flow emplacement from its central vent, along with block-and-ash flow and minor pumice fall activity. Preliminary ZDD ages indicate lava flow and block-and- ash flow eruptions during the uppermost Pleistocene, slightly older than published ZDD ages for a ca. 9 ka explosive event putatively depicted in a nearby Neolithic mural. Zircon crystallization ages also reveal that both volcanoes are underlain by a long-lived silicic intrusive complex which crystallized magmatic zircon over several 100's of ka prior to eruption. Collectively, these data indicate that Mt. Hasan and Mt. Erciyes should be considered active.

S02.02 Poster

Modelling and forecasting volcanic gas cloud dispersal from Masaya volcano: towards a warning system

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Masaya volcano (Nicaragua) releases abundant amount of gases by a low unsteady plume raising from the underneath lava lake. The gas cloud travel few kms before affecting the nearby villages where hundreds of families live in rural houses. A wide area extending WSW from the volcano reveal the effect of a long exposure to these volcanic gases by showing the lack of high trees and of lush vegetation. The persistent release of volcanic gases has a dramatic impact on the daily life of thousands of people who througout the years had to find new ways to survive this hostile environment.

The GCRF Unresp project aims to establish procedures to mitigate the impact of volcanic gases on the health of the population by improving the way to communicate the hazard and by issuing warnings when high concentration of gas is expected. As part of this project the forecasting of SO2 gas dispersal has been setup and it is currently in progress. The CALPUFF model is running daily over an area of 90X50 km in a semi-operational mode. The initial setup was designed to perform a 48-hours forecast by using the ECMWF meteorological data, and recent improvements allowed also the use of NAM data.

The small dimension of the investigated domain and the small-scale meteorological dynamics affecting the dispersal of the gas plume are real challenges to provide a robust forecast for the localities nearby the volcano. Comparison with air quality and meteorological data are key element for assessing the quality of the forecast and identify place for improvements.

The implementation of the entire forecasting system as a routinely procedure at INETER (the Nicaraguense Institution in charge of monitoring volcanoes and providing warnings) is in progress and will see a full commitments of the locals Institutions in operating the warning system.

S02.02 Talk

Holocene Plinian eruptions at Volcán de Colima, Mexico: implications for future explosive activity

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Volcán de Colima is one of North America's most active volcanoes characterised by andesitic lava dome growth with daily explosions sending ash and gas up to 3 km above the vent. However, Volcán de Colima has experienced sub-Plinian and Plinian eruptions throughout the Holocene. The last of these occurred in 1913 and 1818. We present new results for 5 Holocene tephra fall deposits that resulted from Plinian eruptions between 6000 and 4400 years BP. Based on geological field data we have reconstructed the eruptions and generated ash fall footprints using the tephra dispersion model, *Tephra2*. These eruptions produced plumes ≤25 km above sea level, minimum erupted volumes of 0.13-0.36 km^3 and resulted in minimum ash fall thicknesses of 5-10 cm in Ciudad Guzman, 20 km NE of the vent. However, the field sites represent only proximal deposits and are thus biased in respect to the fine fractions. Whole-rock geochemical data reveal that the studied Holocene eruptions are basaltic-andesite to high-silica andesite (54.2 - 60.8 wt. % SiO_2) with little difference in temperature and water content between deposits. More mafic magmas are therefore as capable of producing large explosive events as felsic magmas at Volcán de Colima. Heightened activity in July 2015 resulted in pyroclastic density currents with runout lengths of 9 km, 670 people moved to temporary evacuation shelters, and ash dispersal and fall causing temporary closure of Colima Airport. With >1.7 million people living within 100 km of Volcán de Colima, highly explosive Plinian eruptions could have significant impacts not only on local populations, with thick ash falls affecting critical infrastructure causing disruption to transport, services and industry, but across all scales from local and national to global, with potential disruption to production lines and international flights.

The influence of local environmental and socio-economic conditions on the impacts of ash storms

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Ash storms have increasingly been reported in different areas around the world during the last decade (e.g., Alaska, Iceland and Patagonia). The recent volcanic ash wind- remobilization events related to 2010 Eyjafjallajökull and 2011- 2012 Cordón Caulle deposits demonstrated that remobilized ash is a widespread and long-lasting hazard. In particular, the 2011-2012 Cordón Caulle (Chile) eruption emitted about 1 km^3 of rhyodacitic tephra, which due to the dominant westerly winds in the region was mainly deposited in neighboring Argentina. In addition to the impact of primary tephra fallout during the eruption, a vast area of the Argentinian Patagonia (from the Andes Range to the coast) was also significantly affected by wind-remobilization of ash even several years after the climactic phase of the eruption. In this study, we characterize the phenomenology and assess the impacts of ash storms associated with the deposits of this eruption by combining tools of natural and social sciences. Specifically, we focus our analysis in two contrasting farming communities showing different environmental (i.e., precipitation regime, vegetation cover and structure, topography), socio-economic (i.e., farming activities, land use, ethnic composition) and primary tephra deposit (i.e. thickness and grain size) characteristics. Our study areas included the farming community of Villa La Angostura, located in the Andes Range at ~50 km from Cordón Caulle and Ingeniero Jaccobacci, located in the Patagonian steppe ~250 km from the vent. We investigated the impact of ash storms on the farms and their productive activities, but also on the farmers' emotions. Our findings revealed a large influence of pre-existing local environmental and socio-economic conditions on the frequency, intensity and extension of this long-lasting secondary hazard and in its associated impacts. Furthermore, our results provide valuable information necessary for future development and implementation of mitigation and land use planning strategies.

S02.02 Poster

Clean-up of urban areas after volcanic eruptions

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A ubiquitous challenge of disaster response and recovery is managing disaster waste. Past volcanic related disasters have demonstrated that these events can create enormous volumes of different types of waste, at times overwhelming existing solid waste management systems. Despite this, disaster waste management is rarely planned prior to a disaster. When disaster waste planning is (exceptionally) conducted, volcanic hazards are often omitted – we suspect because disaster waste management is generally absent from volcanic impact and risk assessments. This omission is problematic as volcanic hazards can present unique challenges that other natural hazards (e.g. earthquake, hurricane, flooding) are unlikely to exhibit. For example, a common strategy is to simply remove hazard-related material, yet the insulating properties of lava mean it can take months to years for lava flows to completely cool down. Consequently, removal may need to be delayed or not undertaken at all. Additionally, uncertainty associated with whether an eruption is over means there can be a substantial amount of time before it is deemed sufficiently safe for personnel to enter a heavily damaged area to begin clean-up operations. Here, we present a multi-volcanic hazard assessment approach to identifying the effects of volcanic hazards on disaster waste management systems. We use case studies to explore these effects and develop a suite of semi-quantitative indicators to assist post-disaster clean-up decision- making. We demonstrate how these indicators can be used by applying them to Auckland Volcanic Field eruption scenarios for the city of Auckland, New Zealand to assess implications for disaster waste management systems. Our work will be beneficial for risk- reduction, emergency response and recovery managers to understand clean-up and restoration requirements for urban areas affected by volcanism.

S02.02 Talk

Forensic analysis of the Öræfajökull 1362, course of events from unrest to eruption

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In the early days of June 1362 the Öræfajökull volcano entered into an eruption that lasted throughout the summer. This eruption is among the largest explosive eruptions in Europe in the past 2000 years, emitting a 10 km^3 of tephra into the atmosphere. Westerly winds carried the ash tor the eastsoutheast over the Atlantic to mainland Europe, where it is preserved numerous peat sections. In Iceland this eruption was particularly destructive. Forty farms at the foot of the volcano where completely destroyed, killing everyone in the region. Furthermore, farm land and grazing animals up to 60 km east of the volcano where effected. But what really happened in this eruption? In this presentation we shall go through resent archaeological investigation of two farms that were destroyed by the eruption, which provide new insights into the eruption precursors and the fate of the people in this event. Detailed investigation of the stratigraphy of the tephra deposits produced by the eruption reveal important information about the course of events from the start of the eruption begins to its end. Öræfajökull is the highest volcano in Iceland, rising from sea level and culminating at altitude of 2110 m. It is covered by glacier above 1200 m and has an average slope of 35°. Forensic geological studies indicate that the 1362 event began by intense earthquakes that caused severe damage to houses in the area. It was followed by explosive eruption supporting> 35 km-high plume producing pyroclastic density currents (PDCs) cascading down the slopes of the volcano, followed by a series of dry PDCs. Jökulhlaup/laharic deposits are first observed after the emplacement of the wet PDCs. In places the Jökulhlaup deposits are intercalated with the PDCs or the paroxysmal Plinian airfall deposit that followed indicating that jökulhlaups took place repeatedly throughout the eruption.

Naples the town on the two most dangerous Volcanoes without evacuation plans: previous disasters new volcanological evidences and modeling for risk management and mitigation

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The metropolitan area of Naples with its ca. 3 million of inhabitants lies inside the two volcanic districts of Somma-Vesuvius and Campi Flegrei Caldera, and its underground mainly consists of a sequences of eruptive products.

New evidences from stratigraphy, archaeological findings and laboratory analyses provide decisive constraints on scenarios of the eruptions occurred in the past, their escalation, eruptive mechanisms and impact on the environment and human settlements, crucial for risk assessment and mitigation.

Notably, a common evidence of rapid onset of the explosive eruptions, nearly always associated with very rapid opening of the magma system and magma rising is well documented in the volcanic history of both Somma- Vesuvius and Campi Flegrei .

Sudden evolution toward the critical phase of the eruptions, very wide- spreading of tephra fallout and PDCs since the early phase of the eruption is also common in VEI 3 to 6 eruption.

Depositional and textural features of the products of the very early phase of the eruptions indicate fast unrests with short term precursors.

Furthermore, due to the peculiar topographic setting of the Naples metropolitan area, VEI > 3 expose large part of the urbanized area to PDCs, while the associated fall out may inhibit any evacuation since the very early phases of the eruption, as also confirmed by numerical simulation.

According with above evidences, the setting of alert levels and probabilistic eruption forecast appears very critical.

Thus the only strategy is the prevention with effective evacuation plans, based on the worst case scenarios and including the whole metropolitan area of Naples.

But these planes are still incomplete.

S02.02 Talk

Exposure-based risk assessment and emergency management associated with the fallout of large clasts

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Fallout of ballistic blocks and bombs ejected from eruptive vents represents a well-known hazard in proximal areas. However, fallout of large clasts sedimenting from plume margins extending to medial areas with the potential to produce severe injuries to people and cause damage to infrastructure, is often overlooked. Recent eruptive events at Mount Etna (Italy) provide a clear example where large-clast fallout from plume margins (>5 cm) has posed a real threat both to the many visitors reaching the summit area and to local infrastructure, and, therefore, has been selected as a case study. To quantify this hazard, a new particle- sedimentation model was calibrated with field data and then used for probabilistic hazard assessments. For a fully probabilistic scenario the hazard zone covered 72 km^2 and included some 125 km of paths and roads, and 15 buildings; evacuation on foot to a safe area was estimated at almost 4 hours, but this could be reduced to less than 3 hours if two shelters were provided. Our results show the importance of integrating probabilistic hazard analysis of large-clast fallout within effective strategies of risk management and reduction, especially in the case of volcanoes where visitors can reach the summit areas.

S02.02 Talk

Glacier cave research on volcanoes of the Cascade Volcanic Arc – chances to improve forecasting volcanic mudflows

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Mt. Hood, Mt. St. Helens and Mt. Rainier belong to the Cascade Volcanic Arc among the agglomerations of Washington and Oregon. As all three volcanoes are covered with glaciers there is a bad risk to volcanic mudflows either due to volcanic activity or snowmelt in spring. Whereas there have been extensive studies in the research field of glaciology, the investigation of glacier caves as the entrance to the interior of these systems is rather new. By means of a more detailed study of glacier caves, climatic conditions inside, and the influence of volcanic activity on glacier cave formation there could be the chance to amplify our knowledge about these systems. This in turn could be a powerful tool to analyse the development of volcanic mudflows and to improve forecasting these hazards.

Field research inside Sandy Glacier on Mt. Hood, Oregon and Crater Glacier on Mt. St. Helens, Washington in May and June 2018 will provide first data/results. Among other things the survey comprises the mapping of different glacier cave systems, the measurement of air temperature, humidity and wind flows inside the caves, and the study of hot springs which often lead to an increasing melting process inside the glaciers. Furthermore, rock samples might give information about the stability and the current condition of the volcanic edifices and the influence of hot springs and fumaroles on these formations. More measurements and investigations will be made during the following two years in the framework of an extensive monitoring program.

Glacier cave research (not only) in the Cascade Volcanic Arc represents a highly significant issue since we do have a steadily growing population in the proximity of active volcanoes worldwide and forecasting natural/volcanic hazards becomes more and more important.

S02.02 Poster

Tephra fallout hazard assessment at Tacaná volcano (Mexico)

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The Tacaná Volcanic Complex (TVC) is a chain of four volcanic structures aligned NE in the state of Chiapas, in the southern border between Mexico and Guatemala. The complex begun its construction in the Late Pleistocene with the continuous effusion of lava flows and the development of pyroclastic density currents. Today, the TVC is considered an active dormant volcano due to historic and modern phreatic explosions, the last two occurred in 1949 and 1986. Approximately 30 kys ago a period of explosive activity produced at least four Plinian to sub-Plinian eruptions. Volcanic ash fallouts associated with an eventual renewal of explosive activity at Tacaná volcano could represent a serious threat to the surrounding urbanized areas as much in Mexico as in Guatemala. In this study, we assess the tephra fallout hazard associated with three possible eruptive scenarios: Plinian, sub- Plinian and small phreatomagmatic events. We compute probabilistic hazard maps for the three scenarios on the basis of the geological field data of the Sibinal Pumice eruption (23,540 ±230 yrs BP) which developed a first eruptive column of SubPlinian magnitude (~19 km height) and a second Plinian column of ~22 km height; we also considered the ~760 yrs B.P. phreatomagmatic event mapped mainly near the summit of the volcano. Tephra dispersal is calculated using the FALL3D numerical model. Model input parameters are constrained through analytical models and are varied using probability density functions. Hazard maps presented here can support long term planning and can give support to local and regional risk mitigation strategies.

S02.02 Talk

Quantifying Volcanic Multi-Hazard Impacts at Mt Taranaki, NZ

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Increasing global urbanisation and population growth in actively volcanic regions necessitates a greater understanding of volcanic processes and impacts. Developing robust, replicable impact assessment frameworks are essential in mitigating economic and social losses in the event of a major volcanic eruption. Volcanic impact assessments require information on the hazard intensity, the societal assets exposed to the hazard, and asset vulnerability. The credibility of the resultant impact assessment is heavily dependent on the credibility of each of these components.

The multi-hazard nature of volcanic eruptions calls for the quantification of volcanic hazard interactions (cascading, compounding and interacting) and the incorporation of these findings into any volcanic hazard impact assessment conducted. With few past major eruptions occurring in well populated areas, empirical multi-volcanic hazard impact data is lacking, and must be supported with expert consultation, empirical experimentation and physical modelling efforts. We address these research needs by quantifying vulnerability to single- and multi-hazards using empirically-derived fragility functions, local stakeholder and expert expertise, supported by multi-hazard modelling efforts. We focus on impacts to distributed infrastructure and agricultural sectors, with consideration for their interdependencies.

This work also explores co-creation methodologies in volcanic impact assessment, working closely with end-users and local stakeholders from end-to-end. Current research and knowledge gaps in local policy and risk mitigation strategies are addressed, and the benefits and challenges of stakeholder engagement are investigated.

We demonstrate the application of this process in the Taranaki region of New Zealand, where there is an estimated 33-42% likelihood of an eruption at Mt Taranaki in the next 50 years (Damaschke et al., 2018).

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Using ballistic cannon experiments
to explore new methods of building reinforcement

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Volcanic ballistics are one of the most frequently lethal volcanic hazards but even though ballistics are highly destructive, several recent eruptions have shown that unreinforced buildings can provide life-saving shelter during emergencies. During the 2014 eruption of Mt Ontake, timber buildings halted large, 20 cm diameter ballistics despite their impact energies being nearly two orders of magnitude higher than the predicted penetration threshold for these buildings. This discrepancy is problematic because it creates uncertainty in regards to what preparedness and mitigation advice should be provided (e.g. should people be advised to shelter in place or evacuate ballistic zones? And how could we design shelters better?).

In this study we begin quantifying one of the factors that may have accounted for the better than expected building performance at Ontake. That being the potential for impacts to have been cushioned by tephra deposits which built up on roofs during the eruption. Also we tested a simple method of reinforcing roofs with fibreglass reinforced polymer (FRP). In the lab we simulated ballistic impacts to clay tile and reinforced concrete slab targets which had either been covered with a layer of tephra or retrofitted with FRP prior to shooting. Experiments found 5 cm layers of tephra were able to triple the energy required for ballistic penetration in both building materials. FRP experiments found that having two layers of FRP bonded to concrete was able to nearly quadruple its threshold for generating deadly concrete shrapnel.

These experiments provide a surprising example of how buildings can actually perform better when impacted by multiple volcanic hazards, if they occur in a certain sequence. In terms of the FRP experiments, simulating impacts in the laboratory provides a means for proactive risk management, allowing us to test new methods of building reinforcement without having to wait for the next eruption.

S02.02 Poster

Preliminary report on damage caused by the ballistic block of the 2018 phreatic eruption of Kusatsu-Shirane volcano

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The small scale phreatic eruption of Mount Moto-Shirane, which is the southern part of Kusatsu-Shirane volcano in central Japan, began at about 10 a.m. on 23 January 2018 after 1500 years dormancy. Ballistic blocks of the eruption reached approximately 500m from the vent area. The slope of Mount Moto-Shirane is a popular ski area, and skiers on the slope were struck by the ballistic blocks of this eruption. One person died, and 11 other people were injured by those ballistic blocks. The ballistic blocks from the eruption also hit the summit station of ropeway and the gondola lifts in operation on the eastern side of mountain. At the eruption 50 gondola lifts were in service. Several tens of seconds after the beginning of the eruption, the ropeway lost power due to electrical equipmentdamaged by ballistic blocks. We have conducted a preliminary survey of the damage situation of the 28 gondola lifts which were in operation. 15 gondola lifts were covered by ash derived from ash fall and ground-hugging flow, and 9 of them were seriously damaged such as window breakage and penetration of the ceilingby ballistic impacts. Most of the gondola had cracked walls on the facing side for the crater, three of them also had damages in the opposite wall. Such kind of damagesindicate some of ballistic blocks fell almost vertically.

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S02.03 - From volcanic hazard to risk assessment the key role of exposure and vulnerability

From volcanic hazard to risk assessment

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Volcanic eruptions are characterized by multiple hazards, which pose short to long-term threats to people and property. Experience has shown that the success in volcanic risk management strongly correlates with the degree to which proactive policies of risk reduction are in place before an eruption begins. Such policies should ideally be developed based on comprehensive analysis of the volcanic risk that encompass the full spectrum of vulnerability types (e.g. physical, systemic, social, economic, institutional) associated with individual volcanic hazards (e.g. pyroclastic density currents, lava flows, tephra accumulation and dispersal, lahars, gas emissions). Still, no comprehensive methods for vulnerability and risk analysis are widely accepted and, while some models identify individual interactions between volcanic hazard and vulnerability, the absence of multiple dimensions of vulnerability limit our understanding of the real volcanic risk faced by the society and impede the development of efficient mitigation measures. The first GVM-IAVCEI workshop "From Volcanic Hazard to Risk Assessment" took place in Geneva on 27-28 June 2018 with the main goal being to evaluate the state of the art of risk assessment in volcanology and identifying research priorities. It gathered about 40 participants from 15 countries working in various aspects of hazard, vulnerability and risk assessment. With this contribution, we summarize the main outcomes with a special attention towards identifying the benefits of volcanic risk assessment for decision makers, developing a strategy for multisystem vulnerability assessment in a volcanic setting and exploring the optimum hazard and vulnerability products necessary for achieving comprehensive risk assessments at multiple scales.

What shapes response? Applying a capabilities framework to understanding people's capacity for protection and recovery from volcanic hazard events

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Capabilities, in essence, refer to the ability to achieve wellbeing. It is a concept that has been used to describe many aspects of social justice and risk, but seldom so far in relation to volcanic hazards. Recognition that many aspects of volcanic risk and risk reduction are structurally differentiated according to socially variable attributes suggests that it can be a valuable approach for analysing what shapes the limitations/opportunities for reducing vulnerability to life and livelihood impacts. What shapes the way that people can and do respond to volcanic risk and manage the process of recovery following disasters?

In this paper we apply a capabilities framework to understanding the experiences and capacities of people who live in the vicinity of three volcanoes, Tungurahua in Ecuador, La Soufriere in St Vincent and Nevado del Ruiz in Colombia. These represent three contrasting cases – the first a volcano in major eruptive activity during our research period, the second a volcano that last erupted in 1979 but poses significant continuing threat to the island's population, and the third a volcano that was the scene of a humanitarian disaster in 1985. Using data from qualitative and quantitative research, obtained through the STREVA project, we illustrate how capabilities to protect against hazards and recover from their impacts are constructed from a combination of people mobilising their own resources and drawing on external resources (including intervention support). But capabilities rely not only on the existence of resources but on effective access to use them in a productive way: this ability is shaped by a range of additional factors, including cultural norms and social power relations. The idea of 'capability' underlines that we need to look at response as shaped by many aspects of life beyond simply the existence or provision, for example, of knowledge and infrastructure.

A scenario-based approach to understand the multi-temporal and multi-scale consequences of volcanic eruptions: the Vesuvius case-study

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Volcanic eruptions are generally characterized as multi-hazards events, with different hazardous phenomena arising in different temporal spans and affecting different geographical scales (from a local to a global scale). The peculiar features of volcanic eruptions affect both exposure and vulnerability analyses and significantly reverberates on the way to comprehensively prefigure their consequences.

The occurrence of different hazards, spatially and temporally articulated, affect exposure, since exposed targets can vary in respect to the heterogeneous hazard factors, and vulnerability analysis, being the latter largely dependent on the hazard type. Moreover, the dynamic features of volcanic eruptions let arise the need for embracing a multi-temporal and multi-scale perspective, focusing on the complex chains of direct and indirect impacts that, starting from the physical impact of each hazard that is generally limited to a local scale, may reverberate on a regional, or even a global, scale.

Based on the above, this contribution will explore the potential of a scenario-based approach to prefigure, through quantitative, semi-quantitative information or even through qualitative descriptions, the spatial and temporal development of a volcanic event and of its multiple consequences. The main goal is to go beyond the physical damage, crucial to support emergency planning, to account for "systemic damage", arising from the interdependencies among the different components of natural and built environment, that is crucial to support long term land use choices.

In detail, with reference to the Vesuvius area, characterized by the presence of an active volcano in a densely populated area, and based on current event scenarios provided by the Civil Protection, the contribution will provide a quali-quantitative description of the temporal and spatial evolution of the expected hazardous phenomena and of their main consequences, highlighting how different types of damage may occur at different times and scales.

Volcanic ash impacts on critical infrastructures. Physical and systemic Vulnerability Assessment in Villa La Angostura (Argentina) and on Vulcano Island (Italy)

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A new methodology is proposed to identify the systemic vulnerability and provides a complete overview on the interdependency and hierarchical relevance among the critical infrastructures (transport, power, water and telecommunication systems) subsequent to volcanic ashes deposition in the two case studies examined: Vulcano Island (Italy) and Villa La Angostura (Argentina).

A framework was developed which combines the vulnerability characteristics with the damage aspects and deals not only with the physical features of a single lifeline, but also with the functional and the systemic aspects among different lifelines. The quantitative and qualitative data were combined in order to develop the complete vulnerability assessment and the systemic damage analysis.

A preliminary phase of mapping and data collection on field was performed; then, with the support of matrices, data for each infrastructure were collected taking into account the features and the relevant components of each asset.

The possibility to perform an analysis “ex ante” the event on Vulcano island (Italy) and “post event” in Villa La Angostura (Argentina) affected by the 2011 Puyehue-Cordon Caulle eruption allows to differentiate and better understand elements of fragility of the critical infrastructure systems, the possible future impacts on them and to avoid long term damage due to poor decision-making strategies.

Identifying among lifelines cascade effects, redundancy and transferability becomes a key aspect for response actions, for appropriate mitigation strategies and resilience aspects.

Keywords: systemic vulnerability; physical damage; loss of function; critical infrastructures; volcanic ashes.

S02.03 Poster

Transformational moments in interdisciplinary research: reflections from the 'Strengthening Resilience in Volcanic Areas' (STREVA) project

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Interdisciplinarity is now embedded in broader research strategies aiming to generate new hybrid research designs to tackle global challenges. This type of research offers opportunities to engage with diverse disciplines, create new perspectives and different ways of thinking about - and ultimately helping to solve - intractable problems.

We reflect on our learning from a six-year interdisciplinary project, 'Strengthening Resilience in Volcanic Areas' (STREVA). Devised at a time when interdisciplinarity in the geosciences was relatively new, our flexible research design gave us space to conceive novel methodological processes, evolve our thinking about risk and generate innovative research outputs that were unimaginable at the outset of the research.

We hypothesise that transformational 'moments' from STREVA significantly advanced (and sometimes re-directed) our thinking and practice during the project. We identify many of these 'moments' as the source of greatest societal impact too. While highly interconnected, we theme our 'moments' under: a) shared experiences around boundary objects (in our case, volcanoes); b) storytelling and c) emotion. Our 'moments' have several principles in common for good interdisciplinary practice: collaboration, co-production, open ontology, dialogue, reciprocity and contextual understanding.

While our 'moments' of transformation may be useful for development of interdisciplinary research architecture in general, perhaps more importantly, they highlight the need for stronger focus on the interdisciplinary research *process*, particularly around building and nurturing relationships within research teams, with collaborators, and ultimately with those who might benefit from access to this type of knowledge.

Exposure and vulnerability: As important as hazard in quantifying volcanic risk

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Quantifying volcanic risk suffers from at least three sources of data limitation: 1) Incomplete eruption histories (and thus definition of hazard), 2) Lack of detailed exposure datasets, and 3) Few evidence-based estimates of vulnerability. In the volcanological community, much of the focus thus far has been on better understanding potential hazard. While this is critical for quantifying risk, we argue that the characterisation of exposure and vulnerability is equally important, and much less well understood.

Here, we present case study volcanic exposure and vulnerability assessments for buildings as a way of critically reviewing current approaches. For exposure, volcano hazard-specific ground surveys have been carried out at a range of scales from part of a community to a full city. Resource requirements often make such surveys unattainable across large areas; however, remote sensing, crowd-sourcing and automated image recognition approaches will enable us to gather pre- and post-eruption exposure information more rapidly across large areas. For vulnerability, forensic post-eruption impact assessments and experimental testing will continue to supplement the sparse physical impact data set. Cataloguing available data in a format that allows us to interrogate across multiple data sets is key, so as to infer the level of impact from a given hazard intensity, with appropriate uncertainty bounds. The many types of vulnerability that are important to robustly characterising volcanic risk are clearly more complex than can be described by one index, function or threshold. Rather, they are hazard, context, socially, politically, and time dependent. Exposure and vulnerability are also dynamic and vary through time before, during, and after an eruption, and as a function of human or environmental actions such as clean-up or rainfall: can we account better for these complexities?

How to integrate the human dimension of volcanic risk in a data poor context? Mapping the population exposure and vulnerability of Goma city, at the foot of the Nyiragongo volcano (D.R. Congo)

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In most volcanic risk assessment, the vulnerability concept is approached from an engineering perspective. However, in the case of hazards with binary impact such as lava flows, it might be more relevant to consider the socio-economic capacities of the population to face the long term impacts of the eruption. Considering socio-economic vulnerability is even more relevant in a developing context with population having fragile livelihoods and limited external support for recovery. Here we present a contextualized methodology for assessing the risk due to lava flow volcanic eruption in the city of Goma (D.R. Congo), facing lava flow eruptions from Nyiragongo volcano.

Conducted in the framework of the GeoRisCA project (2012-2017), the volcanic risk assessment was achieved by combining a probabilistic modelling of lava flow invasion with quantitative and qualitative approaches to characterize the population density and its characteristic vulnerability at neighborhood level. This involved a large household survey, several focus groups, in-depth discussions with key informants and a Delphi survey among local and international experts to target the most adapted vulnerability factors.

A crucial step was to involve the local scientists in the data collection and analyses, as their knowledge of their environment and their history has played a decisive role in results' interpretation. Moreover, throughout the project, presenting several times our work and (intermediary) results to the stakeholders concerned with disaster risk management and the authorities of the city and the North Kivu province was also essential in order to make them aware of the quality of this first global risk assessment, as well as the importance of taking it into account in contingency and evacuation plans. Here, we also assess the impact this research had after the end of the GeoRisCA project, through continuous interactions with local stakeholders.

Estimates of the social impact of a volcanic eruption: The assessment of social vulnerability, psychological and behavioral factors in São Miguel (Azores)

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To foster the adoption of mitigation and preparedness policies that address population's vulnerabilities, social vulnerability must be assessed. The concept has been understood as the susceptibility to damage, including the ability to deal with, respond and cope with a disaster, assessed through individual socioeconomic characteristics, structural characteristics, and community characteristics. Some authors defend that vulnerability should not equal poverty or victimhood; instead, it should be considered a set of fragilities, which if addressed can foster resilience. Following previous research, we suppose that the assessment of social vulnerability for volcanic hazard benefits from the assessment of psychological and behavioral dimensions, portraying a more complete view on the individuals' vulnerability, integrating the assessment of variables such as volcanic risk perception, trust in officials, and attitudes towards evacuation, as these influence the response and ability to cope with disaster and risk communication. This ongoing study aims to estimate the social vulnerability to a volcanic eruption in Vila Franca do Campo, São Miguel, Azores, using a representative sample and considering census data for sex and age distributions. Preliminary results indicate a socially vulnerable population determined by socioeconomic factors and psychological and behavioral factors. Final results will allow discussing implications for policymaking.

Integrating social and institutional vulnerabilities into volcanic risk scenarios: a case study at Nevado Cayambe, Ecuador

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Many improvements have been done these last years in understanding physical vulnerabilities, while fewer have been produced on human vulnerabilities (either social or institutional). This relative void is probably due to the complexity of the human vulnerability - with a high number of parameters involved - combined with a global lack of methodological framework to build such kind of study. Yet, this kind of analysis is essential to provide accurate volcanic crisis scenarios to the communities and authorities. There is a real need for the scientific community working on volcanic risk to better define a conceptual and methodological framework to produce more systemic vulnerability analysis including social and institutional aspects.

We provide an example of integrated risk analysis at Cayambe Volcano, Northern Ecuador, which began to show signs of unrest in 2016. We aim at discussing with the volcanology community how to achieve an efficient guideline to build integrated risk and crisis management scenarios.

S02.03 Talk

Assessing vulnerability to natural hazards in terms of access to critical infrastructure: an approach combining hazard mapping with road network analysis

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Development of hazard maps is nowadays one measure promoted by the international community to reduce risk. Hazard maps provide information about the probability of given areas to be affected by one or several hazards. As such they are useful tools to evaluate the risk and help with the development of safe policies. Even if the number of maps produced increases, hazard maps have only been employed widely for a couple of decades and practical applications combining hazard mapping with accessibility to services through the road network are few.

In hazardous environments, accessibility of the population to strategic infrastructures is important since emergency services and goods will principally be offered at or provided from these locations. If a road segment is blocked by a hazard, accessibility to services in terms of distance or in time can be lower, or worse, people may be completely disconnected from specific services. The importance of each road segment in the transport network as a connecting element enabling access to relevant services is therefore critical information for the authorities.

In this contribution, we propose a new application of hazard mapping which aims to define the importance of each road segment in the accessibility to services, considering the probability to be affected by a hazard, the road network connectivity, and the distribution of population and services. By removing one segment after the other, changes in accessibility to critical infrastructure are evaluated and an importance parameter considering the hazard probability and the population affected will be allocated to the segment. Visualization of this road importance parameter is a useful way of valuing hazard maps and may help to support discussions about the development of new infrastructure, capacity increase, maintenance and evacuation procedures. To illustrate the approach proposed, a case study on the volcanic Ngazidja Island will be presented.

Building damage evaluation from a medium size explosive eruption in a sector of Campi Flegrei caldera

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Volcanic eruptions can produce a severe damage to the territory where they occur. Nevertheless, the frequent concomitancy of proximity to sea with fertility of soils, sometimes joined to mild climate, encouraged the settlement in these areas, as testified by the Neapolitan area since Greek epoch. Through time, villages grew up to cities and mega- cities exposing to volcanic hazard an increasing number of people. This status postulated the need of volcanic risk mitigation by a reduction of damages and losses in the affected territory.
This research aims to assess the impact on the buildings for a test area of Naples exposed to Campi Flegrei volcanic activity. We considered two types of explosive events characterized by different VEI (Volcanic Explosivity Index): Agnano Monte Spina eruption, the most significant event recorded at Campi Flegrei in the past 5000 years (VEI=5), and Averno 2 eruption, considered the most probable type of event in the next future (VEI=3-4). The roof overload effects caused by pyroclastic fall deposits and the wall collapses induced by dynamic overpressure of pyroclastic density currents (PDC) were considered. Aiming at this, the several types of buildings present in the selected area were classified according to the kind of roofs (plain or pitched) and the structural features (masonry or reinforced concrete building with less or more than 3 floors) by visually analyzing high definition satellite images. Taking into account the load caused by the fall out products and the dynamic pressure determined by the impact of PDCs for each type of building we used fragility curves to evaluate the probability of exceeding the damage thresholds. The main outcome of the present research is the possibility to the identify in the investigated sector of Campi Flegrei the most vulnerable zones where an intervention aimed at risk mitigation could be planned.

Hierarchization of the volcanoes of continental and insular Ecuador based on their threat potential

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The Ecuadorian arc comprises at least 84 Plio-Quaternary volcanic centers distributed along the Andes, with 24 of them considered as potentially active (eruptive activity during the Holocene). Moderate-to-large eruptions have a high recurrence rate and a high long-term probability. In addition, 21 volcanic centers that form the Galapagos Islands were considered in our study where 13 are potentially active. The eruptive products of Ecuadorian volcanoes have covered extensive areas that are now occupied by urban areas, strategic infrastructures, farmlands and pastures. We present the first threat prioritization of all the potentially active volcanoes employing twelve factors to assess hazard, three parameters for recent unrest, and nine criteria to evaluate the vulnerabilities following the methodology proposed by Ewert (2007). Some parameters have been modified to be suitable with the local context. Hazard factors synthesize the eruptive history of each volcanic center. Recent unrest evaluate the permanence of magmatic activity and are defined according to the monitoring carried out by the IG-EPN. Vulnerability criteria have been evaluated relating hazard maps (or geological when not available), the most recent census data and infrastructure networks. As a result, we define 3 classes to categorize the Ecuadorian volcanoes according to their threat index: high (Tungurahua, Cotopaxi, Pichincha, El Reventador, Cayambe), medium (8 volcanoes), and low (24 volcanoes). All Galápagos volcanoes fall into the low threat group. We conclude that, in order to reduce the potential negative impacts of an eruption, these volcanoes should be considered for risk assessment according to their threat ranking. At short term, risk reduction strategy should include full hazard assessment, flexible permanent monitoring (according to the unrest state), emergency planning and education of the population at risk. This hierarchization should be revised periodically since it is likely to change according to the magmatic unrest and population growth.

Creating volcano activity catalogues from historic records to inform risk calculations; Case study from Tongariro National Park, New Zealand and Ambae Vanuatu

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Recently several risk assessments have been undertaken to better understand hazards and risk to infrastructure and visitors to Tongariro National Park. To make these as robust as possible the catalogues of eruptive activity also needed to robust. This presentation is a case study of the methodologies and results from revising the historic eruption catalogues for Ruapehu and Te Maari. The new catalogues document over 700 days of eruptive activity whereas pre-existing catalogues only documented 60-100 days. Several previously unrecorded eruptions are now documented and we are more able to classify the styles and magnitude of eruptive activity and volcanic unrest. Risk assessments and calculations are now more robust. The problem of relating historic catalogues and geological records remains.

The delineation of volcanic hazards and the calculation of risk created by those hazards has become an important and powerful tool in the volcanology tool box. Detailed geological studies are improving our knowledge of eruptions preserved in the geological record, however the details of the historic activity are not always treated in the same detail. Often these studies are conducted by other science sectors and written or oral records are not easy to access. Eruptive activity catalogues if they exist are usually focussed on the stronger or more damaging phases of an eruptive episode, rarely do they record or use data about the lesser pulses of activity that accumulate to produce the phases and episodes.

A similar study is now underway to delineate volcanic unrest and historic eruptive activity at Ambae in Vanuatu.

When soil CO_2 degassing becomes a volcanic hazard: criteria to produce CO_2 risk maps in soil diffuse degassing areas

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Carbon dioxide released from volcanic soils may be a permanent risk for population living in diffuse degassing areas. Several villages in the Azores archipelago (Portugal) are located in areas with anomalous soil CO_2 degassing and previous studies showed frequently high indoor CO_2 concentration (> 3 vol.%) in buildings situated in different volcanic systems. The indoor CO_2 concentration increases were mainly correlated with meteorological changes, such as decreases in the barometric pressure and rainfall periods. This study discusses criteria and a methodology to produce human CO_2 exposure risk maps that can be applied to different soil diffuse degassing areas. Soil CO_2 degassing susceptibility maps are presented based on soil CO_2 flux surveys and are a key tool for land-use planners in order to select advisable building locations. Susceptibility classes are defined by the CO_2 source and the existence of diffuse degassing structures (DDS) and vulnerability maps are performed based on the human exposure along with the outdoor/indoor environments, and the structure of buildings. Thus, the preliminary CO_2 risk maps result from the integration of vulnerability and susceptibility maps considering that the value is homogeneously distributed over the whole area. Furnas and Ribeira Quente villages (São Miguel Island) were selected as study cases and the final risk maps revealed that, respectively, 58% and 98% of the buildings in those areas are at high risk of CO_2 exposure.

Improving building damage forecasts for tephra hazards: Retrospective assessment of damage from the Kelud 2014 eruption, Indonesia

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At many active volcanoes around the world, there are two major limitations on our ability to accurately forecast building damage following future eruptions: 1) a lack of exposure data and 2) a reliance on broad vulnerability models, which may not accurately reflect building performance at the local scale. Here we test the second limitation, the effectiveness of existing tephra fragility functions in forecasting building damage by using them to retrospectively forecast tephra damage and then comparing this forecast with actual observed damage from the Kelud 2014 eruption in Indonesia.

For the retrospective forecast we used a standard approach combining hazard, exposure and vulnerability data to forecast likely damage. Observed tephra thickness and clast size data collected by CVGHM in the days following the eruption were used with tephra modelling to map the tephra hazard across the impacted area. Building exposure was collected from open-source databases with roof and construction type derived from the databases, and supplemented with satellite image analysis and ground-truthing where required. The vulnerability of different building types was modelled by assigning appropriate fragility functions to each building. The distribution and number of damaged buildings was then calculated using GIS.

The actual observed damage was assessed using pre- and post-eruption satellite images supplemented with photos from within the damaged villages. We found that for more than half of the buildings, the forecast did not fully capture the observed level of damage, likely because currently available fragility functions have been developed for collapse only and because multiple hazards (tephra fall plus projectiles) are not accounted for. We are working towards an improved suite of tephra fall fragility functions that account for non- collapse damage and hazard interactions.

Exposure and vulnerability evaluation methods: Vesuvius and Campi Flegrei case studies

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In the framework of emergency planning in the areas subjected to volcanic risk, the analyses of risk and impact scenario assessment constitute a fundamental tool to evaluate the strategies, to quantify the necessary resources and to define the operative intervention organization.
Risk and scenario analyses require the evaluation of the convolution of three aleatory variables: hazard, exposure and vulnerability (Unesco, 1972, Fournier d'Albe, 1979).
In this paper, special attention is devoted to exposure and vulnerability assessment.
The 'exposure' is the geographic distribution of different elements at risk (population, buildings, infrastructures, activities and facilities) which characterize the examined area, whose conditions and/or operation could be damaged, modified and destroyed because of the occurrence of the volcanic events.
The 'vulnerability' is the sensitivity of an exposed element to a given volcanic event. It can be assed as the probability that an exposed element reaches a given level of damage, according to an opportune measurement scale, under the effects of a natural event of assigned intensity.
Vulnerability and exposure represent strictly connected factors. For each category of exposed elements, the assessment of vulnerability due to a natural event must be combined with "a qualitative and quantitative analysis of the exposed element" (exposure), in order to identify the time-spatial distribution of typological classes of exposed element, defined as 'vulnerability classes'. Each of them represents a group of elements with same characteristics, which presents the same behaviour (vulnerability) towards a phenomenon.
The analyses concerning the exposure and vulnerability assessment under effect of earthquakes, ash fall, pyroclastic flows of ordinary buildings are treated with special attention to analyses necessaries to development of volcanic emergency plans of Vesuvius and Campi Flegrei (Campania Region, Italy).

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S02.04 - Volcanic crisis management and evacuations recent case studies and best practices

How adequate is the Ecuadorian volcanic surveillance system? Insights from threat analysis and monitoring network assessment

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Ecuador's last severe volcanic disaster occurred 141 years ago when lahars from Cotopaxi destroyed several villages and part of Latacunga causing thousands of victims. 24 volcanoes in Continental Ecuador and 13 volcanoes in Galápagos are considered as potentially active. Since 1983, the IG-EPN works to create a monitoring network able to detect volcanic unrest and reduce eruption impact. Volcano observatories have been classified into three levels: (1) ≥2 different monitoring methods and ≥4 seismic stations, (2) ≥2 methods with ≥1 seismic station, and (3) ≥1 seismic station. In order to evaluate the surveillance system, we compare the threat that these volcanoes represent to their monitoring level.

Five volcanoes are considered of high threat. From this group, three are equipped with level 1 monitoring networks while two have level 2 observatories. From the moderate threat group (n = 15), three have a level 1 network, two have level 2, six have level 3, and four do not have dedicated seismometers. Finally, only 2 volcanoes from the low threat group (n =17) have level 3 networks. All the continental volcanoes and most Galápagos volcanoes are less than 50 km away from a seismometer.

We conclude that several volcanoes should have a better monitoring system due to vulnerabilities in their vicinity. We also propose to design flexible monitoring networks in order to lower the maintenance costs and optimize instrument use. Improving the surveillance system, combined with efficient communication protocols, is critical to help decision making by the authorities and the lay public.

S02.04 Poster

Collaborative feasibility study on suitability and possible design of parametric insurance for volcanic unrest and eruptions in Asia-Pacific

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We report on progress in a multi-institution collaborative project, commissioned by the World Bank, to explore the suitability and possible design of parametric insurance instruments for volcanic unrest and eruptions for five Asia-Pacific nations: Indonesia, Papua New Guinea, the Philippines, Tonga, and Vanuatu. As opposed to traditional indemnity insurance, which pays out based on the size of the actual loss, the recovery under a parametric solution is dictated by an objective measure of the causal 'triggering' event (e.g., the speed of the wind in a cyclone). Parametric policies are commonly used to manage the risks associated with weather volatility and extreme natural hazard events, such as tropical cyclones and earthquakes, and are often considered the most easily implementable risk transfer solution to mitigate the financial impact of disaster response and early recovery efforts. The first phase of the project specifically explores the suitability of developing a parametric solution to provide early 'forecast-based' financing to help evacuation management during periods of volcanic unrest, specifically when a volcanic eruption is likely but has not yet occurred. We acknowledge the risk of that such an approach may oversimplifying emergencies: major evacuations may take place during an eruption, especially in long lived emergencies, while some evacuations occur without a subsequent eruption. We will present preliminary findings from the early stages of this multi- institutional project, including identification of data needs and gaps.

S02.04 Poster

Will they go, or will they stay? Comparing past experiences and population change to predict future response to a volcanic crisis

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This paper considers future response to evacuation orders with respect to a region's recent experience: the 2010 Eyjafjallajökull eruptions. Following the eruptions we investigated how impacted residents responded to and coped with the events. This paper examines the results of that survey against the changing demographic, economic and political structure of South Iceland. Understanding the changing population and how that may affect future response is important given the volcanic threat in the region - the Hekla, Katla, Grímsvötn and Bárðarbunga volcanoes have the highest eruption frequency and greatest volcanic productivity in Iceland. While nearly half our respondents indicated they did not evacuate, officials were pleased with the public's response. There were no fatalities or injuries due to jökulhlaup hazards - the main reason for activating an evacuation order. While most residents showed respect for authority and acknowledged the necessity of the evacuations, some chose not to evacuate because they were caring for elderly parents or did not believe the warnings were relevant to them. The relative small, homogenous population of Iceland coupled with its peoples' strong desire to cooperate contributed to the success of the 2010 evacuations. Within these communities, people are bound together by common beliefs, values and activities. However, the changing economic, demographic and political landscape will test this phenomenon. Recent political changes have resulted in a lack of available resources for police, civil defence and emergency management. There is also economic change occurring with respect to people's livelihoods. Demographic changes most notably include greater international migration and from the capital region. This paper explores the possible challenges this diversity may bring with respect to generating a proactive response to future evacuation orders.

S02.04 Talk

Managing a large volcanic crisis in a small Pacific island: key challenges and learning from the 2017-2018 Ambae eruption, Vanuatu

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Managing an emerging volcanic crisis and a subsequent sustained eruption at a small volcanic island can present some unique challenges to monitoring agencies and governments. For instance, the small size and constrained distribution of the inhabitable areas around the volcano imply little room for manoeuvre and can make the decision of evacuating people and assets particularly difficult. The fundamental drivers behind government response can also vary drastically between the beginning of a crisis and later during a sustained, established eruption. The 2017 eruption at Ambae, Vanuatu, triggered the first whole-island evacuation in the history of the country. After a period of relative quiescence and repatriation, a renewed and sustained activity in 2018 drove the government to initiate a second phase of evacuation. Here we present the coordinated response to the 2017-2018 Ambae eruption by the Vanuatu government, monitoring agencies and partners and how decision making unfolded at key tipping points during the crisis. We illustrate how the drivers for evacuation varied in a few months and the main challenges they presented to the monitoring scientists, especially with regard to communication with the government and general public. We review how uncertainty can intertwine with Volcanic Alert Level systems and how, coupled with hazard maps and impact assessment, Vanuatu successfully managed one of the largest eruptions in the world over the past two years.

S02.04 Talk

Development of an efficient monitoring infrastructure at Nyiragongo volcano (D.R. Congo). The challenge of capitalizing on 13 years of experience on hazard and risk assessment

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The 2002 eruption of the Nyiragongo volcano has strongly affected the rapidly growing city of Goma (D.R. Congo). Despite the previous 1977 eruption, the population and authorities weren't well prepared to such disaster that was worsen by regional scale political tensions. Since 2005, the RMCA and NMNH/ECGS have developed, in partnership with the Goma Volcano Observatory, study and monitoring capacities adapted to the very specific context of this region. Security and logistics issues, and the necessary development of the local expertise are the most important challenges that teams are facing to significantly improve preparedness and reduce the volcanic risk. We draw here the lessons of this 13- year experience, with a view to consolidating the achievements and making these results sustainable. The developed monitoring tools are now reaching a high level of maturity with the RESIST project (www.virunga-volcanoes.org/data-doc/projects): the monitoring system today consists on the ground of a network of 16 seismic and 17 GNSS stations completed by recurrent visual observations to follow the evolution of the craters of the Nyiragongo and Nyamulagira volcanoes (time-lapse camera, UAV...). Satellite techniques are also used: InSAR time series (SBAS/MSBAS) or amplitude images (casted-shadows) are used to study the eruptive dynamics and quantifying the lava lake fluctuations respectively. Sentinel-5P that is now used to monitor the SO_2 flux is showing very encouraging results. From the societal side, GeoRisCA project output thematic maps on population density, vulnerability and risk perception have been shared, discussed and improved with the local scientists, authorities and the Civil Protection, and will be taken into account in the future contingency/evacuation plans. Today, despite these scientific advances, the greatest challenge is to make them sustainable by guaranteeing the maintenance of the tools and the strengthening of the local expertise. This cannot be envisaged without taking into account the realities on the ground.

S02.04 Poster

Considerations in Partial (Phased and/or Voluntary) Evacuations

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Historically, evacuations in the face of volcanic threat are defined by geographic area, and all residents of that area are evacuated at once. However, where volcanic unrest in an area is worrisome but still uncertain to lead to eruption, some communities might resist total evacuation and, instead, propose partial evacuation that starts with only some segments of the population and expands only if an eruption becomes more certain. In principle, partial, phased evacuations could start with risk-intolerant volunteers and become more complete as risk increases. That seems reasonable. But beyond volunteers, who will be next? Can businesses choose for themselves whether to evacuate? If businesses are to remain open, will employees and customers still be around? If public services like water, electricity, public safety/police, etc. are to be maintained, who will maintain them? How long should schools be kept open and, if they are closed, who will take care of the children? What is the minimum subset of a community needed to remain viable?

The concept of partial (phased and/or voluntary) evacuations may be attractive in principle but difficult in the details. The cost-benefit method proposed by Woo (2008) for evacuation decisions could in principle be modified to treat different groups separately, e.g., the elderly, children, those essential for community services, etc. But if that's done, decisions by or about one group will impact other groups and the respective costs vs. benefits must be modified accordingly. In addition, the decision process is notably easier for predictable, well-understood hazards like floods and wildfires than for less frequent, less predictable hazards like volcanic eruptions. At volcanoes, especially those prone to unrest that does not culminate in eruptions, uncertainty is a major factor. Clearly, an extensive community dialogue would be needed before adopting the concept of partial evacuations, either voluntary or involuntary.

2018 fissure eruption in Leilani Estates on Kilauea's lower east rift zone

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At 2:15 pm local time on April 30th, 2018, Kīlauea's East Rift Zone eruption changed abruptly with the collapse of Puʻu ʻŌʻō's crater floor. Earthquakes over the next four days recorded dike propagation downrift. On Thursday, May 3rd, the first fissure opened in the Leilani Estates subdivision, shifting Kīlauea's activity level to "warning". Rapid evacuation of residents was ordered by the Hawaiʻi County Civil Defense Agency.
Twenty-four fissures opened, migrating uprift and downrift in alternating series, over the following two weeks. The first 16 fissures exhibited vigorous spattering and produced near vent lava pads and spatter mounds. On May 19, activity dramatically increased with low lava fountains feeding fast moving channelized lava flows that cut a major highway (Hwy 137) and rapidly buried a subdivision. Although evacuation orders had been issued, several people were trapped and had to be rescued.
After the opening of 23 fissures, a pattern of westward- (uprift-) migrating reactivation of old fissures began. Prior to these reactivations, the primary activity was east of Leilani Estates subdivision, where people were permitted to return for their belongings. As activity migrated back uprift, lava fountains fed flows that moved into and buried the eastern portion of the neighborhood under >10 m of ponded lava. Fortunately, no one was hurt. Sustained lava fountaining activity in the eastern portion of the subdivision produced a wide ʻaʻā flow,which overran a portion of a geothermal power plant. A channelized flow formed, covered several miles of a second major highway (Hwy 132), and eventually reached the ocean destroying all properties in the Kapoho community.
Many residents have been permanently displaced after losing their homes. While some have been stranded and injured by lava, so far there have been no fatalities as a result of eruptive activity.

Unrest Cotopaxi volcano: A sample of difficulties of the population during the evacuation process of August 2015

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Cotopaxi is an active volcano (5897 m. a. s. l.), It is Located in Ecuador on the Andean Mountain Range. The last big eruption was in 1977 with magnitude VEI4. Lahars traveled the Cutuchi river and produced destruction in Latacunga city, 35 km SE that volcano.

In 2002, Cotopaxi volcano registered an important activity, but it did not produce an eruption. Since Abril 2015, the instruments detected an increment of seismicity. This information was reported by Instituto Geofísico.

The eruption on August 2015 was characterized by explosions, S02 degassing, an emission of 8 km, and ashfalls to NW of volcano. The eruptive episode never surpassed magnitude VEI2, nevertheless, the evacuation process in Latacunga city experimented severe inconveniences and accidents.

This investigation was made in the Mercado Mayorista of Latacunga (MML). It was geographically located between the Pumacunchi and Cutuchi rivers. The place has a high threat destruction by lahars. The popular market put together, 1000 merchandiser, 4000 vehicles circulate and more than 10,000 buyers.

A random research survey to 210 merchants evidenced evacuation failures during the morning in 15 August. The main results showed that 57 % of merchants evacuated, 73% did not about volcanic hazard and risk and the evacuation time exceeded (120 minutes).

Misinformation, lack of education, poor communication were factors which generated panic among merchants. There was a general risk situation, car accidents, merchandise theft and other disturbs. These results have suggested that the critical aspect to avoid repeating the same mistakes is strength communication role as a fundamental role in the decisions.

Finally, the balance for the events occurred around MML on August 15th helped as an experiment for the population and authorities to identify lack preparation society. The socialization of information will help implement new education strategies and in the future reduce their vulnerability.

S02.04 Poster

Characteristics of evacuation shelters for volcanic eruption in Japan

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After the eruption of the Ontake volcano in September 2014, 58 people were left dead and 5 people were missing; most of the deaths were injuries from ballistic projectiles. In response to this disaster, the Cabinet Office, Government of Japan published the "Guide to Enhancing Evacuation Shelters, etc. on Active Volcanoes" (hereafter it is abbreviated as the "shelter guide") in December 2015. After this guide was published, the installation of evacuation shelters began around several volcanoes. In Japan, two types of evacuation shelters are installed around active volcano. One is a special facility to use only for an evacuation of volcanic eruption. Reinforced concrete (RC) construction is common for special facilities. Steel construction is also used as temporary shelters at construction sites of a road and an erosion control dam. Special facilities are installed for evacuation and remained unused on regular days. The other is a dual-use facility where the shelter function is added to tourist facilities (rest house, mountain huts, observation deck, bus stop, toilet, etc.). When a portion of a tourist facility is turned into a shelter by RC construction, tourists can evacuate in the event of an eruption. The "shelter guide" demonstrated a method to use aramid fiber to reinforce the roofs of wooden buildings. Reinforcement using aramid fiber is currently being undertaken in mountain huts around Ontake volcano. Most of evacuation shelters have been built on the basis of experiences of past eruption disasters in Japan. In order to further improve evacuation shelters, detailed research is required regarding the assumed eruption scale and style, collision velocity and energy, a structure suitable for the facility, suitable reinforcement method, etc.

S02.04 Poster

Management of volcanic crisis after long quiescence periods: The case of El Hierro, Canary Islands, Spain

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The management of crises in volcanoes that have not erupted in historical times are specially challenging. As well as the uncertainty inherent to any volcanic system and the range of potential hazards that could present, at operational level, the variety of disciplines involved in forecasting and responding to volcanic emergencies further complicate a typically complex situation. Here we discuss the experience gained from the island of El Hierro in the Canaries.

El Hierro, the westernmost and youngest island in the Canaries, entered eruption in October 2011 for the first time in recorded history. It was also the first eruption in the Canaries in 40 years. Being submarine, the eruption did not cause personal or material damage, but had an important impact on the small local businesses as well as causing fear and anxiety to some of the local population. Informal discussions with the concerned public indicate low levels of awareness and preparedness and the need for better information strategies targeted to the local context.

Analysis of accounts from scientists and emergency managers, as well as those of media reports, highlighted several obstacles to the smooth management of the crisis, which we have grouped under the topics of uncertainty, inexperience and differences in organisational culture.

We conclude that, while some of these three main issues raised require more research and understanding of the volcanic system, many others can be solved or mitigated with recognition of the different needs of different groups, improved communication, interpersonal relations and a detailed protocol, underpinned by an appropriate legal framework. For example, as well as detailing the type, content, amount, format, frequency, storage and use of the information during the crisis, the protocols should consider aspects such as confidentiality, inclusiveness, ethics, financing and legal aspects such as the liability of scientific groups.

S02.04 Poster

Resettlement problems of threathened people from prolonged Sinabung eruption, Indonesia

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Since the awakening of Sinabung Volcano on August 2010, the volcano has been increasing in activity to Awas (Warning Level, the highest from 4 levels) 3 times. The last Warning Level was issued on 2 June 2015, and since then eruption has been continuing. In the period of Sinabung activities, there were 17 casualties, caused by eruption on February 1, 2014, at 10.30 am (local time) in Sukameriah village (3 km from the summit) and 9 casualties after a pyroclastic flow followed by surge hit Gamber village (4.5km km from summit) on May 21, 2016, at 16:48 (l0cal time). In both areas, casualties were caused by breaking through of the exclusion zones.

Due to prolonged eruption (from June 2015 up to now) and highly threatened people around Sinabung, evacuees were transferred to temporary (huntara) and permanent resettlements (huntap). There are 3 three phases in transferring evacuees to resettlement areas. The first phase (3 villages) was completed in 2016, second phase (4 villages) targeted to finish in 2018, followed by phase 3 (11 villages). There are problems in the process of resettlements include location is not as preferred, cultural discrepancy and cultural bonding, interests of a particular group, facilities are not met, livelihoods, different purposes of use, etc.
Continuous eruptions lead to high cost of disaster management, social and economic disturbances, psychological impact (pressure to meet the needs and safety), and increasing demands of community needs (basic needs, employment, education, safety and socio- cultural).

Long term strategies are needed to follow up the process of resettlements include program of economic sustainability through community empowerment, education, infrastructure facilities, monitoring, evaluation and development of activities.

S02.04 Talk

Hospital disaster training assuming urban volcanic disasters

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In Japan, a land of disasters, in recent years, several volcanic disasters (VD) have occurred such as the eruption of Mt.Ontake and Mt.Shirane, and VD as well as earthquake disasters are drawing attention. However, these VD in Japan often occur in deep and remote mountainous areas and rarely in populated areas, and hospital disaster training assumed for volcanic disasters (HDTAVD) are hardly performed and few cases are reported. On the other hand, Kagoshima-city is located only 6 kilometers away from the crater of Sakurajima, which is one of Japan's main active volcanoes, where 600,000 people lives. Our hospital is located at the center of the city. Sakurajima has erupted many times in the past, including the most powerful eruption in 20th-century in Japan, approximately 100 years ago.

Once Sakurajima erupts hard, hospitals will not be able to avoid suffering from damages and accepting many victims. However, although Kagoshima-city currently conducts drills that assume the occurrence of VD, these mainly deal with the evacuation of residents or similar issues, and almost no HDTAVD are being conducted.

Based on above situation, we began HDTAVD from 2018. Specifically, "Trauma Treatment and Facility Countermeasures", "Calculation of Food Amount to be Preserved by Hospitals" and "Training for Many Deaths" were conducted.

These trainings are pioneering urban HDTAVD. In Japan, the eruption of Mt. Fuji also has occurred in the past, and our training can be a prototype of training to be done in urban areas such as Tokyo from now on. We are introducing our HDTAVD to discuss current issues and future tasks.

S02.04 Poster

Hiker dynamics data on Mt. Fuji and climbing road precise topography data for volcanic disaster prevention

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Mt. Fuji is a representative active volcano in Japan, it is a sightseeing spot of World Cultural Heritage registration where many tourists visit from home and abroad. Administrative agencies responsible for volcanic disaster prevention are required to be informed of the risk of a volcanic eruption to tourists including hikers, the necessity of advance disaster prevention such as precise eruption information transmission.

From 2015, we use the method of detecting the beacon signal of the hiker with a receiver installed at several places up to the summit of Mt. Fuji, collects and analyzes about 3000 hiker real-time kinetic data over the three years, we conducted demonstration experiments to “visualize” hiker behavior.

As a result of analyzing the data, about 70% of the monitor hikers stayed at the summit in the early morning time zone, and it turned out that many hikers were aiming for “Goraiko (Sunrise)”, such as hikers of Mt. Fuji the characteristics of the behavior became explicit.

Considering the characteristics of climbing Mt. Fuji by hiker’s behavior analysis using the data collected in this way, we are considering reflecting it in the evacuation guidance plan of hikers at the time of the volcanic eruption.

Mountain climbing roads In addition to the detailed shape of mountain paths, rock falls and instability as well as conducting a thorough verification test of the surroundings including climbing roads using the latest laser measuring instruments. It grasped the distribution of rock mass.

Based on this data, we will quantify the shape and gradient of the mountain path, set indices on the difficulty level of the mountain path, and plan to utilize the set of evacuation places and routes that are easy to evacuate at the time of the eruption.

Efforts of hiker safety measures utilizing IoT in Mt.Fuji

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Mt.Fuji is an active volcano with a history erupted about 300 years ago, and when there are eruptions during summer mountain period where many hikers visit, they have risks of enormous damage. At Mt.Fuji, likewise other mountainous areas, there is no mechanism for grasping the number and dynamics of hikers in real time. It is difficult to search the rescue of the affected hikers, problems of a massive amount of personnel, time, cost, etc. are expected to occur.

Sufficient safety for hikers has not been secured in Mt.Fuji, because active countermeasures are limited by the dilemma with natural environment preservation. Therefore, it is necessary to take measures to guarantee hikers' safety and security, by collecting climbing information.

At Mt.Fuji, about 70% of the hikers for the first time. Communication on volcanic eruption risks and emergency evacuation at these hiking beginners is a big issue.

“Mt.Fuji Challenge” is a project to utilize IoT technology to grasp the actual condition of hikers’ behavior in real time, leading to preventive measures against safety measures and eruptive disasters.

Explicitly, the hiker journey with a small beacon and records the time passed through a plurality of receivers installed in sections up to the summit. By analyzing the data with the cloud server, we can grasp the location of the hikers, the hiking time, the walking speed and so on.

By using a small precision laser measuring device, it is possible to prepare three- dimensional topographical data of the hiking road and to prepare a walkability index by the shape of the mountain path.

Utilizing these data, we carried out demonstration experiments with volcano researchers and local governments for three years to promote measures against eruption and open social implementation of open data platform.

Five years of unusual seismic activity in the region of the Chiles-Cerro Negro volcanoes on the Colombia-Ecuador border

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Since August 2013, significant seismic activity has been detected in the Chiles-Cerro Negro volcanic region, on the Colombia-Ecuador border. A cooperative broadband monitoring network was installed by the Servicio Geológico Colombiano (Colombia) and the Instituto Geofísico of the Escuela Politécnica Nacional (Ecuador). Since November 2013, more than 600,000 VT earthquakes have been recorded with high rates and energy. In addition, the occurrence of large VLPs has been remarkable, but so far, no eruption has resulted. Major VT swarms occurred in August-October 2013, March-May 2014, September-December 2014, and March-April 2018. By the end of 2014, roughly 400 earthquakes > M 3 had occurred with a maximum rate of 8000 earthquakes per day. The largest was a 5.6 ML on October 20, 2014. This event produced InSAR coseismic deformation of ~23 cm. Most VT earthquakes are located in two clusters beneath the southern flank of Chiles. The first cluster is 1 to 3 km south-southwest of the volcano with depths between 1.5 and 6 km, and the second cluster is 5 to 8 km southeast of the volcano, with depths between 6 and 10 km. Using particle motions, most VLPs between October 20, 2014 and March 2018 were located south of Chiles Volcano, near the 2014 InSAR source. A VLP registered on February 14, 2015 was likely located close to summit of Chiles. No degassing or changes in the hydrothermal system have been detected. We infer that magma intrusion and resulting fluid exsolution at depths greater than 5 km are driving seismicity. However, earthquakes are failing in a manner consistent with regional tectonics. Thus, seismicity is likely controlled by an interaction of magmatic and tectonic processes. Monitoring and assessing this prolonged period of activity remains a great challenge for the institutions in charge of scientific and risk management of the crisis response.

S02.04 Poster

Hospital evacuation plans when a large- scale eruption of Sakurajima volcano is expected are inadequate and should be revised. Viewpoint of medical care providers

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The city of Kagoshima, located in Kagoshima Prefecture, includes part of the Satsuma Peninsula and Sakurajima and has a population of 600,000. Sakurajima volcano is one of the most active volcanoes in Japan with a history of large-scale eruptions. Because of its proximity to Sakurajima volcano, Kagoshima City must be prepared for a scenario in which a large modern city is faced with a nearby large-scale volcanic eruption. Medical care providers must be familiar with the dangers and follow up procedures of significant ash falls and lapilli. Local volcanic emergency plans require people living on Sakurajima to evacuate to safer regions when potentially dangerous volcanic events are expected. However, there are no such evacuation plans for Kagoshima City residents, and they remain confined to the city even if the wind blows volcanic ash from Sakurajima. There are more than 500 medical institutions in Kagoshima City and most of them have supplies for about three days and are not equipped to function for periods of 1-week or more even with emergency rationing. Kagoshima City needs to consider either how to maintain supplies to the hospitals when emergency conditions longer than 1-week are in force, or how to evacuate in-patients in advance. If complete evacuation from Kagoshima City's hospitals became necessary, a number of those in-patients would need to be evacuated to hospitals outside Kagoshima Prefecture. However, according to the present plans, transport systems for disaster cannot be used before the disaster happens, and do not work after a large-scale eruption occurs due to the heavy ash falls. As medical care providers of Kagoshima City, we believe it is necessary that Kagoshima City examines these inconsistencies, and designs new principles of organization and practice better suited to future contingencies.

Impact and risk assessment role in the emergency planning at Vesuvius and Campi Flegrei

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The impact analyses of a volcanic eruption on the built environment require a comprehensive framework of studies, surveys, and simulations that include all the different eruptive phenomena and their possible impacts on existing buildings and infrastructure. Moreover, to define effective Disaster Risk Reduction, emergency planning and management strategies in volcanic high risk- prone areas – such as the Campania Region – a broader approach is necessary. In fact, a basic consideration is that the cumulative effects given by a complex eruption produce extremely variable impacts on constructions. Thus, the effects depend on the specific time history of the event, on the building typologies, and on their level of vulnerability.
This specific approach has been recently formalized to evaluate the impact of a sub-Plinian eruption in the Vesuvius and Campi Flegrei area through the development of a numerical model for the definition of impact scenarios. A dynamic model, able to evaluate the cumulative damage distribution in time and space, is developed within several national and international projects. The eruptive phenomena considered include earthquakes, ash fall, pyroclastic flow, and lahars, and their impact on relevant elements at risk, such as population, buildings, critical infrastructures, transport networks and economy is assessed through dynamic scenarios. The basic assumption is that the impact damage due to a volcanic eruption depends on several disastrous events whose effects are cumulated in the final scenario. The damage level along the eruptive history is strictly linked to the number of events, their range of intensity, and the distribution in time and space.
The tool is available to the Italian National Department of Civil Protection to quantify the potential losses consequent to a possible eruption of Vesuvius or Campi Flegrei. The results allow emergency planners and decision makers to assess the resources needed to improve the preparedness measures needed to face the event and to implementat technically feasible and cost-effective mitigation measures on buildings and infrastructure to reduce the expected damage.

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S02.05 - Assessing and managing volcanic hazards and risk for critical facilities

The effect of volcanic activity on ships

Paul Cragg

Private

In many parts of the world active volcanoes are on or near the coast and close to port facilities. Ships may therefore offer the best means of evacuation or getting relief to coastal communities affected by an eruption. Ships may be less affected by eruptive phenomena than aircraft and their means of access to the endangered area may be less likely to be cut off than road or rail transport. However, little research has been done on what adverse effects a vessel may experience when confronted by an erupting volcano.

For a ship's crew to be able to assess their vulnerability, and therefore availability to offer assistance, they require sufficient data to be able to conduct a proper risk assessment; this information is not presently available. In my studies I have attempted to address the adverse effects of volcanic eruptions on a vessel. These include loss of stability, visibility and navigational position fixing data from tephra fallout. Capsize, fire and structural damage may occur if the vessel is struck by a pyroclastic flow. Submarine eruptions may lead to stability loss as well as propulsion failure and resistance to motion. Lahars can also result in stability loss but are also liable to break a vessel clear of her moorings and perhaps grounding. Bradyseismic activity may result in a vessel becoming grounded and unable to move.

As a practicing seafarer I need to know what these effects may be, and how to safely overcome them. By attempting to quantify some of the effects a ship might experience I hope to assist ship's Captains to make a more informed risk assessment and therefore more likely to be of assistance to the local community and civil protection organisations.

A new probabilistic lava flow hazard assessment for the Idaho National Laboratory, eastern Snake River Plain, USA

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We present a new conditional and unconditional probabilistic lava flow hazard assessment for the Idaho National Laboratory (INL) nuclear facility on the eastern Snake River Plain (ESRP), USA. The INL covers 2,310 km^2 of the ESRP and contains the highest density of nuclear reactors on Earth. Our assessment: (1) uses two approaches to estimate the locations of future eruptions on the eastern Snake River Plain (ESRP), (2) stochastically samples lava flow parameters from observed ESRP values for use in MOLASSES, a lava flow simulator, (3) determines the probabilities of lava flow inundation for the INL through Monte Carlo simulation based on two different models of ESRP volcanism (single eruptions and whole eruptive events), and (4) couples inundation probabilities with recurrence rates in order to determine the annual likelihood of lava flow inundation for the INL. Our results suggest a relatively high conditional probability of inundation (31.1-32.1%) arises due to the position of the INL in an area of spatially dense volcanic activity and the location of the site within a low topographic region relative to its surroundings, which tends to focus lava flows from vents outside the INL boundaries onto the property. The annual probability of inundation ($8.4 \times 10^{-5} - 1.8 \times 10^{-4}$) exceeds the International Atomic Energy Agency's guideline for which further hazard assessment should occur (10^{-7}).

S02.05 Talk

International Atomic Energy Agency Technical Document on Volcanic Hazard Assessments for Nuclear Installations

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Volcanic hazards assessments for critical facilities, such as nuclear power plants, often must consider the potential effects from phenomena that have very low likelihoods of occurrence. The International Atomic Energy Agency recently released a Technical Document that provides detailed guidance on conducting practical volcanic hazards assessments that include rare phenomena, using both deterministic and probabilistic approaches. This guidance develops a graded approach to the analysis, and provides a range of model complexities for assessing hazardous volcanic phenomena. Although this guidance focuses on the safety of nuclear installations, it is applicable to other sites that warrant consideration of low likelihood volcanic hazards that have potentially high consequences. We present several recent examples of application of the Technical Document to analysis of volcanic hazards at nuclear facilities.

Probabilistic estimation of long-term volcanic hazard under evolving tectonic conditions in a 1 Ma timeframe

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Risk assessments in relation to the siting of potential deep geological repositories for radioactive wastes demand the estimation of long-term tectonic hazards such as volcanicity and rock deformation. Owing to their tectonic situation, such evaluations concern many industrial regions around the world. For sites near volcanically active regions, a prevailing source of uncertainty is related to volcanic hazard. For specific situations, in particular in relation to geological repository siting, the requirements for the assessment of volcanic and tectonic hazards have to be expanded to 1 million years. At such time scales, tectonic changes are likely to influence volcanic hazard and therefore a particular stochastic model needs to be developed for the estimation of volcanic hazard. The concepts and theoretical basis of the proposed model are given and a methodological illustration is provided using data from the Tohoku region of Japan.

Probabilistic tephra hazard assessment at the nuclear facility in Hanford, Washington (USA): can airborne ash concentrations really exceed 1,000 mg/m^3?

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Hanford, Washington (USA) contains a multi-billion-dollar nuclear waste reprocessing facility and lies 200 km east of Mount St. Helens (MSH). Ash from future MSH eruptions could threaten air filtration at this plant. We estimated the tephra-fall thickness (T) and average airborne ash concentrations (C) at Hanford having an annual probability of occurrence >1e-04 (denoted T_{10k} and C_{10k} respectively) by combining the annual probability of a MSH plinian eruption (4 eruptions in the last 500 years=0.008) with the probability of a given T or C at Hanford given an eruption. We evaluate the latter using Monte Carlo methods, running about 10,000 simulations of the Ash3d transport model. In each simulation, we randomly choose historical winds from the European Community's Interim- ERA model, and an erupted volume from the range of Holocene MSH volumes (0.008-2.3 km^3). Plume heights and durations are chosen using empirical correlations among volume, height, and eruption rate. Results indicate that T_{10k} = 5.11cm, and C_{10k} = 1,513 mg m^{-3}. This airborne concentration greatly exceeds the highest known co-eruptive measurements of total suspended particulates (TSP), which range up to ~30 mg m^{-3}. TSP is typically measured in sheltered areas and, unlike our result, does not include falling ash. Our value of C_{10k} is consistent with independent calculations using the simple formula $C=M/u$, where M=mass deposit accumulation rate and u= average fall velocity. From this formula, accumulation rates of ~1 cm/hr, which are common during large eruptions, imply airborne concentrations of hundreds to thousands of milligrams per cubic meter. During heavy ashfall, most fine ash falls as aggregates. Whether falling ash is ingested into lungs or air filters depends on aggregate size, fall rate, and fragility of aggregates, among other factors.

S02.05 Talk

Probabilistic assessment of thickness of tephra using high resolution geological record in western Shikoku

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Large explosive eruptions are low-frequency natural disasters that can have enormous effects. In particular, it is necessary to properly assess the risk of tephra fall which may affect wide area. In this study, we carried out probabilistic assessment using high resolution tephra data in the Uwa basin.

For the probabilistic assessment, 48 tephra data from about 60 ka included in the boring core (core UT) in the Uwa basin by Tsuji et al.(2017) were used. These tephra data are divided into two: tephra layers and tephric sediment layers. Here, a "tephra layer" is highly reliable layer that records the thickness of tephra and the age of ash fall. "Tephric sediment layers" are layers that record the age of ash fall but have low reliability of the thickness. In addition, it is suggested that some discordances may exist before about 350 ka.

Based on the above, we carried out assessments using only highly reliable data since about 350 ka. In addition, we carried out assessments using all data for considering data of a longer period although the reliability is inferior. In the assessment, we assessed the case of using only the highly reliable tephra layer and the case of including the tephric sediment layers. In calculating the probability of exceedance in the year, Poisson process was used based on the frequency distribution of thickness of tephra.

As a result, the probability of exceedance in the year of tephra fall that layers will remain in the stratum in the Uwa basin is a low frequency event of 10-4 or less. In addition, the probability that the tephra fall exceeds about 40cm (Equivalent to AT which is the thickest tephra in the core UT) is 2.8 - 5.0 x 10^{-6}, which is a very low frequency event.

Assessing the Vulnerability of Nuclear Power Generating Plant to Volcanic Ash

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Eruptions of the Icelandic volcanoes Eyjafjallajökull (2010) and Grímsvötn (2011) caused ash to be dispersed across NW Europe. These events highlight the need for future ash hazard probabilities to be assessed quantitatively for European countries (and elsewhere), and for comprehensive appraisals of potential consequences for critical infrastructure, economic continuity and other societal impacts. A two-day expert elicitation workshop on potential effects of volcanic ash on nuclear power plant equipment and operations, in the context of a UK power station, was held at Hinkley Point B NPP, from 25-26 August 2015. The workshop participants were station engineers and power utility technical specialists, and academic volcanologists. This paper provides an overview of the approach adopted, and results from two structured elicitations that were conducted during the workshop. These involved an ash impact ranking exercise using a probabilistic pairwise (stated preference) comparison survey approach, and a structured elicitation conducted for uncertainty quantification of selected factors that could affect power generation operations: e.g. ash event probabilities, ash concentrations and loads, and equipment susceptibilities. Key findings from analyzing the experts' responses are presented here, providing a basis for pinpointing potential critical issues for continued station operation during a significant ash fall episode. Some apparently anomalous or contradictory expert judgements identify issues that merit further investigation, and other elicitation results suggest item uncertainties which could be better constrained by simple tests and experiments.

The potential impact of Nyiragongo lava flow on resources of volcanic crisis management in Goma (D.R. Congo)

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During its two historic eruptions, in 1977 and 2002, lava flows from the Nyiragongo volcano spread near and in Goma city. The very high number of victims was the result of the rapid lava flows, and their emission near inhabited areas. In addition, because of the absence of effective strategies for volcanic crisis management, the impact of these eruptions on resources (health infrastructure, schools, places of work, points of sale and storage of food and water) and the economic consequences of this eruption were significant, and felt in the long term. Today, this densely populated area remains highly threatened by a future eruption.

At the city level, what were the essential resources that were used during the Nyiragongo 2002 eruption? And nowadays, where are located these essential resources in relation to the lava flow hazard? In a context of data scarcity, this study proposes a spatial approach to analyze the distribution of resources - needed and available - taking the specific example of the occurrence of a new volcanic eruption in Goma city. To reach this objective, it refers to a database of about 10,000 resources of volcanic crisis management categorized and located within the city, associated to a lava flow probability map developed in the framework of the GeoRisCA project (BELSPO n° SD/RI/02A).
The results of this study will contribute improving knowledge regarding the resources needed and available in times of crisis, in order to provide the authorities with a tool to optimize their management. It will allow rationalizing the storage of useful equipment and resources during a crisis and improve their spatial distribution. And as such, it will constitute a direct input for the contingency plan of Goma city.

S02.05 Poster

High resolution explosive eruption history of caldera volcanoes in the SW Japan-Ryukyu volcanic arcs reconstructed by Quaternary sediments of the Uwa basin, southwest Japan

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Caldera eruptions are low-frequency natural disasters that can have enormous effects To assess the risk associated with such catastrophic volcanic hazards over long periods, a comprehensive record of explosive volcanism and recurrence rates provided by tephra sequences preserved in Quaternary deposit is useful. We analyzed the distal tephra record in the core UT from the Uwa basin (Tsuji et al., 2017) on western Shikoku Island to reconstruct high-resolution history of volcanic eruptions on SW Japan-Ryukyu volcanic arcs. In addition we analyzed the proximal tephra erupted before the caldera-forming eruptions in Kyushu.

1. The core UT includes more than 50 tephras mainly from the volcanoes and calderas in Kyushu (includes Aso, Aira, Ata and Kikai calderas) in the 800 ky sediments. Above 50 m depth, all known widespread tephras from Kyushu younger than 350 ky were included in the sequence. We expect this well-preserved tephrostratigraphy to be particularly useful for elucidating the frequency of eruptive events and assessing the risk associated with catastrophic volcanic hazards as reported by Onishi et al. (2018).
2. Tephra layers petrographically and geochemically similar to the pyroclastic products of caldera-forming eruptions such as Aso-1, -2, -3 and -4 were often deposited below or above them, suggesting those are regarded as products of the precursor eruption of caldera eruption.

In addition, we verify the evidence of precursor eruption of Aso-4 eruption in the proximal area in Kyushu in this presentation. These observations are important for understanding magma evolution of volcanoes in the SW Japan and Ryukyu volcanic arcs.

S02.05 Poster

Tephra fallout hazard map construction with statistical emulator: application to the Long Valley-Mono Craters region

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Statistical emulators play a key role in the construction of geophysical hazard maps. They approximate the output of numerical models of geophysical processes at untested scenarios based on existing runs. This makes finding the *critical boundary* in the parameter space, which defines scenarios that would lead to catastrophic event at a given location, much more efficient. Gaussian Process emulators can be viewed as an interpolation technique that also quantifies the uncertainty in the estimation. It is thus an ideal method for emulation, and has been applied to generate hazard maps of pyroclastic flows with success.

In this work, we apply Gaussian Process emulators to tephra transport model Ash3d to construct tephra fallout hazard maps. The main challenge is to select the effective and sensitive parameters for the emulator given high-dimensional input parameter space. Additional uncertainties could be derived from the discretization of initial conditions (e.g., wind speed at different elevations).

By studying the analytical solution of the advection-diffusion equation, and examining the interaction between simplified initial conditions and the corresponding outputs (thicknesses), an appropriate combination of parameters is proposed and chosen to construct the emulator. Emulators are then used to calculate the probability of tephra fallout hazard in the Long Valley-Mono Craters region, and to quantify the corresponding uncertainty under different scenarios. Our work marks the first attempt to apply statistical emulator to tephra fallout hazard quantification. The presented emulator and implications from its application may benefit future studies on hazards associated with tephra transportation.

S02.05 Talk

Potential cascading effects induced by volcanic eruptions in Santorini Island on critical infrastructures

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Cascading effects triggered by natural or anthropogenic hazards are recently emerging as a key topic in the field of risk assessment, disaster risk reduction and emergency management. In literature, only a limited number of studies is focuses on the complex issues of cascading effects modelling to quantify the potential impact on the elements at risk (people, buildings, critical infrastructures, economy, environment, etc.).
Generally, sequences of events (e.g. an earthquake triggering a landslide which in turns triggers a power outage) can involve the same element at risk and the combined effects of cascading phenomena can strongly amplify the impact caused by single events in terms of extension of the impacted area and damage levels. The final impact on territory can be very important and its underestimation could result in a failure management and emergency planning strategies in place. This presentation discusses from a theoretical point of view the modelling needs and main issues to be taken into account in the development of cascading effects simulation tools aimed at effectively support decision-makers in their preparedness and disaster mitigation strategies, in the framework of emergency planning at local, national and international level, with special attention to critical infrastructures.
The reference pilot application concerned the simulation of the potential cascading effects triggered by a reactivation of the Nea Kameni volcano in Santorini island. Based on the potential hazard scenarios defined with the support of local and international experts, different Time Histories have been analysed and the consequent cascading effects chains and cumulative impacts quantified.
The model has been developed in EU-FP7 project SnowBall (Lower the impact of aggravating factors in crisis situations thanks to adaptive foresight and decision-support tools, 2015-2017).

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S02.06 - Use and effectiveness of volcanic hazard and risk tools in volcanic crisis management

Use of hazard and risk data in design of parametric insurance for volcanic unrest and eruptions in Asia-Pacific

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Parametric insurance requires independent, objective, transparent and reliable real-time data which can be used as a proxy for hazard and risk, in order to quickly trigger insurance payouts after natural catastrophe events. A single data stream may be used directly as the basis for the parametric index; for example, daily rainfall, as estimated based on data from satellite-based sensors, above a certain threshold in a certain area may trigger a payout on an insurance contract. Or single or multiple data streams may be incorporated into a locked catastrophe risk model to estimate the losses generated by the event, with those estimated losses used as the basis for a payout. Further, in order to price an insurance contract, some historical timeseries for the real-time dataset is required, the longer the better, and if not an exact replication of the real-time data stream then as close a replica as possible is required. If the historical dataset is not sufficiently long to encompass a full range of potential hazard events, then simulation in numerical models is used to bootstrap the original dataset. While parametric insurance solutions for low and high rainfall (for drought and flooding), tropical cyclones (usually including wind and ocean hazards), as well as low and high temperatures, are relatively mature instruments, a parametric basis for capturing the multiple hazards and impacts of volcanic eruptions has not previously been developed. We report on progress in a multi-institution collaborative project, commissioned by the World Bank, to explore the suitability and possible design of parametric insurance instruments for volcanic unrest and eruptions for five Asia-Pacific nations: Indonesia, Papua New Guinea, the Philippines, Tonga, and Vanuatu.

S02.06 Talk

Modern approach for emergency planning in areas exposed to volcanic hazards: risks for the residents

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Information about impending hazards is a mighty delicate process because of the many factors to be considered and the necessity to give a balanced and complete picture of the situation at the same time.

Return periods of events are just the starting point to define a multi-layered process that must take into account other elements such as: competent monitoring activities of authorities and their sanctioned rules and/or indications: the role of scientific community in gathering all available datas and studies to define the correct framework for both emergency planning and risks management; the knowledge and expertise of practitioner to define feasible and effective emergency and risks managing plans; residents awareness and knowledge and the consequent most likely reacting patterns to an actual event.

It is highly interesting to compare current knowledges and practices with well-known and documented examples in modern times in order to assess both differences and common patterns to be rightly put in connection with both historical and social/sociological similarities and differences.

A lead role in the civil protection system is obviously played by local communities, being involved in all activities on the field and responsible for local support. It is hence crucial to define an effective communication plan to make the emergency plan known and familiar to the wider majority of residents. To be actually effective, communication activities must be thoroughly planned and executed both in peacetime and in emergency situations. In both conditions, no improvisation can be tolerated and protocols must be clearly defined and neatly followed. To define correctly all this system, it is rather crucial the closest relationship between local communities and scientific institutions in order to tap directly into the primary sources of information and state-of-the-art best available practices.

Using BET_UNREST probabilistic forecasting model during an eruption simulation exercise in Dominica, Lesser Antilles

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A first 'real-time' application of pyBET_UNREST probabilistic software was carried out during a Volcanic Unrest Simulation Exercise in Dominica (Lesser Antilles), as part of VUELCO (EC-FP 7, #282759) project. Given the 9 potentially active centers, the frequent earthquake swarms at shallow depths (<5km) and recent phreatic explosions (1997), the region is still considered active. The Exercise scenario was developed in secret by a team of scientists from Seismic Research Center (Trinidad and Tobago), Montserrat Volcano Observatory and the University of Auckland (New Zealand) and assumed an eruption somewhere in Southern Dominica. The scenario covered a period of unrest activity of 2 years from July 2014 until July 2016. The simulated activity was provided to the Scientific Team in three 'Phases' through exercise injects comprising processed data (e.g. seismic, geochemical, deformation) derived from the monitoring network. We used the pyBetUnrest probabilistic software to estimate in near real-time the probabilities of having i) unrest of ii) magmatic, hydrothermal or tectonic origin, which may or may not lead to iii) an eruption in a pre-defined iv) location. We report on the set-up of pyBET_UNREST inputs for Dominica, the results obtained and their implications. During the exercise we were able to observe the pros and cons of using a probabilistic model in the decision-making process during a volcanic crisis. We concluded that the BET application itself was successful, however, as with any newly proposed methods and tools it needs more testing, and in order to be able to use it in the future we have made a series of recommendations.

Keywords: pyBET_UNREST; volcanic unrest; probabilistic forecasting; Dominica; simulation exercise; VUELCO.

Requirements for interactive informative systems in support of management in volcanic crises

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In order to make relevant information available to all stakeholders at the right scale at the right time we need to get the most from an interactive communication system. This system should be easy to use, to collect and to distribute data rapidly using a centralized and decentralized way that is accessible to stakeholders, scientists and everyone involved. Confidentiality and internet security is requested. It should serve or be connected at the same time to an emergency system like an emergency operation system.

KoBoToolbox is built to collect reliable informations and analysis in humanitarian crises used in challenging environments following a natural disaster such as a large earthquake or typhoon taking place in a poor country. It was created by the Harvard Humanitarian Initiative (www.kobotoolbox.org). It is an easy tool that is able to collect rapid data and analyse these on android, iOS and many devices. It can work online and offline in any language. The data can be saved by integrity and with strong safeguards (against data loss). It provides an easy connectivity when internet is available. No technical knowledge is required. KoBoToolbox uses the standard XLS form for the data. As the localization of the collected data is registered false data collection can be recognized and eliminated from the data analysis.

KoBoToolbox has been used at Mayon volcano but only to collect Focus Group Discussion data. A scenario of crisis is envisaged on a use of the tool in an interactive way.

Next-generation volcano warnings and maps: Keeping up with the global move to impact-based multi-hazard warnings

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The World Meteorology Organisation (WMO) and the United Nations Office for Disaster Risk Reduction (UNISDR) have fostered substantial global advances in early warning thinking. These include the Guidelines on Multi-Hazard Impact-Based Forecast and Warning Services (WMO, 2015) and the new Multi-hazard Early Warning Systems Checklist (WMO and UNISDR, 2018). This is underpinned by several sections of the UN Sendai Framework for Disaster Risk Reduction.

There is much debate and developing consensus within the volcanology community around (a) what constitutes best practice in hazard mapping, (b) volcanic alert levels, and (c) volcano observatory best practice. However, the global disaster risk management and warning communities are advancing quickly into recommending that warnings include information that clarifies the impact of an event; and that they are delivered in a seamless multi-hazard context. Decades of social science research into warnings clearly shows that the most effective warnings contain all of: what has happened or may happen, what the impact may be, and what people should do to protect themselves. In one message.

Internationally, monitoring and forecasting for hazards is often the domain of two or more different agencies (e.g. across weather, earthquakes, tsunami, volcanoes). And the mandate or ability to calculate and forecast impact is often not developed, or not within the same agency. Telling people what they should do to protect themselves (shelter, protect, prepare, evacuate etc.) is in many cases definitely not within that monitoring and forecast agencies remit.

This raises the question, where should the volcanology community be heading in terms of warning and hazard map content (messages and collaboration) to give effective warnings aligned with these new global initiatives? This presentation discusses this new global framework; how other disciplines are working to align with it; and links to several volcano warning and hazard map case studies, including New Zealand, Vanuatu and the USA.

Volcanic hazard maps or crisis management maps? Printable documents or digital environment? Are we really considering authorities and society demands?

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Event if all recent advances in volcanic hazard modeling and knowledge about volcanic activity are considering, we are still far from being able to forecast volcanic hazards events with the precision demanded by authorities and the public. This situation gets worse in areas with high risk levels, where more detailed scales are needed in order to design and implement mitigation and response strategies.

Nowadays, usage of Geographic Information Systems and web-based services has spread among authorities and the public. These tools provide easy access to hazard and risk-based cartography thanks to the development of digital information and communication technologies. The migration from widespread usage of static, paper maps to zoomable digital terrain models where scenario-type hazard maps are superimposed has proven not to be easy. How different is the printable information from digital environments, and what kind of new rules and demands must be considered by the scientific groups.

The recent Cotopaxi volcanic crisis is a good example to understand the complexities resulting from mixing these two types of information. Threatened by an impending eruption, authorities used a web-map server tool to upload the shapes representing lahar hazards in both Cotopaxi drainages. They used the official 2004 printed hazard map that was developed using a 1956 reference frame (1:50.000 e) to superimpose it over the most recent and detailed Digital Elevation Model. As a result, drainages did not match well and lahar limits were contradicting DEM topography undermining scientists and authorities' credibility built through years of hard work. Hazard maps had to be rapidly updated with new information coming from field work and using different digital tools. This was a great effort made in a short time, which implied not only the improvement of the hazard map, but also an adaptation to the new necessities of the population at risk.

VOLCANBOX: a systematic methodology and e-tools set to conduct long and short term hazard assessment

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VOLCANBOX is a simple multiplatform method for assessing volcanic hazards and risks. It includes a series of e-tools that allow experts to elaborate hazard and risk analysis. Currently, the VOLCANBOX platform includes five modules: spatial analysis, temporal analysis, simulation models, risk analysis, and communication protocols, plus a database design created to structure and store all data necessary to conduct hazard assessment. VOLCABBOX is open to integrate other tools or models that have been developed by other authors. Also, it intends to offer experts different options based on the available data they may have and the accuracy they require. VOLCANBOX is a resource to build the strategies required to successfully confront and minimize the impact of future volcanic eruptions in a homogeneous and systematic way. Experts select the tools in each module that they want to apply in a sequential workflow. The nature of this workflow can be adapted to a long- or short-term hazard assessment, and it takes the different tasks assumed in the volcanic management cycle as a reference. For a long-term hazard assessment, for example, the user may obtain a susceptibility map showing the probability of new vent opening, a temporal analysis of the occurrence of possible eruptive scenarios, a simulation of possible volcanic and associated hazards and elaboration of qualitative and quantitative hazard maps, vulnerability analysis, and cost-benefit analysis to determine the most appropriate mitigation measures. In the case of a short-term analysis (covering a single unrest episode), we would use the previous results and add monitoring information through the use of a specific tool to refine the spatial and temporal constraints of the most probable scenarios. VeTOOLS also looks at how to make scientific information understandable for decision makers and community planners who manage risk in volcanic areas.

S02.06 Talk

Development of an evacuation decision- support framework for volcanic crisis management

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An ever-increasing global population has led to greater exposure to potentially damaging and even fatal consequences from volcanic eruptions. The high-pressure decision to call an evacuation in the midst of a crisis is a difficult one that involves considering uncertainty in the volcano's state as well as political and social factors. Advances in the scientific understanding of volcanoes, the computational power needed to carry out assessments, and a greater societal exposure has led to a surge in volcanic hazards research over the last two decades. Such research aims to better quantify volcanic hazards and their consequences to inform risk mitigation measures. However, little focus has been given to combing these currently discrete elements into a user-friendly framework for supporting decision-making during a crisis.

Here we present a project that aims to develop an evacuation decision-support tool for use in volcanic crisis management that integrates existing hazard, vulnerability, risk and decision-making approaches into a single framework with quantifiable outputs. Previous eruption simulations have highlighted the potential benefits such decision-support approaches can provide (e.g. during the MESIMEX simulation for Mt. Vesuvius and Exercise Ruaumoko for the Auckland Volcanic Field). This project aims to develop a systematic decision-support framework to provide quantitative and tractable hazard and risk information to decision-makers faced with the evacuation decision. The proposed framework will utilise geospatial technology to represent the hazard footprints and exposed elements to determine the extent of any required evacuation area. Cost-benefit analysis will be applied by weighing the cost to evacuate versus the potential loss to stay and comparing it with the hazard likelihood to determine when it becomes cost-beneficial to evacuate. The proposed framework will consider independencies as a component when assessing risk, such as transportation routes and water supply to support those outside of the direct hazard extent, but still at risk.

S02.06 Talk

Database of Volcanoes of China

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There was no enough work done dealing with active volcanoes in China before 1990's because no many scientists believed that there are any volcanoes in China with eruption potential which could bring up large hazard in that period. In 1993, with the great financial support from the central government, Active Volcano Research Center of China Earthquake Administration (AVRCCEA) was established, which marked the starting point of comprehensive studies of active volcanoes of China. With the great efforts from the scientists in the fields of volcanic geology, geophysics and geochemistry for over 20 years, we have confirmed that there are at least 14 Holocene volcanoes with eruption potential in China. The National Volcano Monitoring Network, consisting of 6 volcano observatories, was build up and started in operation in 1999. Since then, a great deal of progress has been made in both volcano monitoring and volcano geology in China. In order to facilitate the assessment of hazards and risk from the volcanoes, as well as to provide the basic scientific information of geological backgrounds of the major volcanoes in mainland China, we are creating a comprehensive database of Cenozoic Volcanoes of China (CVC) based on the product of ESRI, ArcCatlog software, which uses its interactivity, practicability and readability to complete the establishment of the volcano database schema. The database contains information on about 50 volcanoes and over 20 Cenozoic volcanic rock regions. Data fields include: geology maps, eruption histories, hazard maps, geochemical analysis data of rock types, monitoring data (earthquake, GPS, ground levelling, volcanic gas geochemistry, InSAR etc.), geophysical survey (data and results) and etc.. The selected data can be downloaded and the database is expected to be finished and available publically online in the near future.

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S02.07 - Volcanic risk assessment and mitigation for Latino-American cities

Preliminary study to improve false positives of the network -Volcano Ash Cloud Lightning- of WWLLN, in Volcanoes of Argentina – Chile

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In the last years, the volcanism in the south american Andes region, has shown great activity. Since 2006, with the eruption of the Chaitén Volcano, following in 2011 with the volcanic complex Puyehue - Cordón Caulle and the most recent one in 2015 of the Calbuco volcano, they had destructive effects on the environment, the economy and the health of the sectors involved. The fall of pyroclastic material constituted one of the most far-reaching direct hazards related to eruptions. These cited eruptions showed great electrical activity during several phases of the eruptive process.

Varied authors (Behnke et al, 2012, Behnke and McNutt, 2014, McNutt and Williams, 2010, among others), showed that the detection of the electrical activity produced in the volcanic plume during an eruption turns out to be a complementary utility tool to detect explosive eruptions, to determine the existence of a volcanic plume associated with the eruption and estimate its route.

The VOLCANO Ash Cloud Lightning project detects explosive volcanic eruptions from electrical discharges registered with the WWLLN (Wide World Location Lightning Network). It has monitored 1825 volcanoes around the world. The alert is sent by e-mail to the registered receivers when the system detects lightning within an internal central area of 20 km radius and an external one of 100 km with center in the crater of the monitored volcano.

In our work, we propose to improve the alerts emitted by this network, considering the dermatological characteristics of the region. That is, determine the frequency with which thunderstorms are generated and how are wind patterns, in general. Adding this information to the network could reduce false positives, so that the eruption alert system based on the detection of electric discharges will be more efficient and will be coupled with the other tools used.

S02.07 Poster

Combining field-based data, remote sensing tools and numerical modeling to enhance hazard assessment of Pyroclastic Density Currents (PDCs): the case of El Misti, Peru

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Pyroclastic density currents (PDCs) are the most challenging of all volcanic hazards for disaster planners in densely populated areas around volcanoes. 'El Misti' (5,825 m.a.s.l) volcano, located only 17 km from the city center of Arequipa (> 1 million inhabitants) in South Peru, produces large-volume PDCs with a frequency of 2,000 to 4,000 years in average. The most recent Plinian eruption c.2070 yr BP (VEI 4) has been selected as one of the reference events for the hazard assessment and risk mitigation plan of Arequipa. Associated pumice- and lithic-rich PDC deposits were emplaced from at least three phases of column-collapse into radial valleys draining the volcano as far as 13 km towards the city area and the southern flank. Current field mapping and stratigraphical surveys conducted in five valleys affected by the c.2070 yr BP PDCs were combined with a new high-resolution (2m) digital surface model (DSM) of the volcano obtained by fusing two stereo-pairs of Pleiades optical images with lower-resolution (10 m) TanDEM-X radar data. Surveys and DSM embedded in GIS tools allow to better estimate the distribution of individual PDC volumes emplaced in each of the valleys around the volcano impacted by this Plinian event. Such data acquisition is particularly critical for two of these valleys (San Lanzaro and Huarangal) for which the distal parts now constitute the outskirts of Arequipa. Finally, these volumes were used as input parameters to better calibrate numerical simulations of future similar PDC events and assess their impacts (e.g. inundations, runouts, thicknesses, velocities) on the populated areas around El Misti volcano. This multi-disciplinary study will provide the civil authorities a better understanding of the likely effects of PDCs associated with a similar VEI 4 eruption of El Misti on the urban area of Arequipa.

Recent activity and mitigation efforts at Fuego Volcano, Guatemala

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Fuego volcano is the most active and highly-populated volcano in Guatemala, with >63,000 people living between 6 and 10 km from the vent. Thousands are at risk of violent eruptions, affected by pyroclastic flows, lahars, ash, and acid rain. The eruptive activity has increased in the last 3 years, with more than 34 eruptions and pyroclastic flows which have filled valleys, spawning lahars which have affected the population in the southwest and southern flanks. Lahars have damaged houses, bridges, caused flooding and the loss of livestock. Fuego receives more than 6000 mm of rain annually, causing lahars in Fuego's seven major drainages most days during the annual 6-month rainy season. Many roads have been cut, isolating villages and putting people at risk fording lahar channels where bridges have been lost to lahars.

INSIVUMEH monitors Fuego through a local observatory, 24 hours/365 days a year, using 2 seismic stations provided by USAID and an infrared camera provided by the University of Bristol as well as visual observations. During this period of frequent eruptive activity INSIVUMEH continues to evaluate hazards and update hazard maps, providing timely hazard notifications together with CONRED (Coordinadora Nacional para la Reducción de Desastres), to municipal authorities and the public. Other volcanological studies are conducted in collaboration with the US Geological Survey, the Universities of Bristol, Puerto Rico, Liverpool and Michigan Technological University, among others. CONRED's risk management complements INSIVUMEH's volcano monitoring effort, working with the local communities; school students, community leaders, local people who work as observers and collaborators. CONRED and INSIVUMEH coordinate community outreach to alert and inform the people. They also conduct evacuation drills based on scenarios involving violent eruptions.

Probabilistic volcanic risk assessment at Galeras volcano, Colombia

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Probabilistic volcanic risk assessment needs to combine volcanological data, such as those derived from field data analysis, which allow timing, magnitude, intensity, and dispersal of deposits from previous eruptions to be estimated, with robust probabilistic methods. In order to carry out a probabilistic risk analysis for the exposed habitat and infrastructure in the vicinity of the Galeras volcano (southern Colombia), we combined chrono-stratigraphical data available both from the literature and our own survey, and modelling of volcanic phenomena. Volcanological data were used to validate models, and also to provide ranges for potential eruptive scenarios. Our modelling approach considered a statistically valid sampling from multiple hypothetical scenarios. For each of the volcanic hazards at Galeras volcano, hundreds to thousands of hypothetical scenarios were modelled, whose range were constrained by the past events recognized in the field. The results were post processed in order to obtain Probability-Intensity curves at each grid point of the DEM for each of the considered hazardous phenomenon. As an exercise, exposure and vulnerability analysis was carried out for a municipality located 10 km away from the Galeras crater. A house by house survey allowed us to map their locations and determine structural typologies. Damage-Intensity curves (i.e. physical vulnerability) of the typologies were produced, and combined with the exposed elements, they resulted in ranking house vulnerability. The resulting probabilities for each intensity of hazard, exposure in terms of locations and physical vulnerability data were digitized within GRASS-GIS software as raster maps, which allows us to quantify the risk. The major risk was lahar potential impacts on houses located on low river terraces. The resulting maps and information quantify the volcanic risk for the structures and represent a very useful tool for risk management.

S02.07 Talk

Geological Evolution of the San Vicente Volcano (Chichontepec), El Salvador

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The San Vicente volcano is formed by 2 cones, aligned in the SO- NE direction. This twin volcano, andesitic in composition with long periods of eruptive rest, since there no evidence of an eruption during at least the last 1,500 years. It is located in the central area of El Salvador. Its current activity consists of seismic swarms, thermal springs and fumaroles located on its northeastern and northern flanks, at 820 and 850 m.a.s.l. At least 150,000 people are living on their flanks. This is the main reason, to carry out an eruptive hazard assessment including hazard sceneries.

Based on dates $^{39}Ar/^{40}Ar$, petrographic and geochemical studies, carried out by Aiuppa and Rotolo (1998 and 1999), it is proposed to outline the geological evolution of the volcano. These studies indicate that the eruptive activity between 2.2 and 1.2 Ma, builds a prototype volcano called the Carbonera, with a basaltic composition up to dacite. Data reveals that between 0.59 and 0.55 Ma, strombolian activity was interrupted by Plinian phases that produced the collapse of the building. The remains are currently known as La Carbonera Caldera, located 5 km west of the current volcano. The eruptive reactivation in the margins of the caldera forms another building of basaltic - andesitic composition, which according to evidences in the terrain, at some time collapses laterally toward the southeast, probably due to the tectonic instability of the area. It is estimated that the current volcano is formed during the last 0.2 Ma within the escarpment of the collapse. Therefore, assessing and modeling the volcanic hazards associated with the volcano is very important for the country.

Popocatépetl volcano, 24 years of mitigation efforts by CENAPRED

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Popocatépetl volcano, located 60 km from México City (population 25 million), 40 km from Puebla City (population 10 million), and even closer to many smaller towns, has been constantly active for the last 24 years. Since its reactivation in December 1994, it has been actively monitored by the National Disaster Prevention Center (CENAPRED). During this time, the monitoring network has evolved according to budgetary considerations, access to different types of equipment and partnerships with both local and foreign scientists, and has included both standard and experimental instrumentation, which have resulted in the publication of numerous scientific papers both by CENAPRED's personnel and external researchers. In these 24 years, several crisis have been addressed, which have included evacuations of up to 70,000 inhabitants on more than one occassion. Most recently, a new hazards assessment was carried out, which resulted in the elaboration and publication of new hazards maps, and their integration into a single practical map for use by Civil Protection agencies. Since its implementation, the National Risk Atlas, a public access GIS focused on risk analysis, has been especially useful for evaluation of different scenarios and for the publication of alerts and warnings. A new seismic and geodetic network of instruments is currently being installed. Experiences, mistakes, errors, best practices recommendations and other anecdotes will be explained, including the most recent efforts to integrate with other volcano observatories in México (e.g. Colima Volcano Observatory and Chichón Volcano Observatory), in order to create a National Volcanologic Service that can work in a similar way to the already existing Seismological and Meteorological National Services.

S02.07 Talk

Eruption of 1609 Momotombo volcano, Nicaragua. Implications in the hazard assessment

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Momotombo Volcano is a stratovolcano eruptive building located in the central part of the Central American volcanic arc, it is part of the Nicaraguan Volcanic Chain and represents a significant threat to the population in its surroundings and the capital of the country, given the background of its eruptive history. This volcano has erupted every 100 years on average since the sixteenth century. The eruption of January 11, 1609 caused the total destruction of the town of Leon Viejo, then the capital of the country. The building of the Momotombo volcano constitutes an almost perfect cone formed by the accumulation of pyroclastic deposits and lava flows with a crater open top towards the Northeast. This study contributes to the evaluation of volcanic hazard due to ash fall through studies of volcano-stratigraphy and granulometric analysis of samples from the deposits of the eruption of 1609. With this information, isopaque curves and isopleths have been constructed, showing the scope of the pyroclastic deposits and allowed their characterization. Hazard scenario maps were prepared by ash fall that allow to represent the zones of possible distribution of the products which will serve to determine the different degrees of affectation associated to the different levels of ash accumulation in a future eruption. The represented danger scenarios result from the integration of historical information, geological information collected in field works, granulometric analysis, density, total rock geochemistry, meteorological conditions information (wind speed and direction) and computational simulation of the volcanic processes in areas that are more or less likely to be impacted by the products of a given eruption.

S02.07 Poster

Young Latin American Volcanologist network: achievements and future perspectives two years after its launch

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The development of volcanology in Latin America is marked by a common regional scenario, with countries sharing borders, socio-cultural characteristics and facing similar scientific challenges. This scenario illustrates the need to create and promote regional networks. In this abstract we present the *Jóvenes Volcanólogos Latinoamericanos (JVLA)* network, a specific strategy that gathers early career volcanologists from Latin America and aims to strengthen volcanology in the region by encouraging the active participation of new generations. A benchmark in the construction of this network was the CoV9 conference (2016, Chile), where the *1st meeting of Young Latin American Volcanologists* took place. As a response to the needs identified during that meeting, JVLA, together with the *Asociación Latinoamericana de Volcanología* (ALVO), developed an internship program in volcano observatories for highly motivated Latin American volcanology students. In addition to offering the young volcanologists scientific training and experience working in a volcano observatory, this program aims to promote the interaction and cooperation between universities and observatories. With the financial support of IAVCEI, a pilot test of the program will be carried out during the 2018 austral winter at the Observatorio Volcanológico de los Andes del Sur (OVDAS), in Chile. Among other actions, JVLA has been using social media and specialized newsletters (i.e., Gaceta ALVO and IAVCEI Newsletter) to distribute relevant information and to share personal experiences. Recently, on 25 April 2018, JVLA organized the *2nd Meeting of Young Latin American Volcanologist* in Arequipa, Peru. In the future, the JVLA network expects to continue promoting new activities and initiatives (e.g., meetings, summer schools, internship programs) that strengthen the bonds between the new generations of Latin American volcanologists and to enhance the development of volcanology at a regional, and consequently, world-wide scale.

S02.07 Poster

Segemar volcano hazard assessment program for Argentina

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During the past 27 years the recurrence of crisis caused by volcanic eruptions which have occurred along the Andean Cordillera in Argentine or Chilean territory but with influence eastward (this due to the predominance of the winds), have generated multiple problems and material losses, causing great concerns in the populations affected by these events and on national and provincial authorities in Argentina.

The eruptive crises of 1991 (Vn Peteroa and Vn Hudson) showed the enormous damage that ashfall can produce, as well as the scarce geological knowledge and low degree of preparation to face volcanic hazards in Argentina at the time. As a result of this, SEGEMAR, with the support of the United Nations (UNDP) and SERNAGEOMIN, from Chile, prepared the first bi-national map of Geology and Volcanic Hazards for the Planchón-Peteroa volcano (Naranjo et al., 1999). In the following years, specific projects were carried out in other active volcanoes, such as Copahue, Maipo, Lanín and Laguna del Maule Volcanic Complex in order to reconstruct its Holocene eruptive stratigraphy and assess its threat.

Since 2008, due to the reactivation of the Llaima and Chaitén volcanoes in Chile, SEGEMAR implemented a Volcanic Hazard Assessment Program (PEAV) for the Argentine Republic, with the objective of establishing the potential affectation of the territory by Volcanic Hazards/Threats and the potential socioeconomic risks associated. A Rapid Assessment of Volcanic Risk in Argentina (Elissondo and Villegas 2011, Elissondo et al., 2016) was carried out, which allowed to identify the volcanoes with highest risk for the country in order to organize future research activities and volcano monitoring.

Simultaneously, since 2013, after 2012 Copahue volcanic crisis, the project for the creation of the Argentine Observatory of Volcanic Surveillance (OAVV) started with the purpose to mitigate the volcanic risk to which the country is exposed.

S02.07 Talk

CEOS Working Group on Disasters implements demonstration on use of satellite data for monitoring volcanic hazards

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The Committee on Earth Observation (CEOS), the space arm of the Group on Earth Observations (GEO) brings together roughly 60 agencies worldwide in order to coordinate civil space-based Earth Observation (EO) programs and promote the exchange and use of data for decision support that benefit society, including disaster resilience. From 2014 until 2017, the CEOS Working Group on Disasters executed a Volcano Pilot that advanced the objective to study volcanic unrest and eruption in Latin America using radar and optical satellite data. Major achievements highlighted the value of EO-derived information for disaster management, validated methodologies for new product generation, facilitated data access and processing, and supported emergency response. In April 2018, CEOS endorsed a Volcano Demonstrator project, supporting implementation of the 2015 Sendai Framework with its focus on disaster risk reduction (DRR). The Demonstrator considers exposure and vulnerability, targeting areas of highest intensive risk, with objectives to: 1) fill monitoring and observing gaps with satellite remote sensing, 2) advance understanding of volcanoes for risk assessment, preparedness, and prediction, 3) aid incident response and disaster management, 4) strengthen and build capacity for sustainability, and 5) promote open access to demonstrate a durable volcano monitoring and observing system. This presentation will provide an update on the variety and volume of EO data from satellite, airborne, and in situ as well as relevant socio-economic data available for the Demonstrator. We will review lessons learned and some of the new analytical, data management and geospatial enabling techniques, including Interferometric Synthetic Aperture Radar (SAR), that are being used to enhance our understanding of volcanic processes and risks. Presenters: David Green, NASA; Simona Zoffoli, ASI; Michael Poland, USGS; and Fernando Echavarria, DOS.

Simulating past and forecasting future eruptive scenarios at San Miguel Volcano, El Salvador

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San Miguel or Chaparrastique volcano has been active at least for the past 10 ky, erupting 28 times in the last 500 years (historical period). It is consider one of the most active volcanoes of El Salvador. The majority of historical eruptions have been central with ashfall emissions, and only 8 have been effusive flank eruptions mainly giving lava flows. The activity has been mostly Strombolian in nature (VEI 1-2). Products composition is basaltic and basaltic-andesite. The most common volcanic processes associ-ated to the volcano have been ashfall, ballistics, lava flows and secondary lahars.

Using the information from these historical eruptions and applying probabilistic tools designed for volcanic hazard assessment, we simulated scenarios related to: (1) the five most likely scenarios obtained from HASSET (ashfall scenarios short-medium extent and VEI 1-2); (2) the most hazardous scenario (ashfall + lava flow + ballistics medium to large extent with VEI 3); and (3) other scenarios related to lava flows and lahars with similar characteristics than those occurred in the historical period. Finally, we constructed a qualitative integrated volcanic hazard map thought the combination of the simulated scenarios. This study has been developed with the aim of improving the already developed emergency plan. It serves as starting point in the collaboration and coordination between scientist, the national observatory (OA-MARN) and the civil protection agency of San Miguel municipality, and poses to strength this cooperation, in a systematic way, to face the future volcanic activity.

Coupled Seismic-Volcanic Hazard Model for Managua, Nicaragua

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Earthquake and volcano hazard maps are used worldwide to inform the public of geophysical hazards and to assist communities in long-term planning. An essential role of the scientific community is to quantify the geodynamic processes that give rise to hazards, allowing for improved forecasting. Volcanic and seismic hazards are linked across a wide range of temporal and spatial scales, from long-term evolution of plate boundaries to dynamic triggering of eruptions, and coupled seismic-volcanic hazard models will improve long-term hazard assessments for communities and critical infrastructure located in diverse tectonic settings. We investigate the geodynamics of the Managua Graben, Nicaragua, with an aim toward construction of fully coupled volcanic and seismic probabilistic hazard models for the city of Managua and environs. These models will be the first, to our knowledge, to couple seismic and volcanic processes for hazard assessment. Managua is an ideal place for developing coupled hazard models to address these questions. The city sits within a graben riddled with active faults and dozens of Holocene monogenetic volcanoes, and adjacent to several active volcanic systems. The proposed probabilistic hazard models will use new gravity, magnetic, and geodetic observations, in addition to existing geodetic data, geologic maps and the seismic catalog, will be used to provide geometry and boundary conditions for 3D numerical simulations designed to create ensemble models of the response of the lithosphere to far-field stresses. We present initial results of our geodetic and gravity studies to define the strain rate field and crustal structures across the Managua Graben.

S02.07 Talk

Young geologists and the interest of vulcanology in Córdoba - Argentina, in the XXI century

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The objective of this work is to know, through surveys, what students and graduates of the Geology Degree of the UNRC know about volcanic eruptions, when this city is in a province far from volcanoes but that was affected by pyroclasts fall, in a century whose social impact has been greater than in the last century.

The results show that the volcanoes that the vast majority of them know correspond to those that have had volcanic activity in the last 10 years. 45% of respondents recognized that the media perform a job with insufficient information and sometimes sensationalized by failing to report properly to society through specialized people in the subject. Bringing tranquility to the population and reporting on what to do before, during and after a volcanic eruption, is essential to prevent and reduce risks to the population. Cordoba province is more than 400 km of the Andes, so the risks that could affect the region against a possible volcanic eruption are ashfall, as happened in the eruption of Puyehue-Cordón Caulle volcano in 2011.

Volcanic monitoring in Argentina, according to half of the respondents, is scarce, and they should normally resort to information from Chile. In Argentina there are many volcanologists but, the lack of international assistance, hence of budget, does not allow geoscientist to have first world tools for monitoring.

The vast majority of respondents agreed that, in case of emergency, it is necessary and urgent to inform and communicate to society, always taking as much care as possible and implement remote sensing satellite systems that allow monitoring the Anden volcanoes.

Multi-sensor InSAR monitoring of ground subsidence and fissuring in urban environment within volcanic area: Ciudad Guzman (Mexico)

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With the use of multi-temporal SAR interferometry it is possible to study land subsidence and associated ground fissuring processes with high accuracy. This work focuses on the analysis of the ground fracturation that affects Ciudad Guzmàn (Jalisco-Mexico) located in the Northern side of the Volcano de Colima area, one of the most active Mexican volcanoes. This city is situated in a lacustrine basin bounded by fault scarps and volcanic reliefs. In particular, it is located in the Eastern side of a 20 km wide and 60 km long valley flanked by sharp and parallel NNE-SSW-trending active extensional faults. This valley is filled by a ~1km thick sequence of quaternary lacustrine sediments, alluvium, and colluvium. A system of normal fault outcropping in the Eastern and Western mountain ranges likely cuts the bedrock hidden under this recent deposit. On 21 September 2012 this area was struck by ground fissures that caused the deformation of roads and buildings. Moreover, thefield survey showed that fissures alignment is coincident with the escarpments produced during the earthquake (M 8.1) that struck central Mexico on 19 September 1985. In order to continue the observation of the creeping phenomenon, by means of the analysis of the time series of displacement, we are processing a stack of Sentinel-1 images acquired in the 2015-2018 period with a multi-temporal InSAR technique. Therefore this work aims to continue the study performed with ENVISAT (in the 2003-2010 period) and COSMO-SkyMed (from 2011 to 2015) images, which showed that the deformation and fissuring processes are caused not only by geological factors (such as the Subsidence-Creep-Fault Process), but also and mainly by human activities, like water withdrawal and ground loading.

S02.07 Poster

Early alert system and municipal leaders work around Masaya volcano, the use of evacuation route maps in Nicaragua

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INETER has prepared maps of threat around Masaya volcano, and based on these maps, evacuation routes have been created, work has been done with the population, and there have been minor infrastructure works taking into account the areas that may be affected by an eruption. INETER has been performing community work since 2010.

The lava lake appeared on January 2016, after seismicity that began on February 2015. These earthquakes reached 3.9 of magnitude under the volcanic structure.

The maps of threats have been designed based on a wild strombolian eruption, as it occurred in 1772 in the volcano. In the study, we include evacuation routes for ash falls, ballistics, lava flows, and pyroclastic flows.

Due to the lava lake eruption (January 2016) the National Disaster Prevention System (SINAPRED: Sistema Nacional de Prevención de Desastres), together with the municipal leaders, designed the “Volcanic Eruption Plan of Masaya Department”, using the maps of threats and evacuation routes. Thirteen municipalities have been trained to work on and activate the plan in their towns if necessary. At the same time the monitoring system in Masaya volcano was developed with four short period seismic stations, three webcams, a MiniDOAS and a multigas equipment for SO_2 gas measuring in real time, and two GPS stations.

S02.07 Poster

Where will the next monogenetic volcano in the Sierra Chichinautzin be?

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We calculated the probability of a new volcano being born in the Chichinautzin monogenetic volcanic field (CMVF) by México City. The method is based on the analyses of the spatio- temporal distribution of the volcanic activity within the field. The CMVF has 220 volcanoes, and covers an area of ~2,600 km^2. At least fifteen eruptions took place in the last 10 thousand years. Southern Mexico City was built on the monogenetic field, and some eruptions impacted inhabited areas.

We provide relative ages based on cone morphometric analyses and correlated them with the 27 radiometric ages and its cone morphometry. The relative dating obtained for the cones show good correlation with the radiometric dates. From this correlation, an interpolation was made with those volcanoes that do not have a radiometric age and assigned an estimated age.

The birth of monogenetic volcanoes is considered as a Poisson process, independent random point-event in time and space, where the probability of an eruption can be estimated based on the temporal recurrence rate (Mendoza-Rosas & De la Cruz-Reyna, 2009). We constructed a grid of 5x5 km and calculate the probability of an eruption for each of the 104 cells that occupy the field, based on the number of eruptions that have occurred in each cell and the estimated age maximum of each cell. The spatial distribution of the probabilities was analyzed with the kriging geostatistical method. Two areas show high probability for the formation of a new volcano.

S02.07 Talk

Ten-Years-Long JICA Training Activity on Improvement of Mitigation and Management Ability of Volcanic Disasters for the Central and South America by JICA-Hokkaido, Japan

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Japan International Cooperation Agency Sapporo had started a weeks-long short training course on “Improvement of Mitigation and Management Ability of Volcanic Disasters for the Central and South America”. Already 90 participants from 8 CA&SA countries had trained. They came roughly half-to-half from monitoring/information institutes or disaster mitigation offices. The program covers lectures/discussions in Sapporo, field visits to volcanoes Usu, Komagatake and Tokachidake, participating symposium/workshops, and kids activities in classroom or field. Visits to Sapporo District Meteorological Observatory, Hokkaido Geological Survey, Hokkaido Prefectural Government, Museums/Visitor Center are also included. The unique lecture is given by Ex-Mayor Mr. Kiyoshi Yamanaka, who managed the successful 2000 Usu eruption crisis. The program also includes discussions with local disaster officials and people who had experienced eruption(s) and evacuation(s). The common question from participants is, ”why do you still prefer to living here ?”. Typical answer is I love the area and it is safe and comfortable now, but we have to be ready anytime for quick evacuation if necessary. Lectures/discussions with long-term volcano covering journalists are also important experiences. The area of Toya and Usu is a member of UNESCO’s Global Geoparks. Unique activities are educational, both for local people and kids. Craters, damaged buildings, deformed roads such as “Great Graben Road” due to the volcanic uplift are the attractive educational targets. Volcano Meisters is a unique certification system. They work as a guide when volcano is dormant, and play a key person when crisis arises. Some participants tried Volcano Meister Network after return back to their home country and others tried field study with kids. In 2016, the midterm program evaluation visit to 3 CA countries was conducted, and we were glad some members had already become a senior key person and many are working continuously in volcano disaster mitigation program.

S02.07 Poster

The 1993 subplinian-plinian Lascar eruption: a case of study for the volcanic hazard assessment in northwest Argentina

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The Lascar volcano (23º22'S -67º44'W) with cuasi permanent yellow alert, is the most active volcano of northern Chile. For its proximity to the Argentina-Chilean border and the wind directions characteristic in this region, is the most hazardous volcano for the NW and Central Argentina, especially for the aeronavigation. The most common volcanic events are vulcanian eruptions, that usually affect its proximal area. However, several subplinain- plinian eruption had place in some occasion (1986, 1993) that affected a big area, especially NW and central Argentina region covering up of 850.000km^2. In this work we use our own unpublished 1993 Lascar subplinian-plinian eruption data information. The largest historical eruption of Lascar volcano, began on 18 April 1993 producing a 20-22km eruptive column above the crater. We reconstruct the ash isopach and calculated the total volumen of the eruption. Also, it was produced grain size distribution from several sample points. The samples were obtained immediately, ensuring there were pristine and unaffected by post- deposition environmental conditions. With this samples, the total grain size distribution was reconstructed. Column heights, eruption times, rate of discharge and other volcanological parameters were obtained since descriptions of the Teacher of the Talabre school located next to the volcano, a privileged witness of this eruption, and own information. With this data, we perform a tephra dispersion simulation using the ATLAS model. Meteorological data from ECMWF ERA Interim reanalysis, obtained from the ECMWF data server, were interpolated at each particle position. The simulation results were compared with field data. Finally, we propose as future work, the elaboration of tephra dispersion hazard map focused on the Lascar volcano.

The first two Meetings of Latin American Volcano Observatories (Encuentro de Observatorios Vulcanológicos de Latinoamérica)

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The Latin American Association of Volcanology (ALVO), together with Peru's INGEMMET Volcano Observatory and the USGS Volcano Disaster Assistance Program organized the first two Meetings of Latin American Volcano Observatories. Held in Arequipa (Perú) in 2015 and 2018, and with the institutional support of IAVCEI and WOVO, these events gathered the volcano observatory representatives from Latin America. In both opportunities, the meetings had a duration of two days and the program was divided in thematic sessions, with oral presentations, group activities, and discussions.

The first meeting took place on October 12-13, 2015 and had about 70 participants from 23 institutions and 8 countries. It was focused on learning about advancement and innovations in the institutions, exchanging experiences in volcanic crisis management, and discussing the challenges that the observatories face, together with limitations and difficulties. The 2018 meeting, on April 23-24, had about 50 participants from 18 institutions and 11 countries. This time, the focus was on exchanging recent experiences on crisis management, debating on effective communication strategies, and on strengthening cooperation in topics like training, instrumentation, processing and interpretation of data. The main session was dedicated to the development of guidelines for emergency protocols. For that, a group activity was carried out, in which the observatories shared the existing protocols, and their contents were analysed and discussed. The group discussions will be used to develop summary documents that will be shared with the participants, in order for them to revise their existing protocols or to develop new ones.

In this work, we summarize the key points of both meetings and present the results and main challenges identified during them. Some of the results and conclusions have been gathered through questionnaires, which were developed for both meetings in order to have the direct input from the participants on important points discussed.

Volcanic ash in argentina: Hudson, Chaitén, P-C Caulle, Calbuco and Copahue volcanoes

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After the eruption of the Eyjafjallajökull volcano in March 2010, satellites adapted instruments to remote sensors in order to obtain more information to understand and predict the trajectory of the dispersion of volcanic ash and plumes. Parameters of the eruptive plume (height, temperature, mass, etc.) are determined early using instruments located on satellite platforms. However, its application has been slight in the population "on the ground", both in small villages or in megacities. It is assumed that several cubic kilometers of volcanic ash were released from, the sum of, Hudson (1991), Chaitén (2008), Puyehue-Cordón Caulle (2011), Calbuco (2015), Copahue (2000, …) volcanoes, and have fallen mostly in Argentina. Research of over 500 analysis of volcanic ash were performed in laboratory and SEM-EDS laboratory. Historical tephrostratigraphy, recent eruptions and remobilized (by wind or flows) volcanic ash samples were carefully collected and classified. Characterization of volcanic ash and a "Binational" database based on environmental statements, georeferenced and time-referenced tephra archive is part essential of this project. Populations of Chile and Argentina have effects and impacts by volcanic eruptions in different ways. Volcanic ash not only effects on human health but also on infrastructure, industry and environment. Meteorological information and massive communication of the real situation is priority to decision makers and for civil protection actions. The migration of young people and families with children due to lack of economic resources leaves unpopulated territories in Patagonia and in the Andes mountain range, which take many years to recover. A case study was the volcanic eruption of Hudson in 1991. Los Antiguos, a small town near the Chilean border, took 10 years to recover its crops and currently produces high quality red fruits. Disaster risk prevention and preparedness for recovery and resilience would be more effective if aerospace agencies focused on this issue.

S02.07 Poster

Multiple geohazards in Caviahue caldera lake: Copahue volcanic complex, Argentina

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Caviahue lake is in the ancient caldera of Copahue-Las Mellizas volcanic complex, Northwest Patagonia, Argentina. This lake is acidic (pH 3-5) due to the influence of the Upper River Agrio (URA) whose springs crosses from Copahue volcano crater (2965 m.a.s.l.) eastward downstream. The lake has a horseshoe shape that consists of two drowned river arms, glacial canyons and volcano-tectonic troughs. The URA (upper Rio Agrio) and Agua Dulce, glacial meltwater rivers, are the main water inputs for the lake. In the North arm of the lake, the maximum depth is 95 m. The URA at its mouth in the Caviahue lake forms a delta with seasonal overflows, interflows and underflows, generating periodically turbidite currents. Through high-resolution remote sensors (Landsat and Terra) sequential images, delta growth, geomorphological changes and eruptive episodes were detected. Comparable data studies with delta's progression in mountain rivers, also inferred the generation of lateral expansions that generate surface fractures and liquefaction at deep phreatic levels. Water saturated soils can behave as pseudo-solid muds; stress or disturbance causes liquefaction and this material is gradually deposited through low velocity streams. Different stages from a quasi-solid deposit to a sudden collapse of a loose framework, are transition processes that vary widely in intensity and duration, depending on the kind of soil and its consistency. Thixotropy, liquefaction or gravitational collapse can explain the processes occurred in bank sediments of the URA delta and Caviahue lake coasts. Local lore suggests that minor subaqueous hot springs may exist in the lake. Triggers like tremors, blasts and bangs are more frequent since the 8.8 Richter scale earthquake in Chile (2010) and the lake water color darkened since then. Due to the increasing accidents that occurred lately; we´re leading a project focused on a sectorized map of Caviahue lake-URA delta coastal hazards.

GEVAS RED (Network) ARGENTINA – Civil Association (Non-Governmental Organisation) Commitment to Geology, Volcanoes, Environment and Health

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GEVAS RED ARGENTINA was founded in 2013 by seven expert geologists (founding members), as a Non-profit Civil Association aimed at constructing links between society and geosciences in Argentina, based on applying the best practices in the management of hazard situations facing volcanic eruptions. The creation of this Association intended to fill a gap in the link between science and society, since some communities are not adequately aware and trained about how to manage natural disasters. In the last 10 years, before its official constitution, the Association founding members actively participated during volcanic events occurred in the Southern Andes impacting the argentine territory, as Hudson (1991), Chaitén (2008), Puyehue - Cordon Caulle (2011), Calbuco (2015), Copahue (intermittent) volcanoes. GEVAS encourage studies on Geosites to promote Geological heritage conservancy and environmental education throughout geoparks and georoutes. GEVAS RED ARGENTINA contributed in diverse local and international scientific teams working during and after the occurrence of the events, such as IVHHN, the University of Cambridge, Univ. of Canterbury (New Zealand), SEGEMAR, local universities, etc. We are working on projects according to IAPG Geoethics statements; develop activities for applying geoethical principles in early warning systems with E/OES/S/SAT, NASA and Spatial agencies. Link bridges of transfer networks between Science-Art-Community through exhibitions and simulations focused on disaster risk reduction, prevention and resilience before multiple volcanic risks that impact in Argentina. We present the fundamentals and background of our Association to enhance the links with international associations and experienced teams on multiple volcanic hazards management. Special acknowledge are given to GEVAS RED ARGENTINA founding members, partners and collaborators, such as Eva Donari, Juan Manuel Lirio, Monica Bravo de Laguna, Silvia Corral, Mónica Alvarez, Karina Rodriguez, Gabriel Asato and Alexander Cottescu. Keeping in our heart the best memories of a late dear friend and founder member Palmira 'Ester' Nuñez.

S02.07 Poster

Methodology for assessing exposure, vulnerabillity and risk due to mass flows in the city of Arequipa

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Assessing hazards and risk in large cities exposed to multiple hazardous events has long been a challenge. The case of Arequipa (Peru), the largest Latin American city exposed to multiple hazards, is no exception. A multidisciplinary project aims to address exposure, physical vulnerability of habitat and infrastructure, as well as risk perception of flash floods and debris flows along two of the five ravines that cross the city. The goal is to contribute to scenario-based hazard maps and to propose mitigation procedure usable by Civil Defense and affected people.

Scenarios for flash floods, hyperconcentrated streamflows, and debris flows have been derived from recent disastrous events (c. 100,000 m^3) to simulated extreme events (500,000 m^3). Simulations using high-spatial resolution DEMs and numerical codes show that mass flows commonly spill over bends from sinuous ravines that cut down the volcaniclastic fans of El Misti and avulse in previous channels that have been filled and now built up. Exposure and physical vulnerability of constructions were investigated using surveys at the scale of city blocks together with remotely sensed Pléïades imagery. Experiments showed that flow dynamic pressure acts differently on parallel, angular and perpendicular house walls, which directly affect exposure. Experimental lab tests and in situ measurements have determined the resistance of the materials made of lapilli stone, several types of bricks, ignimbrite, reinforced concrete, and confined frame. Seismic design is scarce and construction procedure usually poor in the most populous districts upstream of the city centre. Physical vulnerability increases from the high terrace to the ravine channel; where the most vulnerable habitat is located without property titles. Social characteristics together with risk perception among the dwellers along both ravines have been collected from at least 30% of the building total amount. Surveys show that risk perception exists but hazard knowledge remains low.

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S02.08 - Coordination of Civil Protection and Scientific community best practices to support the management of volcanic crises and the long-term risk mitigation plans

Monitoring the December 2015 activity of Etna (Italy): an example of real time management of volcanic eruption

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In early December 2015, a powerful eruption occurred at the summit craters of Mt. Etna, in Italy. The eruption started on 3 December and until 5 December took place at the Voragine crater where four paroxysms produced high eruption columns and intracrateric reomorphic lava flows that caused important morpho-structural changes of the inner portion of Voragine and Bocca Nuova summit craters. Eventually, from 6 to 8 December, the activity shifted to the New South East Crater with Strombolian explosions and lava flows spread out toward the western wall of the Valle del Bove depression. Finally, activity once more shifted to the Northeast Crater, where ash emission and weak Strombolian explosions took place for several days. The explosive activity from the Voragine Crater generated intense and widespread tephra fall that impacted the northeastern Sicily and the southern Calabria areas, posing hazard mainly to air traffic. During the eruption, routinely monitoring and surveillance activities were carried out at the INGV-Osservatorio Etneo, following scheduled protocols developed side by side with Civil Defense. Near and real-time volcanological, geochemical and geophysical data were collected such as to get insight into the on-going activity and forecast its evolution. Thanks to the experience gained in decades by INGV- Osservatorio Etneo in monitoring multidisciplinary Mt Etna unrest and eruption, a potential eruptive scenarios was outlined and available to Civil Defense for evaluating volcanic risk and to plan mitigation strategies for the population. The December 2015 Mt Etna eruption represented a typical example of real time management of volcanic eruption in a highly densely populated region.

S02.08 Talk

Volcanic risk communication strategy in Colombia

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Hundreds of thousands of people live in volcanic areas in Colombia. Preservation of lives and livelihoods, management of volcanic crisis and long-term risk mitigation plans are the main responsibilities of the scientists, national and local authorities and local decisionmakers.

A project between the National Disaster Risk Management Unit – UNGRD and the Colombian Geological Survey - SGC, with participation of the Colombian Science and Technology Observatory – OCyT, has been carried out in the last two years. The project is focused on the formulation, validation and implementation of a volcanic risk communication strategy in Colombia. Special emphasis has been placed on the active participation of diverse actors from local decision-makers, such as members of the local and regional disaster risk management committees, community leaders and teachers from areas of influence of 4 volcanoes: Nevado del Ruiz, Purace Cumbal and Chiles, that comprise 4 departments and 20 municipalities. They also include three indigenous councils. In order to define the risk communication strategy, a study was made of perceptions associated with volcanic risk, organizational practices and information consumption of the communities. Therefore, the types of media, content and communication pieces that make up the strategy were defined.

The project has delivered 53 different pieces of communication, co-produced with communities such as an explanatory video to engage people to learn more about volcanoes, social maps of high public visibility,and posters, 28 pieces for radio transmission, since radio was found to be one of the preferred means of communication in most of the communities, and in some cases the only medium available, and a Digital Learning Object - OVA, by its acronym in Spanish, which was designed for teaching in the last grades of high school in Colombia. The project implements the strategy in places where it has been working with the local decision-makers.

Expert judgement as a tool for geohazard assessment for civil protection volcanic hazard assessment of the poorly known submarine volcanoes, and submarine parts of insular and coastal volcanoes. The case of the Italian "working table"

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The Italian National Civil Protection Department appointed a "working table", made up by height marine geologists and volcanologists, to assess the geohazards of the active submarine, insular and coastal volcanoes in Italy.
The aim was to define the state-of-the-knowledge, identify potential scenarios, measure and rank hazard conditions, highlight knowledge gaps and to evaluate possible monitoring systems.
Yet, since the beginning it was clear that existing data and knowledge were absolutely not homogeneous and generally not adequate to perform a full and "classic" hazard assessment, mainly due to the extreme difficulties (up to impossibility) in analyzing type and age of products present in the seafloor and sub-seafloor. Notwithstanding this, the adoption of a novel iterative process of collective discussion based on data, and cross-comparison/inter- calibration of results, made it possible to reach a set of important results, with the involvement of external researchers endowed with specific expertise and/or information. Ten different kind of hazard were defined, 5 related to mass wasting 5 to volcanic or exhalative processes. Seventeen active apparatuses or group of apparatuses were identified; two volcanic islands were added to the original list, as recent volcanic activity was only submarine and therefore they were previously classified as non-active. Finally, for each hazard and each apparatus minimal recurrence time and hazard intensity were defined.
The outcome of the initiative was very valuable in terms of homogenizing the knowledge and express an expert judgment for the underestimated and ill-defined source of volcanic geohazard lying below sea level. In fact, despite the difficulty in defining them, these are of special relevance for the security of coastal communities and infrastructures, in particular in the highly tourist-exploited volcanic coasts of the Mediterranean seas.
The initiative should therefore be considered as a possible best-practice of knowledge transfer from the scientific community to civil protection agencies.

S02.08 Talk

Network of community vigías in Nevado del Ruiz volcano influence zone: formalization of a cooperative relationship in volcanic monitoring of great importance in risk management processes

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Within the framework of the "Nevado del Ruiz Volcano" project sponsored by USAID / OFDA and executed through the AMERICAN RED CROSS and the CRUZ ROJA COLOMBIANA, the communications coverage for monitoring activities in the area of influence of the Nevado del Ruiz volcano was expanded (VNR), and interinstitutional communication has been facilitated between the National Disaster Risk Management System in the departments of Tolima and Caldas and also with vulnerable communities. As an important part of the actions of Social Appropriation of Scientific Knowledge, the strategy of "Community Vigilance" was formalized in monitoring and management of VNR volcanic risk in the departments of Caldas and Tolima. Sixteen communities were prioritized according to criteria of degree of threat, vulnerability and exposure as well as strategic location to distribute information to the residents in their neighborhoods. As an example of inter-institutional and interdisciplinary work, professionals of the geology-hazard assessment and electronic groups of the Volcanological and Seismological Observatory of Manizales of the Colombian Geological Service worked in coordination with representatives of the Colombian Red Cross to select the appropriate equipment considering environmental conditions for the sites of radio communication stations, which are equipped with solar panels to guarantee the permanent supply of energy and continuity in communication, especially in times of crisis. The communities are committed to participating as vigías to help prevent the occurrence of disasters in Colombia such as the one that occurred on November 13, 1985 as a result of the eruption of the Nevado del Ruiz volcano. In that case it was impossible to alert the inhabitants of the low-lying areas and inhabitants distant from the volcano of the occurrence of the eruption and generation of lahars. The community vigías show that strategies contribute in addition to their well-being in moments of non-crisis.

S02.08 Poster

Life in the Auckland Volcanic Field: Integrating natural hazards into city planning and preparedness

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The physical and social profile of Auckland presents a number of challenges and opportunities for emergency planning, unique to New Zealand and rare in the world. Auckland is one of only a handful of cities worldwide where over a million people live within reach of volcanic eruptions. Auckland's landscape and hazardscape is dominated by the 53 volcanic edifices around which the city has grown. At its heart is an isthmus stretched between two harbours. The isthmus, 1200m wide at its narrowest point, is the corridor for major lifeline utilities and transport routes in and out of the Central Business District and is at the southern margin of the Auckland Volcanic Field. Planning for the substantial growth of a city of this size with consideration for its place within a volcanic field is a challenge requiring a fairly unique approach.

According to a recent survey, ~85% of Aucklanders feel they have a good understanding of the types of emergencies that could occur in Auckland and know the actions to take if disaster struck. However, when asked specifically, only 47% of residents feel they would know how to respond during volcanic unrest. Auckland Emergency Management works with world-class research institutions to prepare for these events, developing a range of response plans, as well as a modular training framework and novel evacuation planning tools. Additionally, the development of the Natural Hazard Risk Management Action Plan aims to incorporate appropriate consideration and planning for the effects of natural hazards across all facets of city governance, planning and administration. This, coupled with close partnerships with lifeline utility operators and the emergency services, allows practitioners to translate science into operationally meaningful processes, and develop integrated and effective long-term mitigation strategies that will provide positive outcomes for the people of Auckland in the event of volcanic unrest.

Civil protection and scientific community in Italy: a long history of interaction and cooperation aimed at volcanic risk mitigation

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Since 1992 the scientific community of Italy is considered by law as an essential component of the National Civil Protection Service. Over the last decades the Italian Department of Civil Protection and the scientific community have been collaborating on many aspects to improve volcanic risk forecasting, prevention, response and management.

This cooperation reaches its climax during the management of emergency phases, when the interaction becomes continuous and often hectic to ensure timely and accurate scientific information to decision makers. This is possible thanks to the cooperation of a variety of entities: research institutes including the volcanic observatories, university departments and centers, the experts of the specific volcanic system and the Commissione Grandi Rischi (National Advisory Committee).

Nevertheless, what mentioned above would be extremely difficult without a continuous and constant collaboration between the different actors through the carry out of applied research projects, development of pre-operational tools for civil protection purposes, maintenance and upgrade of monitoring and surveillance systems, activities finalized to the elaboration of hazard maps, event and impact scenarios, alert levels, etc..

It is also necessary to take into account that, according to the Italian law, decision making aimed at volcanic risk mitigation is under the responsibility of different levels of Civil Protection authority, depending on the intensity and extension of the expected impacts. For this reason Regions and local authorities have their specific role and are involved in the decision-making process.
Therefore the Italian Civil Protection Service represents a complex collaborative system in which the daily work of each of its components is crucial for the effective management of future volcanic crisis.

10 Years of DEtermining VOlcanic Risk in Auckland (DEVORA)

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Auckland (pop. 1.5M), New Zealand's largest city, is built atop the Auckland Volcanic Field (AVF), a dormant monogenetic volcanic field that has erupted ~55 times in the past 200,000 years, with the latest activity occurring just ~600 years ago. Since 2008, the Determining Volcanic Risk in Auckland (DEVORA) project has been working to increase our understanding of the field, its associated hazards, and the risk it poses to Auckland's population, infrastructure, and economy. As a multi-agency, transdisciplinary project, DEVORA incorporates research from multiple fields, including geology, volcanic hazards, risk assessment, public communication, and decision making, to create a wider understanding of the potential impacts of an AVF eruption. Throughout the research process, DEVORA scientists work closely with emergency managers and other policy and decision makers to strengthen and maintain critical relationships, obtain input regarding practical, usable future research directions, and to offer advice regarding what measures they can take to prepare the city for future volcanic events. Over the past decade, DEVORA has gained significant international and local recognition, supported 25 PhD students, completed >200 work packages, and led to ~225 published papers. This talk will give an overview of the major scientific findings and milestones achieved during the programme's first 10 years, and discuss how DEVORA works to implement these new research outputs for use in policy and decision making around natural hazard events.

Communication strategies between volcano observatories and the Volcanic Ash Advisory Centres

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Effective communication between the scientific community and decision makers is crucial in the management and mitigation of volcanic hazards. In the interface between science and decision making is the connection between the volcano observatories and the Volcanic Ash Advisory Centres (VAACs). The VAACs are responsible for issuing Volcanic Ash Advisories (VAA) for their regions of responsibility, to support decision-making by the civil aviation authorises, air traffic control companies and airlines. The VAACs rely on information from volcano observatories for input to the production of the advisories. The two European VAACs (London and Toulouse) act as a back-up for each other. Whilst they may have close links with volcano observatories and some institutes in their own region, links to their back- up regions are not as strong. A workshop will be organised within the EUROVOLC project to establish formal contact and coordinate the interaction between volcano observatories and the two European VAACs. The aim of the workshop will be to define and harmonize avenues of communication and data-sharing and possible protocols for these interactions. This poster presentation will outline the key concepts of the workshop, and encourage feedback from the audience, particularly staff of the European volcano observatories, on developing effective communication procedures.

S02.08 Poster

The evacuation plan by the Campania region in the red zone of Vesuvius area

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The Red Zone in Vesuvius area includes 25 municipalities with more than 600 000 residents. The area limit has been formalized by both Campania Region and by the President of the Italian Council of Ministers. The precautionary evacuation is the only safeguard measure for the population living in the red zone because of the consequences of the possible invasion of pyroclastic density currents or roofs collapses due to ash accumulation. This is the reason why the strategy for people protection, establishes their precautionary evacuation and transfers to others Italian Regions.

The Italian Civil Protection Department has subsequently formalized "Guidelines" with operative instructions useful to the components of the National Civil Protection System. The document provides indications for emergency plans and assigns to Campania Region the task of drawing up the population departure plan. The Campania Region Civil Protection is finalizing this plan with the related activities and measures to be implemented for the Red Zone evacuation when the alert level “ALARM” is reached, with the peculiar contribution of The Campania Regional Transport Agency (ACAMIR).

Nine “meeting area” have been identified on the Campania territory in which the citizens of the red zone will be moved. These areas of exchange are the starting point for the hosting plans of the other Italian Regions: the Vesuvian citizens will be housed by the “twin regions” according to their specific hosting planning.

On the main road network 21 access gates have been identified: access points from local roads to the primary network. Other important planning elements are being defined through a consultation activity with local authorities and by means of technical insights.

S02.08 Poster

Volcano Observatory Crisis Operations – VDAP and USGS Perspectives on Best Practices

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USGS Cascades Volcano Observatory, USA

The Volcano Disaster Assistance Program (VDAP) has assisted foreign observatories respond to more than 60 volcanic crises during the past 32 years and USGS Observatories have responded to multiple domestic eruption crises. We consider the following to be ***best practices in observatory preparedness*** *for* crises response:

1. **Knowledge of the volcano experiencing unrest and an ability to forecast outcomes of unrest.** Ideally, this includes: knowledge of eruptive chronology, and availability of formal hazard assessments, zonation maps, information about analogous volcanoes, and modeling to develop eruption scenarios and forecast potential outcomes. Probabilistic event trees are used to elicit expertise of observatory staff, aid internal communication, and quantify forecasts. Preparation of scenario-based models and event-tree frameworks in advance of crises enables and expedites forecasting.
2. **Adequate real-time monitoring and interpretation.** *Ideally* this includes multi- parametric real-time monitoring installed and maintained in advance of crises and used to develop an understanding of baseline behavior. Scientists with the training and experience required to interpret subtle changes in monitoring data are essential.
3. **Hazard communication.** To a large degree, success in crisis response is dependent upon effective communication. Well-developed and rehearsed protocols for communication of hazards to emergency managers are essential. Routine communication with the public about hazards contributes to observatory credibility and consequent authority. Scientists are essential contributors to communication, whereas, designation of a Public Information Office (PIO) organizes information flow, ensures consistency and frees up scientists' time for other crisis operations. Most observatories use Alert Levels to convey the state of unrest or eruption and where used, they are invariably linked directly or indirectly to mitigation actions. VDAP and USGS experience confirm the well-known adage that monitoring and scientific knowledge are of little value in crisis response without effective hazard communication and consequent mitigation.

S02.08 Poster

Volcanic alert levels and rational decision-making

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Volcanic Alert Level Systems (VALS) are of large use at volcano observatories, as a means of communication of the current state of the volcano and its possible medium and short-term evolutions to civil authorities, to the media, and to the society. However, VALS imply predictive capabilities not supported by current knowledge of the volcanic processes, and mostly relevant, they imply decisions and responsibility that go by far beyond the expertise and – in most countries – the societal mandate of volcano scientists. In fact, the discretization of the volcano status associated with VALS has its exclusive meaning in the mitigating actions associated to each level change. In highly urbanized areas such mitigating actions have a cost themselves, therefore, alert level changes should follow a cost/benefit analysis where negative and positive consequences are evaluated. Negative consequences may include economic losses from closure of touristic or productive activities, collapse of the value of properties, social and political disruption, etc., while positive consequences are obviously related to increased chance to save lives and values in case of eruption. While experts from many different fields are required to evaluate costs and benefits under the large uncertainties usually associated with the evolution of a volcanic system, the decision to act in favor of the society, e.g. by changing alert level and implementing mitigating actions thereby, is a political act and can only be made under a corresponding societal mandate. On this rationale, we discuss a general framework for the definition of VALS that takes advantage from the contributes by experts from many disciplines, providing decision-makers with the comprehensive knowledge required for informed and rational decisions.

S02.08 Poster

The evacuation plan by the Campania region in the red zone of Campi Flegrei area

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The Red Zone in Campi Flegrei Area includes 7 municipalities with more than 450 000 residents, about 300 000 in the city of Naples. The precautionary evacuation is the only safeguard measure for the population living in the red zone because of the consequences of the possible invasion of pyroclastic density currents or roofs collapses due to ash accumulation. This is the reason why the strategy for people protection, establishes their precautionary evacuation and transfers to others Italian Regions.
The Italian Civil Protection Department has extended the guidelines of Vesuvius Area to the Campi Flegrei one. The document provides indications for emergency plans and assigns once again to Campania Region the task of drawing up the population departure plan.
The Campania Region Civil Protection basing on the Vesuvius experience is finalizing the departure plan. Related activities and measures are to be implemented for the Red Zone evacuation when the alert level "ALARM" is reached, with the peculiar contribution of The Campania Regional Transport Agency (ACAMIR).
Six "meeting area" have been identified on the Campania territory in which the citizens of the red zone will be moved. These areas of exchange are the starting point for the hosting plans of the other Italian Regions: the citizens will be housed by the "twin regions" according to their specific hosting planning. On the main road network 12 access gates have been identified: access points from local roads to the primary network. Other important planning elements are being defined by means of technical insights.

S02.08 Poster

Review of multiple hazards in volcanic islands to enable the management of long-term risks: the cases of Ischia and Vulcano, Italy

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The management of long-term volcanic risks represents a challenge that requires a close cooperation between science and decision-making. This is particularly crucial in volcanic islands, which are characterized by multiple hazards concentrated in a relatively small environment, often associated with a large seasonality of exposure due to tourism. The scientific challenges are mainly the quantification and the characterization of the interactions among the multiple hazardous phenomena that may occur during the different "states of the volcano" (quiescence, unrest, eruption) and the definition of robust methods to forecast the transition between these states. For these topics, the emerging scientific knowledge is often rather limited and uncertain and, also in case it was well constrained, difficult to communicate to decision makers due to its intrinsic complexity. On the other side, the challenge for decision making is to assimilate this uncertain knowledge and translate it into actions.

Here, we discuss the experience gained in two working groups (WGs) in charge of reviewing the state of knowledge about volcanic hazards for the Italian volcanic islands of Ischia and Vulcano to build the scientific ground for subsequent decision making. These WGs, formed within the agreement between INGV and the Italian Civil Protection Department, involved about 20 researchers from INGV and Universities, as well as representatives of the Italian Civil Protection, to facilitate the reciprocal understanding and to address the work toward useful results for decision making. The WGs reviewed all the potential volcanic hazards for Ischia and Vulcano based on literature, results of previous projects, as well as ad hoc audits of other experts on specific topics, and organized a workshop to present the results and receive feedbacks from the extended scientific community.

Knowledge Exchange and Volcanic Risk Governance: Lessons from Policy Mobility Studies

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~800 million people are exposed to disaster risk from volcanic activity. National and regional governments are generally responsible for the development and implementation of *public policy* strategies for volcanic risk reduction (VRR) within their territories.

VRR practices and institutional frameworks vary significantly between jurisdictions. However, a priority of the international community of volcanology is the identification and promotion of improved practices in VRR through collaboration and knowledge exchange. In a globalised world, the mobilisation of policy, expertise and resources has profoundly shaped VRR policy.

This investigation applies *policy mobility studies* to volcanic risk governance around the globe. The mobilities field aims to understand how certain approaches come to be identified as 'best practices' at an international level, the networks through which policies move, how policies evolve whilst moving, and their (frequently unexpected) impact in new jurisdictions. Policy mobility investigations 'follow' case studies, constructing narratives from archival research, interviews and observations to document and map the events, agents and networks that shape policies, their movement and their reception in new settings. We present a study of policy mobility in volcanic risk governance at Volcán de Colima, Mexico, examining how knowledge exchange at the local, national and international level has interacted with both volcanological and social aspects of the local setting in complex, unpredictable and unintended ways to produce a dynamic and uneven policy field of VRR. These findings carry lessons that should be taken into account, such that those involved in future knowledge exchange in VRR are aware of the complexity of the processes, and stakeholders in volcanic risk scenarios may achieve their policy goals more efficiently. with fewer unintended consequences.

Key words: Volcanoes, Disaster Risk, Governance, Policy Mobility

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S02.09 - Scenario-based hazard and risk assessment. Development and application for volcanic risk management

Natural hazards in Goma and the surrounding villages, East African Rift System

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The city of Goma and its surrounding villages (DR Congo) are amongst the world's most densely populated regions strongly affected by volcanic hazards. In 2002 Nyiragongo volcano erupted destroying 10-15% of Goma and forced a mass evacuation of the population. Hence, the ~1.5 million inhabitants of Goma and Gisenyi (Rwanda) continue to live with the threat of new lava flows and other eruptive hazards from this volcano. The current network of fractures extends from Nyiragongo summit to Goma and continues beneath Lake Kivu and gives rise to the fear that an eruption could even produce an active vent within the center of Goma or within the lake. A sub-lacustrine volcanic eruption with vents in the floor of the main basin and/or Kabuno Bay of Lake Kivu could potentially release ~300 km^3 of CO_2 and 60 km^3 of CH_4 dissolved in its deep waters that would be catastrophic to populations (~ 2.5 million people) along the lake shores. For the time being, ongoing hazards related to Nyiragongo and Nyamulagira volcanoes silently kill people and animals, and slowly destroy the environment and seriously harm the health of the population. They include mazuku (CO_2-rich locations where people often die of asphyxiation), the highly fluoridated surface and ground waters, and other locally neglected hazards. The Nyiragongo permanent gas plume causes poor air quality and acid rain, which is commonly used for drinking water. Given the large number of people at risk and the continued movement of people to Goma and the surrounding villages, it was urgent to assess natural hazards in this region. Here we present a general view of natural hazards in the region around Goma, describe the volcanic eruption history with hazard assessment and mitigation implications, and consider social realities useful for an integrated risk management strategy.

S02.09 Poster

Assessing tephra-fallout impact to infrastructures at Öræfajökull volcano (Iceland) by using a scenario-based approach and a numerical model

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The ice-capped Öræfajökull is one of the most dangerous volcanoes in Iceland with potential for a VEI=6 eruption exposing the local community and tourists (>2000/day) to a range of volcanic hazards.

Öræfajökull has featured two eruptions in historic time (= last 1150 years): a 10 km^3 Plinian eruption in 1362 and the 0.6 km^3 explosive event in 1727. In the 1362 the eruptive plume reached the stratosphere, dispersed toward south-east resulting in ash fallout in Europe.

Future events are likely to feature pyroclastic flows, tephra fallout, gas pollution and jökulhlaups and represent the primary hazards that will impact Iceland and other regions of the North Atlantic.

We investigate the impact of tephra fallout from a future 1362-like event on critical infrastructures in Iceland (i.e. roads, airports, electrical power-lines). The analysis is done using the VOL-CALPUFF dispersal model to simulate atmospheric dispersal of ash and subsequent surface deposition. A MonteCarlo approach is used to calculate the probability of the tephra fallout to exceeding the thickness critical for the abovementioned infrastructures across Iceland. By using a spatial analysis, quantitative assessment of potential impact to selected infrastructure is provided.

The results show that for a future VEI=6 eruption at Öræfajökull there is a likelihood between 50-100% that >160 km of the National Electrical Power-grid will fail; 50-100% probability that >900 km of the main ring road will be affected by critical driving conditions and 50-100% chance that three of the main domestic airports will be affected by tephra fall on the runways.

Using Eruption Scenarios for Generating Volcanic Ash Forecasts

Frances Beckett, Claire Witham

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Knowledge of eruption scenarios is critical for activities at volcanic ash advisory centres (VAACs). This presentation will demonstrate the application of volcanic eruptions scenarios at the London VAAC.

Daily scenario-based forecasts are generated for the most active volcanoes in Iceland using the NAME dispersion model. Information on the past eruptive behaviour at each volcano is provided by the Iceland Volcano Observatory and used to assign the plume height. The simulations are used to consider the potential impact a future volcanic eruption would have on airspace. 'What-If' forecasts are also generated for any volcano that has a raised aviation alert level. On the 17th November 2017, the aviation colour code was increased to yellow for Öraefajökull. Information on its eruptive history was drawn from datasets, including the Smithsonian's Global Volcanism Program database and the Catalogue of Icelandic Volcanoes, and used to advise stakeholders on likely eruption scenarios and ash transport.

During an eruption, information on key source parameters needed to initialize dispersion model simulations may be unavailable or poorly constrained, for example: plume heights, mass eruption rates and particle size distributions. Predefined scenarios can help provide a first guess in these instances. The computer systems at the London VAAC have the functionality to allow forecasters to run multiple simulations with varying source parameters to assess the impact of the scenario uncertainty on the forecast.

Information on possible eruption scenarios also plays a key role in emergency preparedness, in addition to direct response. Eruption scenarios are used to define regular exercises used by the London VAAC to test the generation of products and its communication systems.

Onticism to epistemicism: a spectrum of pragmatic hazard and risk scenarios

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Scenarios play a key role in our understanding of the volcanic risk by helping us conceptualize factors controlling the outcomes of future eruptions. Volcanic risk in its simplest form is a function of the hazard and vulnerability. Eruption hazard scenarios result from the interpretation of partially complete geological, geochemical and historical records and attempt to capture the life-cycle of a volcanic system. Vulnerability is a complex, multi- facetted and poorly-constrained concept which is typically characterised at the local scale and by broad assumptions. Both aspects are characterized by important aleatoric and epistemic uncertainties that require a component of probabilistic modelling, where the number of parameters modelled stochastically usually depends on the purpose of the study. Pragmatic scenarios must fall within a spectrum bounded by deterministic (finite outcome) to fully probabilistic (continuum of outcomes) approaches.

Here, we review the use of hazard and impact scenarios in volcanology. We discuss how the geological and historical records inform long-term eruption hazard scenarios and the need to define analogues for poorly documented volcanoes. For the vulnerability, we present some shortcomings preventing quantitative impact assessments and illustrate how a combination of exposure analysis and empirical data can help frame potential impacts of future eruptions and increase preparedness. Volcanic risk assessment suffers from observational biases preventing the characterization of the full range of processes, feedbacks and thresholds acting on both hazard and vulnerability. Rather than relying on fully probabilistic techniques that suffer from data scarcity, we argue that pragmatic scenarios that identify and communicate assumptions and limitations, coupled with tools such as event-trees, form a comprehensive basis for risk studies.

Development and application of scenario- based hazard and risk assessments: observations from New Zealand

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The majority of volcanic hazard and risk assessments fall somewhere on the spectrum spanning from deterministic to probabilistic approaches. There are benefits and limitations to both end-members; it is critical to understand the fundamental question being asked by the stakeholder and/or the researcher and apply the appropriate method in full recognition of method limitations.

Here, we focus on the benefits and limitations of deterministic scenario-based approaches to hazard and risk assessment, using examples from New Zealand. First, we will discuss the use of scenarios to convey eruption complexities, explore consequences, and generate fruitful discussions and awareness-building with stakeholders, using examples from ongoing work on the Auckland Volcanic Field. We will consider approaches to ensuring scenarios reflect the best available data, along with strategies employed to effectively communicate the deterministic – as opposed to probabilistic – nature of these scenarios. Next, we discuss the use of scenarios during a volcanic crisis as a communication tool and support the delivery of more quantitative information. We will end with a consideration of efforts to combine the best of both deterministic and probabilistic approaches to produce relevant, credible, and suitably accurate hazard and risk information for stakeholders.

Numerical modeling of multi-hazard eruption scenarios at Lassen Volcanic Center, California

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It has been more than 100 years since the most recent volcanic eruption in California, the 1914 - 1917 CE eruption from Lassen Peak. This gap in activity has limited the awareness of volcanic hazards in the state, despite significant infrastructure, populations, and recreational use near many Holocene volcanoes. Eruption scenarios offer a means of improving recognition and knowledge of the potential hazards and impacts of volcanic eruptions by conveying the variety, styles, and timescales of volcanic hazards, as well as investigating impacts, and facilitating communication with stakeholders. With these aims, we construct eruption scenarios of the past three events from the Lassen Volcanic Center: 1050 ybp Chaos Crags eruption, 1666 CE eruption of Cinder Cone, and 1914 - 1917 CE Lassen Peak eruption. This selection demonstrates the wide range of hazards during the most recent events.

Our eruption scenarios are built from an analysis of published data on the dynamics, properties, and deposits of these eruptions, combined with numerical modeling of eruptive hazards in present-day conditions. We incorporate isopachs and isopleths of tephra deposits, as well as grain size data, to inform Ash3d modeling of tephra dispersal and fallout. Scenario wind fields are chosen from an analysis of the "most likely" deposits out of 1000 tests in random historical wind fields. We also model the advance and final extent of lava flows and pyroclastic flows from these eruptions with the VolcFlow model, and associated lahars with LaharZ. Properties for these geophysical flow models are derived from analyses of deposits, analogue events, and fitting model results to actual deposit extents. Our results constrain the footprints, intensities, and durations of a range of volcanic hazards from these eruption scenarios, illustrating the dynamics of such events with maps and videos, and providing the necessary data for an analysis of the impacts from these eruptions.

Short-Term Hazard Assessment at Nevados de Chillán Volcanic Complex

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Nevados de Chillán (Central Chile) is a volcanic complex with two adjacent subcomplexes and more than twenty active eruptive centers during the Holocene. Currently, the volcano has a 1:75,000 volcanic hazard map published by Chilean Geological Service (SERNAGEOMIN), which considers a long-term hazard assessment with an observation time of the volcanic activity of last 40 ka. Although this map is useful for risk reduction strategies according to temporal and spatial scale of evaluation, this is not useful for emergency management because it considers the activity of all the eruptive centers, generating a 115 km^2 area of very high hazard, overestimating the real hazard zone of an specific eruption,due it is very unlikely that all centers will be activated simultaneously. In December of 2015, an eruptive cycle began, which has lasted for more than two and a half years. Nowadays the volcano in on orange volcanic alert, with a lava dome extrusion in the active crater. On January 8, 2016, the first surface activity of this cycle is recorded, when an explosion with ash emission was generated in the NE sector of the Las Termas subcomplex. From this moment, SERNAGEOMIN assess the short-term hazards for present eruptive cycle. Initially, in yellow alert, hazard radios due to ballistic projections for 15 days of evaluation were considered. With the scaling of the volcanic activity, the radios were increasing their extension, and after the extrusion of the dome, other processes like block and ash flows and lahars were incorporated. At this moment the hazard maps become polygons that represent all the mentioned processes and not only radius around the active crater. Finally, with new eruptive parameters, a detailed study of historical eruptions and the review of the global statistic of domes growths episodes, a probabilistic map has been incorporated for two scenarios.

The DEVORA Scenarios: Introducing a suite of multi-hazard eruption scenarios for the Auckland Volcanic Field, New Zealand

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Auckland is the most populous region in New Zealand with 1.6 million residents and accounts for over one third of New Zealand's Gross Domestic Product. The Auckland metropolitan area is built upon the monogenetic Auckland Volcanic Field (AVF), which poses a considerable threat due to the high exposure of people and infrastructure to future volcanic hazards. The Determining Volcanic Risk in Auckland (DeVoRA) research programme was established in 2008 as a collaborative effort between GNS Science, numerous New Zealand based universities, and both local and central government agencies to improve volcanic hazard and risk management in Auckland. Since DeVoRA's inception, substantial advances have built on earlier research by using tools and approaches from geological, volcanic hazard, engineering, and societal risk disciplines. Volcanic eruption scenarios can integrate findings from each of these disciplines and produce outputs that benefit many stakeholders. The 'Mangere Bridge' eruption scenario illustrated the impact an AVF eruption could have on Auckland's urban functionality in a series of papers published in the Journal of Volcanology and Geothermal Research. However, this is but one scenario: the impacts of an AVF eruption could differ substantially depending on the specific area of Auckland that is affected by an eruption. The geologic record shows that eruption size, duration, style and sequence vary considerably within the AVF. Here, we build upon the Mangere Bridge eruption scenario and present seven new eruption scenarios that cover the spectrum of credible eruption phenomena expected from a future AVF eruption. The scenarios are based on research on AVF volcanic hazards and analogous eruptions from around the world. Our expectation is for the scenarios to be used within AVF volcanic impact and risk studies and to support volcanic risk mitigation and asset management practices.

Assessing tephra hazard and risk for Erciyes volcano, Turkey: A scenario-based approach

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Erciyes volcano in central Anatolia, Turkey, is a large stratocone that is commonly considered extinct, yet has evidence for explosive activity as recently as 2000 years ago in Roman times. Erciyes is constructed within a large caldera and consists of the eroded stratocone summit peak and more than 40 parasitic cones and domes on and beyond the caldera rim. The city of Kayseri (1.3 million population) lies approximately 20 km to the north of the summit and is built around a number of the flank cones and domes. Relatively few geological studies of past deposits exist so that defining the full range of future eruption scenarios for hazard and risk assessment is challenging.

We have defined two initial eruption scenarios from field studies: 1) A magnitude 5 to 5.5 rhyodacitic dome-forming eruption along the ring fracture surrounding Erciyes; and 2) The Plinian phase of a magnitude 7 to 7.5 caldera-forming summit eruption. We use the open- source probabilistic tephra dispersal framework of TephraProb to model the extent and intensity of the tephra fall hazard, coupling this with exposure and vulnerability data to identify areas where damage or disruption may be most significant. We find that the seasonal effects are limited, with tephra most likely dispersed towards the east or north-east year-round, peripherally affecting Kayseri and its industrial areas. Very dry summers are expected to promote repeated remobilisation of any tephra deposits, although winds are most likely to blow tephra towards the less populated areas south of the volcano. The greatest influence on future hazard and impact is the location of a future dome eruption, with the largest impact associated with a new vent along the ring fault to the north or northwest of the current summit.

Reconstructing the 17th century Long Island eruption, Papua New Guinea

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Inversion is an effective tool for constructing tephra hazard scenarios based on past events. Inversion methods allow us to utilise historical or geological data to produce estimates of tephra accumulation for areas where information is lacking due to poor preservation or inaccessibility. Resulting scenarios can then be used to consider the impacts if a similar eruption were to occur again. One such scenario is the eruption that produced the Tibito Tephra, first identified in the Western Highlands of Papua New Guinea in the 1970s.

In 1982, Russell Blong concluded that the tephra originated from Long Island in the Bismarck Sea, and estimated a compacted volume for the deposit of > 11 km^3 or a mass of > 1.6×10^{13} kg. However, estimates of volume and mass were difficult given a lack of proximal data. Blong's inner isopach was derived from a single measurement on Crown Island, 25 km northwest of Long Island. All other measurements were taken from mainland New Guinea, > 70 km from source, and some from elevations exceeding 3,000 m. Recent inversion modelling of tephra dispersal, however, has provided consistent mass estimates between 3.0 and 3.4×10^{13} kg.

We present the mapped scenario, and optimal eruption parameters and environmental conditions determined to reconstruct the tephra deposit. In replicating the 17th century eruption, inversion suggests tephra accumulations of approximately 180 and 16 mm in the coastal cities of Madang and Lae respectively. In the highlands of Papua New Guinea, Mount Hagen and Goroka cities each received approximately 60 mm of tephra. The robust scenario developed here allows the consequences of a future eruption from Long Island to be investigated, particularly for the largely isolated highland regions, where livelihoods rely heavily on agriculture.

Exposure of roads to volcanic ash from a future eruption from Mount Fuji, Japan: Implications for evacuation and clean-up

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Although volcanic ash fall is not seen as an immediate threat to life, this hazard has the ability to travel far from source and impact livelihoods, by damaging crops, farmland and, in severe cases, causing roof collapse. Moreover, even small amounts of ash can impact the operation of critical lifeline infrastructure such as electricity and transportation, which has the potential to hinder disaster response and recovery operations.

To better prepare for future volcanic eruptions, potential impacts on lifeline infrastructure need to be included in the development of eruptive scenarios. Disaster risk management should be approached holistically, using multi-disciplinary approaches and including all stakeholders. This research proposes the use of mathematical graph theory techniques, alongside GIS tools and hazard modelling - with an understanding of the use and vulnerability of particular lifeline infrastructure - to help envisage potential problems that could result from lifeline failure and aid in disaster planning going forward.

A future eruption of Mount Fuji, Japan, was used as a case study scenario to assess the usefulness of graph theory techniques in aiding disaster mitigation, response and recovery. In particular these techniques, alongside input from lifeline sectors and prefecture governments, were used to assess the impacts that ash induced road closures could have on current evacuation plans for Yamanashi Prefecture, with regards to a future 1707 Hoei type eruption.

In the case of a future Hoei type eruption, with similar westerly wind conditions, ash induced roads closures would affect current evacuation plans for Yamanashi, particularly for those in the northeast of the prefecture. Ash fall accumulation on roads can inhibit road use, resulting in long detours or the inability for residents to be able to evacuate unassisted, and delays in the return of evacuees to their homes after the eruption, until the completion of ash fall clean-up operations.

Investigating volcanic eruption impacts on water infrastructure using a scenario approach: damage to networks, outage maps and potential public health consequences

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Critical infrastructure systems provide essential services to modern societies. Water supply and wastewater networks (water infrastructure) are critical for firefighting, public health and sanitation, habitability, the provision of health care services, and business continuity. We use a scenario of a small basaltic eruption in the Auckland Volcanic Field, New Zealand, to explore consequences for the water infrastructure of Auckland (New Zealand's largest city). In partnership with water utility managers, we developed 'Level of Service' (LoS) metrics that range from full service to no service for the water infrastructure networks. We used a series of network status maps to summarise impacts of the hypothetical eruption sequence on the networks' physical assets. The maps also account for evacuation zone considerations and the cascading impacts of concurrent power outages. We then created a series of regional maps showing the LoS for water supply and wastewater over the course of the eruption and recovery period. For water supply, despite relatively localised damage to the network, service interruptions could last over a year over the entire city, well beyond the end of the month-long eruption. Auckland's wastewater network is severely affected by the scenario given the eruption location, with the city's wastewater treatment plant lying within the zone of heavy damage. Its estimated repair time is 2-3 years, during which there could be extended duration discharges of untreated and partially treated sewage to the city's waterways, necessitating public health measures such as imposing bans on recreational contact and food gathering in receiving waters. A concerted and sustained environmental and public health response would be necessary to manage the substantial risks to public health. Our findings highlight the complexity and challenges of managing water infrastructure during and after a volcanic eruption.

S02.09 Poster

Development of an event tree for eruptions at a peralkaline rhyolite caldera system: an example from Aluto volcano (Ethiopia)

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Ethiopia hosts 45% of the 126 known African Holocene volcanoes (GVP, 2013). In addition, it is the second-most populated country in Africa (108M inhabitants) and in the top 10 of most densely populated countries in mainland Africa (108 people/km², 2018 estimates: United Nations, 2017). Many of these people live and work close to volcanic systems that have experienced mild to large explosive activity in their recent geological past. Thus, assessing volcanic hazard, including the associated uncertainties, is of paramount importance in such a natural and social environment.

In this work, we focus on Aluto volcano (central Main Ethiopian Rift), an inhabited peralkaline rhyolite caldera system located near Ziway town (almost 50,000 inhabitants). Post-caldera silicic volcanism (since ~300 ka) has originated from many different vent locations, mostly along the caldera ring fault, and has primarily consisted of explosive eruptions that range in style from (violent) Strombolian to Vulcanian or even sub-Plinian events, typically ending with an obsidian lava-flow phase. Phreatomagmatic eruptions are also recorded and future eruptions may also involve a phreatic phase. Accordingly, volcanic hazard from tephra fallout, concentrated and dilute pyroclastic density currents, lava flows and, likely, lahars, is relevant at Aluto. In terms of eruption frequency, field evidence suggests that 1-3 eruptions/ka may be expected while estimates obtained through expert elicitation indicate a higher (mean) eruption frequency around 7 eruptions/ka.

We incorporate all the aforementioned information into a graphical probabilistic model (an event tree) to assess volcanic hazard at Aluto volcano. In the first instance, the event tree aims at merging varied information/data (eruption frequency, vent-opening pattern, eruptive behaviour, etc.) under a unified probabilistic framework and model the aleatory uncertainty in the volcanic hazard. Once fully parameterized, the event tree will allow us to estimate total and conditional probabilities for any hazardous event in the model.

Selecting lava flow hazard models for eruption scenarios: application to Auckland, New Zealand

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Over the past few years, improved accessibility of lava flow models has made it easier to create quantitative lava flow hazard footprints for the development of eruption scenarios. However, there are many lava flow models to choose from with varying data input requirements and model output applications. Therefore, when selecting a lava flow model - or a suite of models - to create hazard footprints it is necessary at least to consider: available input data, intended application of outputs, and overall model suitability. The Determining Volcanic Risk in Auckland (DEVORA) research programme has been developing a series of eruption scenarios to assist local stakeholders plan for a future Auckland Volcanic Field (AVF) eruption. Here, we review available lava flow models and develop a set of criteria to aid in selecting quantitative lava flow hazard models for four effusive DEVORA eruption scenarios. We select our suite of lava flow models based on the data available for the AVF as well as the hazard intensity metrics we are interested in quantifying, including lava flow thickness, velocity, and temperature data. We then create and compare lava flow hazard footprints using both a digital elevation model (DEM) and a digital surface model (DSM). Our results demonstrate how the built environment may alter lava flow advancement and the benefit of using numerical lava flow models to develop credible multi-hazard eruption scenarios. As populations living close to volcanoes grow, being able to model lava flow footprints with DSMs will likely become increasingly important since the built environment can influence lava flow advancement. By refining the lava flow hazard footprints included in the DEVORA scenarios using quantitative models, we can provide stakeholders with additional information about the timing and potential hazardous conditions their assets would experience in each scenario.

A scenario-based approach for assessing volcanic hazards at Mt. Meager Volcanic Complex, B.C.

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Canadian volcanoes are inherently remote and exhibit intermittent to low levels of volcanic activity and have thus far exerted negligible impact on Canadian society. However, populations have been established along with infrastructure growth since the last explosive eruption in Canada, occurring at Mt. Meager 2360 years B.P. A volcanic hazard assessment is being developed for this volcanic system, a volcanic complex of rhyodacitic to andesitic composition. This will be the first comprehensive volcanic hazard assessment developed for a Canadian volcano. In 2016, two fumaroles were detected breaching the ice cap on top of Mt. Meager. This has spurred interest to better understand the system and its potential impacts from any subsequent volcanic activity given the existence of nearby populations, agricultural operations and high value infrastructure. Limited data on the geologic history and eruption parameters is available for this volcano; well documented volcanic deposits only exist for the last eruption. Due to these data limitations, eruption scenarios will be discerned from analogous volcanic systems depicting a range of possible eruption styles and magnitudes. Scenario parameters will be used for numerical model simulations specifically demonstrating the potential extents of lahars, pyroclastic flows, lava flows and atmospheric ash dispersal and deposition; all of which have been determined as likely hazards stemming from an eruption at Mt. Meager. While this hazard assessment focuses on one volcanic system, this project aims to produce a framework for developing future volcanic hazard assessments in a Canadian context.

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S02.11 - Assessing the impact of volcanic risk reduction activities Are we achieving our goals

Alaska Volcano Observatory: analyzing forecasting success from 1988-2017

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The Alaska Volcano Observatory has been monitoring Alaska volcanoes and issuing notifications of volcanic unrest and eruption since 1988. We assess whether or not AVO issued an advance notification for 53 eruptions at 20 volcanoes, and examine the results with respect to available monitoring instrumentation and data in place at the time of the event, and individual volcano and eruption characteristics.

At seismically monitored volcanoes with longer repose periods (>15 yrs) and larger eruptions (VEI3+), AVO has a 100% success rate (Redoubt 1989-1990 and 2009, Spurr 1992, and Augustine 2005-2006). The success rate is only 6% for eruptions at volcanoes without local seismic monitoring (successfully forecast: the VEI 4 eruption of Kasatochi 2008, and the 2014 VEI 1 eruption of Shishaldin) and 20% for eruptions at more mafic, seismically monitored, frequently-active volcanoes. Volcano-specific characteristics should be considered when designing monitoring programs and evaluating forecasting success. More proximally-located sensors with different data types are likely needed to forecast eruptive activity at frequently active, more mafic volcanoes that generally produce smaller eruptions.

This analysis also illustrates the importance of designing metrics for success within individual monitoring agency's policies, alert levels, rationales, and procedures. Each alert level system has its own definitions and parameters for use; success or failure must be measured within the particular details of each system. When remote volcanoes are completely without ground-based instrumentation, eruption forecasting is rare, and our goal is to decrease the delays between onset, detection, and notification. A metric of success in these cases may not be eruption forecast, but instead whether or not the time between eruption onset and notification is decreasing. Long periods of elevated color codes may be appropriate for prolonged unrest at remote volcanoes (in Alaska), although this may be undesirable in more populated areas.

Seismic crisis and the loss of institutional memory: the Volcan Baru, Panama

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In 2006, a disconcerting seismic crisis occurred in the Volcan Baru area of highland Panama and shook local residents, national politicians, and international investors in the highland resort area out of their belief in real estate agents' claim that the volcano was extinct. The volcano has been dormant for hundreds of years, though oral history and archaeology clearly indicate that it has erupted multiple times within human occupation of highland Panama. A network of monitoring devices was set up around the volcano, but funding for them quickly evaporated once the earthquakes stopped. The lack of historical memory of eruption events and their consequences combined with political corruption and benign neglect combine to leave local residents in the Chiriqui province unprepared for a future eruption. While recent attempts were made to stage an evacuation drill, it never happened. Oral history of Baru eruptions encapsulated indigenous accounts of pre- Columbian eruptions through use of metaphor in ways that facilitated understanding of subsequent eruptions after several generations of repose. Little or no funding or awareness, though, exists in the current non-indigenous context. If nothing else, this presentation is a meditation on a lack of political will and a query for input from others.

Reaching out to young students - experience of primary school outreach in St. Vincent & the Grenadines 2013-2018

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For the past ten years, the National Emergency Management Organisation of St. Vincent and the Grenadines with the support of The UWI Seismic Research Centre has organized "*Volcano Awareness Week*". This focused week of events uses the anniversary of the April 1979 eruption of La Soufrière volcano to raise awareness about volcanic hazards and the potential impact it can have on their future livelihoods. Reaching out to primary schools throughout St. Vincent has been a key component of the week for the past five years and student workshops have been conducted throughout the island. We provide an overview of our experience during this period, including a review of the techniques used, materials and experiments designed and implemented and assessment of their effectiveness in engaging young children. We present a simple method for monitoring and evaluation of the workshops by assessing students' knowledge about volcanoes pre and post workshops. We note the changes in the outreach programme over time with factors such as increasing knowledge levels among the student population, advances in technology and the increase in research in volcanic risk communication playing significant roles. Finally, we present plans for primary school volcanic outreach using the latest techniques and products available.

The Volcano Disaster Assistance Program's Journey to Developing a Systematic Plan to Monitor Program Progress- Learn from our Mistakes and Successes

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The Volcano Disaster Assistance Program (VDAP) has developed a systematic monitoring and evaluation (M&E) plan to communicate progress towards meeting our goal of reducing loss of life and property from volcanic eruptions. Reviewing the progress of scientific programs is not new for a long-term disaster risk reduction program like VDAP, but applying traditional systematic M&E parameters to such a program is new. VDAP's original method of determining the program's level of success utilized informal assessments, anecdotes, and personal communication and was sufficient when VDAP began in 1986 with 5 staff members, but over time the team has grown to include more than 20 people and a wider range of activities. Consequently, program management and performance monitoring is now more complex than when VDAP began. In 2014, at the direction of the donor partner, the US Agency for International Development's Office of U.S. Foreign Disaster Assistance (USAID/OFDA), VDAP began the journey to develop a systematic method to capture program-performance monitoring data. This was done to better communicate progress with USAID/OFDA, improve VDAP's performance by applying lessons learned from past responses, share best practices with counterparts in volcano hazard institutions, and to improve crises response overall. The team had to answer questions such as: What is the minimum number of objectives that describes the goal of our program? What items can be quantified to illustrate the impact of our work? How can we quantify something we are trying to prevent (i.e. disasters)? While designing our M&E plan, we learned lessons that may be applicable to other types of volcano-related programs, such as the importance of involving the entire group in M&E plan creation, finding the right balance of detail and realistic goals, and ways to make the plan most useful for internal learning and improvement.

The most dangerous volcanoes of Colombia and populations in its area of influence. Are we prepared for the next eruption?

Maria Luisa Monsalve

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Active volcanoes in the Colombian Andes, the most densely populated area of the country, present a wide variety of eruptive styles and many populations, including intermediate cities (> 400,000 inhabitants) and nearby municipalities, that would be exposed to volcanic phenomena that may occur during a future activity of these volcanoes. Cities such as Manizales and neighboring towns, in the department of Caldas and Tolima (≈1,000,000 inhabitants), would be affected by the activity of the Cerro Bravo volcano. Its geological record comprises Plinian to Subplinian eruptions, which have generated pumice falls, 10 cm thick at distances of 25 km; ash and block flows, ash and pumice flows and, lahars that have reached distances up to 60 km. The hazard map is in update, but there is still no awareness of its danger in the population. Machín volcano, showing signs of reactivation since 2012, is considered the most dangerous volcano in the country. Cities such as Armenia (Quindío) and towns of Tolima (≈1,200,000 inhabitants), could be affected by its eruptions, since its geological record, of Plinian and Phreatoplinian type, shows tephra falls, more than 10 cm of thickness at distances of 40 km, ignimbrites, and lahars that have reached distances of up to 70 km, and volumes of up to 22 km^3. The Galeras volcano, having mainly a Vulcanian type behavior, could affect the city of Pasto and nearby towns (> 600.000 inhabitants), distant < 9 km from the volcano. Despite its activity, since 1988, and institutional efforts to communicate the hazards, the small eruptions occurred have reduced the credibility onthe phenomena that may affect the population due to major events.

Monitoring volcanic unrests and the risk mitigation measures taken at Zao volcano, Japan

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Zao volcno is located at the middle of Northeast Japan arc. The Japan Meteorological Agency (JMA) started 24-hour basis instrumental monitoring in 2010. At the present, the continuous monitoring network consists of 14 instruments (3 seismometers, 2 microphones, 2 tiltmeters, 2 GNSS, 4 cameras and 1 thermal camera) by JMA and several others by Tohoku University and Geospatial Information Authority of Japan (GSI). Volcanic unrests in the 2014-2015 and the January-February 2018 were successfully monitored, and Near-crater Warnings were issued by JMA. Although no eruption occurred in both cases, they provide good opportunities to assess risk mitigation measures taken by stakeholders during the crises. The start of the 2018 unrest was noticed by the small tilt change which were preceded to the occurrence of the volcanic tremor at 19:28 on 28 January 2018. This tilt change indicated rapid ground uplift on the summit. Coexistence of a couple of volcanic tremors with continuous ground deformation by the tiltmeters let Sendai Regional Volcanic Observation and Warning Center to issue Near-crater Warnings and raise level from 1 to 2 at 14:38 on 30 January. This resulted in the partial closure of the ski park as well as hundreds of cancellations for booking hotels in spa resorts and many tours to watch the frost-covered trees around the summit which are one of the most popular winter activities in Zao. Lessons learnt from the recent volcanic crises of Zao indicate (1) the effectiveness of using precise ground deformation measurements such as tiltmeter to detect smaller unrests and (2) the importance of mutual communication among stakeholders, media and the local people/tourists in which not only the relevant warning message predefined in the Volcanic Alert Levels Systems (VALS) are transmitted in one-way, but also possible volcanic risks are shared including limits and uncertainties of science.

S02.11 Talk

Volcanic Hazards, Land and Labour

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We study the behavior of farmers living under the threat of the Tungurahua Volcano in Ecuador. Recent eruptions have caused significant losses, including loss of crops, death of livestock, and dwelling destruction. We collected a unique data set after a major eruption in 2016. We interviewed 222 farmers in the risky zone and 260 in a nearby control zone to understand why farmers choose to remain in the risky zone despite the existence of public programs aimed at relocating them in safe zones. We examine land and labor, which are farmers' main productive assets. After repeated ash fall events, a portfolio position in these becomes at least temporarily irreversible. The land may become hard to trade when desired or sold at a discount price. Agricultural human capital and skills have a farm-specific component; knowledge is experientially obtained and thus may not be easily transferable to other places. In addition, occupational mobility is limited by workers abilities and geographical mobility constraints. Farmers are thus trapped in a portfolio that they cannot exit. Meanwhile, land remains a strategic asset that provides the basis for rural livelihoods whereas labor skills match the needs required by agricultural tasks. This leaves little option other than to "rationally choose" to live with volcanic risk.

Firstly, we investigate the capitalization of volcanic hazards in farmland values and find a negative price premium of 21% compared to the control zone. Secondly, we explore nonfarm labor in response to volcanic risk. Finally, we argue that repeated ashfall events increase the illiquidity of farm households' assets such as farmland and that agricultural human capital is difficult to convert into non-agricultural one. Our results convey important information for public policies aimed at supporting adaptation and resilience of people living under the threat of volcanoes.

Measuring and Monitoring Disaster Risk Reduction Projects - Does it Work?

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The US Agency for International Development's Office of U.S. Foreign Disaster Assistance (USAID/OFDA) leads and coordinates the U.S. Government's response to disasters overseas. USAID/OFDA supports disaster risk reduction (DRR) programs implemented by partners to lessen the impact of a disaster, such as the Volcano Disaster Assistance Program that is implemented by U.S. Geological Survey (USGS). Over the past five years, USAID/OFDA has explored methods of measuring and monitoring DRR programs through the development of output and outcome indicators used to monitor activities. USAID/OFDA has also supported external evaluations and assessments of regional DRR programs. The purpose of monitoring and evaluation is twofold: to measure whether current projects are effective and to build an evidence base for improving DRR programming. Effective DRR programs reduce risk, but traditional indicators often measure increase or change over time. Two of the main challenges for measuring effectiveness of DRR programs are that 1) indicators often measure what did not happen, rather than what did happen (e.g., a volcanic disaster); and 2) indicators often measure outcomes for large populations rather than a select group of beneficiaries. USAID/OFDA approaches monitoring of DRR from two directions: standard indicators that can be aggregated across programming, and customized indicators that strive to measure outcomes specific to the activity. Other volcano-related DRR work may benefit from USAID/OFDA's successes and lessons learned from current DRR projects and external evaluations of regional DRR programming in the Latin America and the Caribbean and the East Asia Pacific regions. We will discuss the importance of monitoring DRR programs, the difference between measuring outputs and outcomes, and the purpose of external evaluations. Finally, we will provide practical recommendations on how the volcano DRR community can better measure and monitor its programming to ultimately result in more effective programs.

Volcanic and Seismic Household Emergency Preparedness in Families in S. Miguel Island (Azores, Portugal): What have we learned?

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Volcanic and seismic hazards can become disasters, threatening individuals and communities, enhancing the importance of developing disaster resilience. Albeit its significance, resilience resources such as household preparedness are underachieved. The Azores is a volcanic archipelago located in a triple junction of tectonic plates. While earthquakes occur on a daily basis, volcanoes are in a quiescence period. This study intends to characterize the volcanic and seismic preparedness of families in S. Miguel, the largest and most populated Island, aiming at producing scientific knowledge that can be helpful in designing better policies and practices. Semi-structured interviews were applied to 145 participants. Current preparedness practices were assessed and some participants were asked to construct new measures, as they were currently inexistent or insufficient. Other variables such as risk perception were also included. Results point to low levels of volcanic and seismic household preparedness, although participants revealed higher engagement in seismic preparedness, as participants majorly developed measures consistent with a seismic scenario. Nevertheless, the measures were perceived as adequate for both hazards. There seems to exist a lack of knowledge regarding preparedness, especially concerning the volcanic hazard. The reasons accounting for this lack of knowledge should be further discussed in order to produce recommendations to enhance preparedness in the island.

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S02.13 - Strategies for eruption forecasting and early-warning to support operational hazard evaluation during volcanic crises

Operational reliability of a system based on lightning data for early estimation of eruption site location

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At the onset of an explosive eruption, the early determination of the exact eruption site may be critical to activate civil protection evacuation plans. Powerful subglacial volcanism is expected to produce volcanic lightning during its early hours. In April 2013, an automatic real-time system was installed at the Icelandic Meteorological Office, that monitors and analyses lightning to locate the eruption site. This system is based on lightning data from the ATDnet long range system of the UK Met Office. During these first five years of operation, the system has never been tested by an explosive eruption, as none has occurred. A dormant automatic monitoring system waiting for a rare event is quite susceptible to degeneration during the waiting period, and IT-system upgrades pose a serious threat. However, ordinary weather thunderstorms in Iceland are used to monitor the status of the system. At high latitudes, thunderstorms are rare and during these first years of operation, the system was automatically activated on average once per week. The time from the first observed lightning strike of a thunderstorm until the system had finished analysing the data and sent an E-mail warning was usually 7-18 minutes (90% of warnings). In late 2017 this system went through a major IT-systems upgrade, where programs needed to be recompiled and moved to a new computer. Furthermore, the responsibility for the operation of the system was changed. As expected this change had noticable effect on its reliability. This study reviews the use of the lightning detection system as an important monitoring tool for an early detection of eruption source location, and its long term sensitivity to computer upgrades.

Enhancing the Failure Forecast Method using a noisy mean-reverting process

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The Failure Forecast Method (FFM) for volcanic eruptions is a classical tool in the interpretation of monitoring data as potential precursors, providing quantitative predictions of the eruption onset. The basis of FFM is a fundamental law for failing materials: $dX/dt=AX^{\alpha}$, where X is the rate of the precursor signal, and $\alpha \geq 1$, A are model parameters. The solution X is a power law of exponent $1/(1-\alpha)$ diverging at time t_f, called failure time. The model represents the potential cascading of precursory signals leading to the final rupture of materials, with t_f a good approximation to the eruption onset t_e. We generalize this approach by incorporating a stochastic noise in the original equation, and extending the uncertainty quantification beyond previous efforts. Embedding noise in the model can enable the FFM equation to have greater forecasting skill by focusing on averages and moments. Sudden changes in the power law properties are indeed possible, and this is particularly critical when the method is applied to calderas like Campi Flegrei (Italy) which are prone to prolonged unrest and ambiguous monitoring signals. In our model, the prediction is thus perturbed inside a range that can be tuned on previously observed variations, producing probabilistic forecasts. In more detail, the change of variables $\eta=X^{1-\alpha}$ implies $d\eta/dt=(1-\alpha)A$, i.e. a straight line which hits zero at t_f. The most efficient graphical and computational methods indeed rely on the regression analysis of inverse rate plots. We re-define η with $d\eta_t=\gamma[(1-\alpha)A(t-t_0)+\eta_{t0}-\eta_t]dt+\sigma dW_t$, called Hull-White model in financial mathematics. Parameter σ defines the strength of the noise, and γ the rapidity of the mean- reverting. We test the new method on historical datasets of precursory signals already studied with the classical FFM, including tilt, line-length, and fault movement at Mt. St. Helens 1981-82, seismic signals registered from Bezymyanny 1960, and surface movement of Mt.Toc 1960-63.

Aided Volcano Surveillance: an Automatic Early Warning System for Paroxysms at Mt. Etna

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Volcanic paroxysms at open conduit systems are not easily predictable, often posing a significant hazard to local population and to air traffic. The instrumental monitoring of active volcanoes and the continuous evaluation of their potential hazardousness play a key role for civil protection purposes. The significant investments of the last years in new monitoring techniques have improved our capabilities to sense volcano health, but the path to promptly and automatically recognize signs of potentially hazardous unrest is still long. Indeed, real-time surveillance of most monitored volcanoes worldwide is delegated to human experts, who interpret data coming from different monitoring networks. Unfortunately, the high nonlinearity of the complex and coupled volcanic dynamics lead to a large variety of different volcanic behaviors. Moreover, continuously measured parameters (e.g. seismic, deformation, infrasonic, video and geochemical) are often not able to fully explain distinctly the ongoing phenomenon, thus making the rapid volcano assessment a puzzling task for volcano observatories.

With the aim of aiding the personnel on-duty in volcano surveillance, we present a system based on an ensemble of data-driven classifiers to infer automatically the ongoing volcano status from all the available different kind of measurements. The system, named iASPE (integrated Alert System for Paroxysms at Etna), consists of a heterogeneous set of independent classifiers, each one built on different data and algorithms. Each classifier gives an output about the estimated volcano status regarding paroxysmal activities. The ensemble technique allows defining optimal rules on the considered classifiers to combine all the classifications into a single status that maximizes the performances of the warning system.

The developed early warning framework iASPE was tested on Mt. Etna by considering a record of multivariate data from 2011 to 2017. Results have showed the effectiveness of the ensemble model in improving the warning performances compared to single warning systems.

Seismic goats and radioactive ash: Fake news and challenges of communicating volcano hazard alerts during the 1980 eruptions of Mount St. Helens

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The 1980-86 eruption of Mount St. Helens volcano, USA, issued in the era of modern volcanology in several ways, not the least of which was in making, and communicating, specific predictions of the timing and nature of eruptive activity. This required the USGS to create the new job of Public Information Scientist (PIS), a position that was distinct from the PR specialists employed to dispatch new items from regional USGS centers. As senior-level volcanologists were too busy to take on this role, early career researchers filled the PIS slot on a rotating basis until the USGS realized that they needed a single “voice of the volcano”, which was my role from December 1980 – September 1982, a time period during which the eruptive activity changed from mostly explosive (May-Oct 1980) to mostly effusive (Dec 1980 – Oct 1986). This time period also included the last explosive eruption (in Mar 1982) and associated snow-melt lahars. It was also a time when geodetic, gas and seismic measurements made within the crater allowed eruption predictions to be made with increasing precision. This presented both opportunities and challenges: opportunities in that we could make increasing accurate predictions of dome-building eruptions, and challenges in both associated “fake news” forecasts by psychics and seers, and the need to communicate probabilities and error brackets. Looking back, the late l1980-1982 activity at Mount St. Helens provided an unusual set of circumstances for eruption prediction, with both consistent geophysical and geochemical precursors to effusive activity and the localization of that activity within the volcanic crater, well away from human populations.

Quantitative evaluation of ashfall damage around Tokyo Metropolitan area based on the combination between numerical simulation and infrastructure database

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We develop a volcanic-risk evaluation system combining both numerical simulation and database of infrastructure. Ashfall hazard gives damages on our life, e.g., transportation, electricity, agriculture, buildings, etc. Especially, a huge eruption causes a terrible damage around the wide area, and it is important to evaluate a quantitative risk in advance and prepare for the countermeasures like evacuation and logistics in advance. As a case study, we focus on an ashfall hazard around Tokyo metropolitan area by Mount Fuji eruption. For ashfall numerical simulation, we adopt JMA-RATM model, which includes the meteorological data from JMA numerical predication model of GPV and gives a precious ashfall distribution evaluation sequence. The infrastructure information around Tokyo metropolitan area is imported from the database by JoRAS of CSIS, University of Tokyo, into our relational database system of NIED disaster mitigation information system. The intersection matching between two big-data, i.e., the numerical simulation output and the infrastructure database, is realized by the quick search algorithm, and provide the quantitative information about the ash-fall risk in a target area, each individual municipality.

S02.13 Talk

Prospects of the short-term forecast of volcanic activity on the base of predictability of volcanic seismicity

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The present study considers the predictability of seismicity to be the requisite basis that would make it possible in the future to predict the phenomenology of a volcanic process from future changes in the level of seismic activity at a volcano of interest. The first step on these lines is to make a proper estimate of whether seismicity can be predicted. This was made using volcanic seismicity in the Northern Cluster of Kamchatka (Shiveluch, Bezymyannyi, Klyuchevskoi, Tolbachik, and Kizimen) and some other volcanoes (Etna, St.Helens) as examples.

We use the following equation for the dynamics of self-evolving naturally occurring processes (Malyshev, 1991, 2005). In working form our equation is similar to the equation proposed by B. Voight (1988) to describe the dynamics of increasing volcanic activity before the culmination of the ongoing eruption. The Voight equation is used in the forecasting failure method (FFM), but recent works (Bell et al., 2011, 2013, 2016) have argued that this method is subjective and inaccurate, even for retrospective analysis. The statement shows that these researchers tried to use the Voight equation but have not been able to achieve stable simulation, even at the fitting stage. The cause of this failure with the method is the choice of a suitable optimization criterion (Malyshev, 2016); the least squares method that they used is ineffective here.

The results show that the predictability of seismicity can be used as a tool in the overall prediction research, mostly aiming at identification and prediction of tendencies in extrusive and effusive activities and accompanying explosive activity. The prediction of large bursts of explosive activity related to failures on the arising volcanic structure requires additional monitoring of the dome structure and of the stability of constituent rocks to look for situations that favor large collapses in the edifice of the volcano.

The Predictability of the Seismicity on Shiveluch Volcano

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This report presents the results from estimating the predictability of the seismicity of Shiveluch Volcano based on the P.I. Tokarev earthquake catalog for the 1964 Shiveluch Volcano eruption and the earthquake catalog for the Northern Group of Kamchatka Volcanoes for 1971–1996 and 1999–2013. The mathematical model that we employed is a nonlinear second-order differential equation, while the algorithms of optimization and predictability are ours. The calculations show that seismicity can be successfully predicted for time intervals of a few weeks to a few months during phases of higher activity and for times of between a few months and a few years during phases of lower seismicity. The prediction distances are in excess of the error by factors of 20 to 50 on average. The nonlinearities in both times of higher and lower rates are close to the law of an equilateral hyperbola. We concluded that the predictability of seismicity can possibly be used in an integrated complex to predict extrusive and effusive activity and accompanying explosive activity. The prediction of major bursts of explosive activity related to failure in the existing volcanic edifice requires additional monitoring of the dome structure and the stability of the rocks that make up the dome.

Infrasound monitoring of eruptive volcanoes: new perspective for early warning at a regional scale

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With the advent of Civil Aviation and the exponential growth in the air traffic the problem of volcanic ash encounter has become an issue of paramount importance.

Among the different monitoring techniques infrasound has great potentials being able to detect ongoing volcanic explosive eruptions at source-to-receiver distances up to 1000s of km. However, while at short distances (< few 10s km) its operational use is feasible and well demonstrated, at long range its efficiency is still debated, mostly because of time varying propagation effects and the ubiquity of infrasound signals produced by multiple sources.

We present infrasound array analysis of eruptive activity at Etna volcano, Italy, performed at source-to-receiver distances > 500 km and apply detection algorithm to identify in real- time ongoing eruptive activity. We show how frequency-dependent semi-empirical relationships derived from parabolic equation simulations coupled with realistic atmospheric profiles allows to correct for attenuation and reconstruct the pressure time history with great accuracy. This allows applying the same threshold parameters defined for the local array. We show how regional arrays at distanced of >1000 km are able to pick eruptive activity of Etna with an efficiency of 87% and no false alerts.

Considering the latency of ~1 hour related to propagation time, we show that remote infrasound detection of eruptive activity would be available before the actual notification, thus opening new perspective of real-time volcano monitoring at regional scale, especially for poorly instrumented remote volcanoes.

S02.13 Poster

Early-warning systems and related civil protection procedures at Etna and Stromboli (Italy)

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Eruption forecasting is always a challenging task and requires at least a basic knowledge of the volcano behaviour and the presence of a well-structured monitoring network. In fact, although all the monitoring signals are useful to understand the general behaviour of a volcano, only a few of them are usually decisive in providing significant indication that an eruption is going to occur.

The challenge can be even more demanding at open conduit volcanoes, where precursor monitoring parameters can vary only when the eruption is imminent. In these cases early- warning systems can make the difference in ensuring a timely alert to civil protection authorities and to stakeholders, especially in touristic areas.

Depending on the time of development of the phenomena civil protection response can be different. In some cases an evaluation phase is possible and hopeful, in some others an automatic alert can be needed. Here we give an overview of the early-warning systems operating at Etna and Stromboli (Italy) and of the different related operational procedures.

Infrasonic Early-Warning for Explosive Eruption as operational tool for volcanic risk management

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Explosive volcanic eruptions can inject millions of cubic meters of ash into the atmosphere posing a serious treat to population living nearby the volcano. The abrupt occurrence and the short duration of such events require a prompt and rapid response, to allow the properly evaluation of the volcanic hazard in real-time. Current monitoring procedures still require man-supervision to reduce the number of false alerts, thus resulting into a significant latency of several minutes to hours from the occurrence to the notification of the event. We show how dedicated infrasound array processing can be used to detect and to notify, automatically and in real-time, the onset of explosive eruptions. Conceptually, our method relies on the strong coupling between infrasound and explosive process and it is not based on probabilistic consideration but on a quasi-deterministic approach. This infrasonic procedure has been tested and tuned for the last 8 years and it is currently being applied to issue early-warnings of explosive eruption at Etna volcano. We show that the proposed early-warning system is able to provide a pre-alert ~ 1 hour before the occurrence of the eruption and it has a 96.5% rate of success with only 1.7% positive false alerts and no negative false alerts. This is, in our knowledge, the first example of an operational Early- Warning system totally based on automatic and un-manned algorithm that provides notifications of eruption to government agency automatically and without man supervision. Moreover, we show that the same early-warning concept might be applied to arrays at regional distances (>500 km) suggesting that infrasound could be successfully used to issue automatic notification of on-going eruptions at a regional to global scale.

S02.13 Talk

The new volcanic observation and information system of the Japan Meteorological Agency (JMA)

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JMA monitors Japan's 111 active volcanoes, 50 of which are observed intensively with seismometers, GNSS, tiltmeters, infrasonic microphones and cameras. The real-time observed data are sent to four Volcanic Observation and Warning Centers, and JMA issues Volcanic Warnings or other information if abnormal activity is detected and an eruption is expected. The data are processed in the Volcanic Observation and Information System (VOIS), which issues warning/information messages as appropriate. In August 2017, VOIS was updated to a new system known as VOIS3. As eruption precursors and the processes of volcanic activity vary widely, appropriate evaluation requires an understanding of conditions inside the volcano based on observation data, eruption history and the results of volcanic research. In the previous system, observation data on phenomena such as volcanic earthquakes and crustal deformation were displayed individually, and evaluation of volcanic activity was directly conducted from the results of data analysis by JMA's staff. This approach was limited in terms of efficiency, and was also time-consuming. To support more rapid and precise response to anomaly events, the system's analysis method required improvement. In the new system, observation data on variables such as earthquake hypocenters and crustal deformation sources is superimposed onto a known model of velocity structure and electrical resistivity structure. The volcano's internal structure related to magma plumbing and the hydrothermal system (such as magma chambers and geothermal water chambers) are estimated by the superimposed images, which supports quick and appropriate volcanic activity evaluation. This presentation will cover JMA's volcano monitoring and evaluation using VOIS3 with analytical examples of recent volcanic activity in Japan.

S02.13 Talk

10-year Review of Japan's Volcanic Alert Level System

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Since 2007, the Japan Meteorological Agency (JMA) has issued Volcanic Warnings in relation to expected eruptions and identified potentially affected areas. Warnings include Volcanic Alert Level information based on the target area and details of action to be taken, with descriptions based on action summary keywords. Residential-area Warnings are issued to populated areas when the Level is 4 or 5, and Near-crater Warnings are issued to areas around the crater or non-residential areas near the crater when the level is 2 or 3. Information on alert levels is set by local Volcanic Disaster Management Councils for potentially affected areas to support advance coordination of disaster mitigation efforts. As of April 2018, alert level information was being issued for 39 of the 50 volcanoes in Japan that are kept under constant observation. The Volcanic Alert Level system is appropriately operated, and the information provided can be used for disaster prevention measures with changes in volcanic activity based on past eruption scenarios and a body of observation data from relatively recent eruptions (e.g., Mt. Kirishima (Shinmoedake) eruption in 2017). However, the system has limited applicability to volcanoes with a sparse history of eruption, or if volcanic activity differs from that of the eruption scenario (e.g., Mt. Ontake eruption in 2014; Mt. Kusatsu-Shirane eruption in 2018). This presentation will detail the application of the level system over the past 10 years, and will highlight related issues and possible solutions.

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S02.14 - Volcanic alert level systems rules and competencies in managing volcanic risk

Communicating volcano status and volcanic hazards in Iceland: how to improve?

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Since 2012 the Icelandic Meteorological Office, as the Icelandic Volcano Observatory, has been using the Aviation Color Code (ACC) as the main and official tool to communicate the status of volcanoes and their potential for hazards. Changes in the ACC triggers activities and contingency plans at other institutions. The use of the ACC has been discussed between IMO and the Icelandic Air Navigation Service Provider (ISAVIA), between whom it has been agreed that for potential subglacial eruptions, the ACC would be raised to red upon detection of volcanic tremor, since it is likely to preceed the visual confirmation of an eruption. Additionally, the National Civil Protection (NCIP) is most often linking their warning levels to IMO's changes of the ACC.

The experience gained using the ACC over the last years includes one eruption (the 6- months long Bárðarbunga-Holuhraun eruption in 2014-2015) and several unrest phases at other volcanoes, most recently at Öræfajökull.

By reviewing our use of the ACC we can identify a major deficiency for communicating proximal hazards possibly affecting those closest to a volcano. Despite this clear lack, we have not yet applied or developed a suitable proximal hazard alert level system that is collectively agreed upon by the responsible parties. So far, it has been easier to maintain a well-established, but insufficient tool, rather than instituting a new one.

We will present how we are currently using the ACC for aviation-related hazards and how it has been linked to proximal hazards assessment through the NCIP alert level. We will also describe the attempts that have been made to apply VALS established at other volcano observatories to the Icelandic volcanoes with the aim to have a new system in place in the coming year.

S02.14 Talk

Rational or relational: the use of Volcano Alert Level Systems

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As the WOVO Volcano Alert Level Systems (VALS) Working Group, we respond to the arguments raised by Papale's (2017) discussion paper on VALS. While we agree with a number of aspects raised by Papale, such as the need for "deep reconsideration of present alert level systems" and that forecasting is useful for informing decision-making, we have a number of discussion points:

- Probabilistic models have large uncertainties, and cannot be meaningfully used for many volcanoes. For example, numerous volcanoes are not monitored, small eruptions are missed in geological records, and magmatic models are not known, resulting in limitations to Bayesian network approaches.
- We argue that, like VALS, probabilistic models are not objective, and are affected by human biases. In New Zealand VALS Guidelines assist volcanologists with keeping the decision to change levels consistent over time.
- Variations in cultures, volcanoes, resources, and legislation/policies (amongst others) mean that different approaches should be taken - no one size fits all.
- VALS do not need to be linked to forecasting of future eruptions or actions. Considerations such as the foundation of the VALS system (e.g. should it be based on phenomena/hazard, impacts, risk, forecasting, or mitigation actions), and the roles and responsibilities involved shape the purpose of the VALS.
- The purpose of volcanic information communication must be consciously determined - is it to provide legal protection, or address the needs of the audience? VALS have value in their simplicity, and research has found that multiple tools and communication methods are best. Stakeholders should be consulted about what information they want, and how they want to receive it. Probabilistic forecasts can be contained in text-based Volcanic Alert Bulletins alongside VALS.
- Warning systems for other hazards (e.g. weather) are moving towards impact-based warnings that deliberately integrate phenomena/hazard with exposure/vulnerability information, driving decision-making. This requires collaborative approaches with stakeholders, often drawing on risk modeling.

Volcano alert level systems: managing the challenges of effective volcanic crisis communication

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Over the last four decades, volcano observatories have adopted a number of different communication strategies for the dissemination of information on changes in volcanic behaviour and potential hazards to a wide range of user groups. These commonly include a standardised volcano alert level system (VALS), used in conjunction with other uni-valent communication techniques (such as information statements, reports and maps) and multi- directional techniques (such as meetings and telephone calls). This research, based on interviews and observation conducted 2007–2009 at the five US Geological Survey (USGS) volcano observatories, and including some of the key users of the VALS, argues for the importance of understanding how communicating volcanic hazard information takes place as an everyday social practice, focusing on the challenges of working across the boundaries between the scientific and decision-making communities.

It is now widely accepted that the effective use, value and deployment of information across science-policy interfaces of this kind depend on three criteria: the scientific credibility of the information, its relevance to the needs of stakeholders and the legitimacy of both the information and the processes that produced it. Translation and two-way communication are required to ensure that all involved understand what information is credible and relevant. Findings indicate that whilst VALS play a role in raising awareness of an unfolding situation, supplementary communication techniques are crucial in facilitating situational understanding of that situation, and the uncertainties inherent to its scientific assessment, as well as in facilitating specific responses. In consequence, 'best practice' recommendations eschew further standardisation, and focus on the in-situ cultivation of dialogue between scientists and stakeholders as a means of ensuring that information, and the processes through which it is produced are perceived to be legitimate by all involved.

S02.14 Talk

Volcano alert level system and the volcano disaster mitigation system in Japan

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Volcano alert level system (VALS) was introduced 10 years ago in Japan. It consists of 5 levels, and each level is assigned to the measure for disaster mitigation through the key words of the level; preparation for evacuation, evacuation, etc. At present, VALS is adopted in 39 volcanoes among 50 which are monitored by JMA 24hours/7days basis.

The difference from the foreign VALS is that the operation is not managed by researcher because JMA is rare to hire volcanologist but mainly accept those who passed national examination for government employees in the field of physics and engineering.

Because the volcano monitoring by JMA is not made by researcher and the main monitoring items are limited, the coordinating committee for the prediction of volcanic eruption which is mainly composed of researchers of university volcano observatories and national research institutes has been established. The university observatories and some national research institutes supply their monitoring data to JMA in real time. The committee is supposed to give advice voluntarily to JMA in terms of evaluation of volcanic activities; however, the occasion of advice may not be sufficient because the committee is held only three times a year.

After the Ontake 2014 eruption which killed 63 people while the alert level was kept at level 1, the cabinet office that is responsible for the mitigation of disaster have been seeking the way to build a better system for the mitigation of volcanic disaster. A time line recently released from the cabinet office will be discussed. It is supposed to strengthen the coordination among related universities and national research institutes in order to give adequate advice to JMA.

The hazard/risk separation principle in volcanology

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In most cases, the risk posed by natural hazards can be reduced without being formally assessed, just following a (loosely defined) “precautionary approach”. This happens when risk reduction strategies are easily affordable from an economic and logistic point of view, and/or when the uncertainty on the occurrence of the hazardous event is small. However, for volcanoes with the highest risk, this naive precautionary approach cannot be embraced, because it may lead to unethical decision-making. In this case, rational decision-making has to be rooted in a right balance between the economic, societal and political costs of impacting risk mitigation actions and of the hazardous event, accounting for the scientific forecast of the threatening event. In this framework, science is one basic component of risk reduction, but the achievement of this goal requires competences that go beyond pure science. Nowadays, the importance of the non-scientific contribution is often and dangerously overlooked, possibly leading to decision making that cannot be rationally justified. Here we explore the basic components of an ideal decision making process, identifying roles and responsibilities of the different partners/tasks that are involved. In particular, we advocate the use of the hazard/risk separation principle, which can help to discern unambiguously the role of science in the whole risk reduction process. Volcanologists can play different roles in the decision making process, but they must acknowledge that this demands competences that go beyond being a good scientist. The final intent of this talk is to foster of a multidisciplinary approach to volcanic risk, where all different experts cooperate together, keeping separated their own tasks, to establish fully transparent decision-making protocols well in advance volcanic crises. These protocols can be very helpful to audit the decision making process at any time, and they may be an excellent communication tool for the interested stakeholders.

The alert level system for continuously active volcanoes in Italy (Etna and Stromboli). Integration and coordination of competencies at different levels of authority and responsibility

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Italy hosts a number of active volcanoes located in the vicinity of densely populated areas. Some of them are quiescent since long time while some others are almost continuously active.

For quiescent volcanoes, like Vesuvius and Campi Flegrei, alert level systems established since long time are based on the increase of monitoring parameters, considered as possible precursors of an imminent volcanic activity. Increasing operational phases for civil protection response are linked (after evaluation of the operational component) to the corresponding scientific alert levels.

For permanently active volcanoes, like Etna and Stromboli, some scenarios require the activation of the civil protection at national scale, whereas other scenarios affect only small portions of the surrounding territory and can be managed at local or regional level.

Alert levels for these volcanoes must therefore take into account not only a general increase of parameters toward national scenarios, but also possible minor scenarios that are sometimes produced within a short time interval and with very short-term precursors.

Over the last years the Italian Department of Civil Protection, in cooperation with the Regione Siciliana and the scientific community, developed an alert level system that includes a number of potential events these volcanoes can produce with increasing possible effects and the related civil protection response at different level of competence and responsibility.

An assessment of the current use of the Aviation Color Code and VONA in communicating volcanic behavior: Open questions and plans for the future

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The hazard that volcanic ash clouds pose to aviation is well known and mitigation of this hazard requires a consistent international approach. Accordingly, in 2002 the International Civil Aviation Organization (ICAO) convened a group of experts under the International Airways Volcano Watch Operations Group (IAVWOPSG) to evaluate and standardize an Aviation Color Code system as a means for State Volcano Observatories (VOs) to inform aviation users about pre-eruptive and eruptive activity. The Aviation Color Code endorsed by ICAO has four levels: green, yellow, orange and red, and explicitly pertains to activity at the volcano, not to the resulting drifting cloud.

To further improve how volcanic information is provided to aviation users, the IAVWOPSG developed a structured message format - the Volcano Observatory Notice for Aviation (VONA) - to deliver the color code and critical observations in a manner easily understood by non-volcanologists. ICAO affirmed the use of the VONA in 2010 as a “suggested practice” and recommended that VOs issue a VONA when the aviation color code at a volcano is changed or when an ash-producing event or other significant change in volcanic behavior occurs. The VONA is intended to provide volcanic information in clear, concise language that can readily be transcribed into other warning products and used to inform dispatchers, pilots and Volcanic Ash Advisory Centers about precursory unrest at volcanoes. This provides a means of alerting aviation users before the hazard has occurred. Airlines find such forewarning of value as it gives them time to select alternative flight routes.

ICAO is considering upgrading the use of the VONA to a “recommended practice”. We aim to bring this issue to the attention of Volcano Observatories to emphasize the need for these products and to promote the use of the VONA and the Aviation Color Code.

S02.14 Talk

Low alert levels and volcano tourism

Gordon Woo

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The management of low alert levels is challenging for volcano observatories because the wish to maintain visitor access to a volcano as long as possible needs to be balanced by the imperative to keep visitors safe. In contrast with resident populations, visitors to an active volcano can manage their personal exposure to volcanic risk much more flexibly. Non- residents have a choice as to whether to visit a volcano on any given day. Some visitors may be content to postpone or cancel their trip; others may be eager to persevere with their plans, despite the volcano risk.

On 27 September 2014, at least 58 hikers were killed by a crater eruption of the Japanese volcano Ontake, which was preceded by little precursory activity. There was some unusual seismic activity detected two weeks earlier, but no volcanic tremor or crustal deformation was detected. The alert level remained at the normal level 1, which recognized a possible threat to life in the crater. The next level 2 would have explicitly warned against approaching the crater. Level 1 has since been clarified as having the potential for increased activity.

At active volcanoes around the world which attract tourists, the 2014 Ontake eruption has concentrated attention on reducing the chance of a repeat tragedy. Short of denying visitor access during a low level alert, one approach is to apply modern ‘nudge’ methods which have been effective in altering public behaviour in a voluntary manner, without the need for legislation. A review of possible nudges is given, which might reduce the potential public risk exposure, whilst still allowing keen volcano tourists the freedom to ascend a volcano during a low level alert.

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S02.15 - Perspectives on volcanic hazard and risk communication Insights and advice from research and experience

Encounters with the volcano: Community knowledge exchange on responses to impacts to volcanic ash in Ecuador and Peru

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In recent years, innovative methodologies to communicate volcanic hazards and risk have been developed through film, art and past narratives of volcanic eruptions. At the same time, it has been recognised that understanding hazards, managing risk and building resilience requires transdisciplinary research that engages with communities at risk. Despite this, more attention needs to be paid to how different types of knowledges, including non-scientific forms of understanding and experiencing volcanic hazards can help people respond to them in the long term. This presentation will explore the results of a knowledge exchange workshop where farmers, scientist and local authorities from Ecuador and Peru shared their experiences and responses to volcanic ash impacts. The workshop was designed as a medium of knowledge exchange and learning using different methodologies and approaches from the social and physical sciences complemented with art.

Specifically, the presentation considers the transfer of knowledge and experience gained through long term exposure to volcanic ash that allowed people to adapt and transform their livelihoods at Volcán Tungurahua, Ecuador. Adaptation measures included, changes in types of crops farmed locally and the development of a range of measures to protect livestock. During the workshop carried out in the surrounding communities of Sabancaya volcano, Peru, Ecuadorian farmers and scientist shared their knowledge with their Peruvian counterparts though presentations, video, conversation, storytelling and visits to farms. Art, including drawing and painting was used to generate spaces for dialogue and knowledge exchange between the different participants.

Perception of volcanic risk in support of emergency planning and management: case study of municipalities subject to the Vesuvio Risk (South Italy)

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Residents in Campania Region (Southern Italy) are potentially exposed to a combination of natural hazards, such as hydrogeological (flood and landslide) events, as well as seismic and volcanic activities. At the present day, for some of these hazards, particularly volcanic eruptions, there are no recent experiences to properly assess potential consequences on population, infrastructures and environment.

In this framework, it is of paramount importance that a "risk awareness culture" could be developed in the exposed population, alongside with the scientific knowledge and the updating of emergency plans. In order to improve the effectiveness of communication strategies, a study of risk perception has been carried out in 12 municipalities and 2 territorial unions of Campania Region. Many of these investigated municipalities fall into Yellow or Red Zone of the current National Emergency Plan for Vesuvius, whose last eruption took place in 1944.

The results of the surveys show that confidence in responding to an emergency is greater among those who have had direct experience of an hazard and/or have higher educational qualifications. However, few communities consider that they have been be sufficiently well- informed by civil protection agencies/authorities about the natural hazards specific to their locations and about practical evacuation procedures. A simple remedy for solving this out is to get emergency plans designed, developed and practiced through the collaboration of all key stakeholders, from civil protection agencies to the communities at risk.

Scientists as Storytellers: sharing experience and uncertainty in volcanic crises

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Narrative theory is a well established field that draws on e.g. neuroscience, philosophy and sociology as well as literary criticism and creative writing. It can be used to understand the way in which individuals or communities bring together experiences to make sense of events that have happened. Narratives are not static entities but dynamic; the telling of stories is also framed by the time and place of production or telling and the effect the 'storyteller' wishes to achieve. Increasingly narratives are being used as engaging ways to describe future volcanic risk, but scientists also use the telling of stories and 'anecdotes' to one another to make sense of difficult and often uncertain situations during volcanic crises.

Ultimately, we want to explore the value that the information in these (often less visible) narratives could bring to volcanic risk reduction. Using a case study of the Soufriere Hills Volcanic eruption we used narrative analysis to explore the stories scientists told during a series of semi-structured interviews and the insights they had into why and when they told them. This had the aim of understanding how scientists transmit important knowledge about risk reduction through the stories they tell one another. This is not about the 'story' of research findings but the sharing of experience and important knowledge about how to manage and cope with volcanic crises, particularly their inherent uncertainties. We compare these interviews with more overt means of communication (contemporary interviews, official written accounts and published papers) and the narratives told by the population at risk. Scientists and communities at risk demonstrate many similar elements to their stories and a similar desire to explain and exemplify uncertainty. We suggest that more overt sharing of these stories could create a better shared understanding of volcanic risk between scientists, decision-makers and communities at risk

S02.15 Talk

Developing a multi-institutional communications plan for a high-profile volcano: Coordinating the Yellowstone Volcano Observatory

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Communicating about Yellowstone as the Yellowstone Volcano Observatory is challenging, both because of a sensationalist media environment and ample misinformation, and because the Observatory is comprised of multiple, geographically dispersed partners. In this presentation, we will discuss our efforts to develop a coordinated communications plan for YVO with lessons learned that can be applied to other institutional and volcanic settings. The plan was developed through a recognized need for coordination between partners, with the support of engaged leadership and via partner collaboration. Every two years, YVO partners meet in person to discuss current science and science goals. This year, in May 2018, a full half day of the 1.5-day meeting was devoted to communications. The session included all meeting participants and focused on current communication efforts and addressing misinformation. In a smaller breakout session, representatives from each attending partner and all other interested attendees discussed the coordinated communications plan that will serve both the public and YVO partners. As an outcome, partners developed a guiding document articulating roles, internal and external communication channels, communication protocols, best practices, and common messaging. The result is improved internal communications before communicating with the public about events, more unified messaging from partners to the public, and increased engagement from partner institutions due to improved internal communications and sharing of best practices.

S02.15 Talk

Bad tourists!
Reducing risk-taking behaviour among Iceland's increasing tourist population

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Providing accurate and timely early warnings to local residents in Iceland is a difficult task even when scientists, civil protection authorities and government officials have a basic familiarity with the at-risk population. An even more challenging task is communicating that same information with a transient population i.e., the ever-increasing number of tourists who visit Iceland and who engage in activities on and around Iceland's volcanoes. With increased tourism, come increases in the number of tourists exposed to potentially harmful and life-threatening situations. This phenomenon, however, is not isolated to international visitors; domestic tourists are also vulnerable. Timely information is not only paramount with respect to generating a proactive response but also with respect to the constant public broadcast of near-real time information. Any person may view near real-time hazard data on the Icelandic Meteorological Office's website. Depending how that information is received and interpreted by the public, it may result in optimistic bias to the detriment of their safety. Alternatively, it could result in fatalism causing cancelations to the detriment of the tourism sector and local economy. This paper explores current practices for communicating hazard and risk and the actions tourists need to take to ensure their own safety. By highlighting risk-taking behaviours of tourists in Iceland, the paper also considers the challenges communicators face. The paper concludes by offering solutions where scientists, civil protection authorities and government officials work together with tourists and the tourism sector to identify the most appropriate methods for reducing tourists' risk-taking behaviours.

Governance, accountability and blame – Are they "The Good, The Bad and The Ugly" of volcanic risks?

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Risk governance has definable qualities against which performance can be measured. Accordingly, the concept of good governance of volcanic risks exists. Quality assurance standards are the unwitting parents of accountability and the grandparents of responsibility and blame.

We favour a four-dimensional model of risk governance. A physical volcanic hazard may threaten a vulnerable society of people and valued assets. A third managerial dimension embraces risk-mitigation decision makers - those entities (often civil protection authorities) and individuals that must make hard value-laden decisions based in part upon scientific characterisations of physical hazards. Our novel fourth dimension of risk governance - scrutiny - reflects the extent to which decision-makers and their decisions will be scrutinised and influenced by legal and other processes that seek to promote better governance with reference to standards set by, inter alia, international, national and local laws, and less formal initiatives and expectations. Assessors of volcanic hazards and risks are accountable by reference to standards of acceptable practice that exist but may be far from equivocal. To be good at governance, to confront the bad and avoid the ugly, we argue that further methodical attention should be given by volcanologists to six potential sources of risk governance standards that we label as external, collective, employer, expert, personal and user.

S02.15 Talk

Never let the truth get in the way of a "good story": the case of the "mega- eruption" of Teide volcano, Tenerife, Canary Islands

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In the year 2016 the word "post-truth" was chosen as the Oxford Dictionaries 'Word of the Year'. Post-truth journalism has also arrived to earth science discipline, and so on to volcanoes. By relegating facts and expert opinions to a secondary role, a new "scientific" journalism appeals to emotion rather than rationality. Teide volcano is a clear example that has been the epicentre of intentional misinterpretation by some British media. Teide is the third largest volcano on Earth, and is dormant since the last eruption on the so-called NW rift, back in 1909. In the last year and a half, a number of seismic swarms have been detected at Teide and surroundings, prompting a massive wall of fake news that have raised concerns regarding the current status of the volcano. British media claimed about an impending "mega-eruption" on Teide, unveiling practices far away from fair journalism. Most of the news were a self interpretation of the Volcanological Institute of the Canary Islands (INVOLCAN) statements, always searching for an emotional rather than rational reading. These tabloids have never contacted INVOLCAN for a contrasted opinion, or at least for a correct interpretation of data. As such, this appears to reflect a clear "post-truth" pattern of behaviour with the aim of trying to divert the attention from the fact that nothing unusual is happening on the volcano. This irresponsible attitude is amplified by the echo of social media, avid of sensationalism and trickery. Learning to deal with this new situation must be a close call for colleagues around the globe. Through these processes INVOLCAN has released clear advisories on the activity of the volcano and stating that coming to Tenerife is safer than ever before in part because of the constant scientific attention paid to it.

S02.15 Poster

INVOLCAN's Facebook: A reliable meeting point between researchers and society

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Social media has become one of the most powerful communication tools in the science and research world. INVOLCAN's Facebook was born to fill the communication gap to the wider population in order to have a reliable meeting point were infomation about volcanic activity is released. By avoiding intermediaries, scientific concepts can be communicated more directly. Nowadays our profile is followed by more than 28,000 people originating from 45 different countries. One of the most important features of our profile is that all the content we upload is organic; there is no paid content. This means we can be confident on the quality of our publications as there are no captive followers. Regarding the publications, we range from local posts, about the volcanic activity in the Canary Islands, to international news about eruptions around the world, as well as different ones about the activity of our group. If we look back at the evolution of our profile, we can see a transition in our followers preferences. At the beginning the most followed posts (those with more likes and shares) were all related to pictures of eruptions worldwide rather than local news, data or facts. The last eruption in the Canaries, at El Hierro in 2011, was a game changer. Our followers turned their attention in local events, and this was taken as an encouraging sign that validates our approach. Since then, and with the changes to the volcanic seismic activity on Tenerife island, all the posts regarding local data are praised by our fans. This consolidates our Facebook channel as the reliable meeting point between us, researchers, and society. We anticipate that any future volcanic activity that may attract wide attention will be directed in the first instance to this meeting point, and the value of its existence will grow accordingly.

S02.15 Poster

USGS News Media Management Plan provides framework for effective eruption response

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Volcanology literature contains an abundance of case studies that illustrate how excessive news media attention can threaten scientists' ability to respond effectively at a reawakening volcano. Commonly, it is only during times of crisis that besieged observatory staff recognize the magnitude of resources and pre-crisis coordination required for effective news media response.

This was the case during the 2004 reawakening of Mount St. Helens when our news media response overtook available resources at the USGS Cascades Volcano Observatory (CVO), and required the aid of many non-observatory staffers. What became necessary, essentially overnight, was establishment of a framework for quickly scaling up a news media response with clearly defined roles for observatory and non-observatory staff. A simple news media management plan emerged from observations of needs.

Recently, this initial plan has been expanded and updated as the formalized CVO News Media Management Plan Guidelines and Protocols. The plan describes staff roles and strategies for news media engagement at four levels normal interactions, brief engagement, intense engagement, and use of a multi-agency Joint Information Center. Appendices provide guidance for creating messaging, giving effective interviews, using social media, and developing communication plans. It is a living document that can be upgraded easily.

Having a news media management plan offers many advantages over relying on a spontaneous response. A news media management plan can be developed and practiced before a crisis. It helps observatory management to recognize the intense attention that news media will draw, and to allocate necessary resources. It helps scientists to plan and train for their roles as communicators, and to develop a cache of video, maps, images, and graphics that are easily modifiable during crises. News media management plans help observatory staff to understand social complexities of an eruption response, and can turn potential communication breakdowns into communication successes.

S02.15 Talk

How does risk perception influence societal behaviour in indigenous communities. A case study in Southern flanks of Fuego Volcano, Guatemala

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This piece of work reviews perception of volcanic hazards and associated risks in three communities around Fuego volcano in Guatemala and attempts to explain the relationship between lahar hazards in those communities and social construction of risk. Significant differences in risk perception can be identified between neighbouring communities which have similar exposure to hazards and history, proving that perception and social resilience depend on various and complex factors. Identifying and understanding the latter is a key process when trying to address effective and targeted risk policies. This study analyses how risk, communication, personal, contextual and cognitive factors determine lahar risk perception on the Southern flanks of Fuego Volcano. We also highlight how spatial and environmental elements shape risk awareness and preparedness. The findings support the assumption of the risk perception paradox proposed by Wachinger et al., (2013), which proves that higher risk perception does not necessarily lead to better preparation or mitigation behaviour.

Two key elements of social resilience are awareness and preparedness, which directly dependent on the planning and level of organisation. In order to achieve higher resilience, communities must also have a high level of support from local political leaders and agencies (Tobin, 1999), as well as some level of trust in scientific experts and authorities (Heitz et al., 2009). These relationships of trust and risk governance have complex implications and form the basis of risk perception of indigenous communities. Across Central America and especially Guatemala, civil war, ethnic cleansing and corruption are part of the cultural history and landscape. Not surprisingly, generalised mistrust can be observed, not only towards political authorities, but also towards governmental agencies including science institutes and civil protection. In this study we present an initial analysis of the impact of risk perception factors and how these influence societal behaviour in Central American communities.

S02.15 Poster

Memory and Forgetting in Forecasting. Bradyseism in Pozzuoli: a case study

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This presentation intends to address the theme of forecast and memory applied to the concrete case of bradyseism in Pozzuoli, Campi Flegrei, Campania. Rione Terra, a long- standing district of the town, was evacuated on 2 March 1970: only from that moment, citizens of Pozzuoli rediscover the phenomenon of bradyseism, which gives rise to the abandonment of the ancient citadel and the creation of a new area in the immediate urban edge. An eruption was expected, but it did not happen. Nevertheless, the quarter was closed: the forced abandonment of Rione Terra is now perceived as a severe dispossession and not as an action of securing.

The scientific unpreparedness and the speed at which the evacuation is prepared will mark the memory of the displaced. In the 1980s, the community knew a second bradyseism crisis: to what extent previous experience influences the population, the scientific community and the political one in the choice to be made? If risk and disaster are conceived as complex phenomena with a multiple reading, memory plays a fundamental role, acting in the process of reconstructing history and predisposing tools with which to deal with present and future. This is true both for the population – still carving the wounds caused by the evacuation - and for the experts, who are concerned about communicating properly the risk, even before the disaster.

This presentation is based on a field work done by the Author since 2011 using an oral history approach: the inhabitants of Pozzuoli are the main subjects of this history and therefore they are also the main sources of this research. In particular, in-depth and biographical interviews are a fundamental instrument to reconstruct the architecture of memories, bringing out stories that are not told by institutions.

Living with Hazards: Prediction Uncertainty and Personal Protective Behavior at Frequently and Infrequently Erupting Volcanoes Tungurahua and Cotopaxi, Ecuador

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This project compares citizen knowledge of volcanic hazards, scientific prediction, and personal protective behavior in two South American communities with varying degrees of exposure to active volcanoes. The central research question is how knowledge and confidence in volcano monitoring organizations (volcano prediction science) are related to citizen knowledge of protective actions (e.g., hazard awareness, evacuation strategies, mitigation actions). Tungurahua volcano (Ecuador) entered its current eruptive phase in 1999. As activity continued scientists worked to deepen their educational outreach and engage the local community in the actual monitoring process. This evolving relationship has theoretically increased public safety and resulted in a stronger community understanding of volcanic processes and prediction science. The eruptive activity of Cotopaxi volcano started in late summer 2015. Prior to this, standard monitoring capabilities and communication were in place in the nearby communities of San Francisco and Rumipamba, but attention by the government and nonprofit organizations began to increase. Cotopaxi now provides an excellent location to collect baseline data on citizen hazard knowledge, prediction awareness and protective actions from a volcano that has just entered an eruptive stage. Comparing these two sites (including pilot data from volcán Tungurahua from 2004) will allow us to test important hypotheses about how emerging risks are communicated to citizens and result in protective behavior.

Families Preparing for Volcanic and Seismic Events: Assessment and Dynamics

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Volcanic and seismic preparedness are a recognized important resource in achieving more disaster resilient communities. Nevertheless, studies reveal lack of preparedness in populations in risk-prone areas, meaning that the concept should be better understood. The Azores is a volcanic archipelago located in a triple junction of tectonic plates. Volcanoes in the islands are in a quiescence period and the seismic activity is of low magnitude but high frequency. This study intends to assess volcanic and seismic household preparedness of 145 families in the largest and most populated island, S. Miguel, through characterizing the measures adopted and the dynamics involved. Semi-structured interviews were conducted. Current preparedness practices were assessed and some families were asked to construct new measures. The dynamics involved (i.e. participants, information sources, difficulties) were also assessed. Results demonstrated that planning measures were the most adopted. Constructing preparedness measures was mostly a group activity, with the internet being the main source of information. Nevertheless, participants revealed difficulties regarding information accessibility and understanding. Achieving a deeper volcanic and seismic preparedness understanding can provide valuable insights, being helpful to better adjust the current policies and communication practices, aiming at enhancing preparedness motivation, reducing the difficulties and barriers and promoting actual preparedness.

S02.15 Poster

An extraordinary time at Kīlauea volcano: 2018 lava eruptions, seismicity, deformation, and ash explosions

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U.S. Geological Survey, USA

Kīlauea Volcano's long running East Rift Zone and summit eruptions took dramatic turns in late April 2018, significantly altering hazards and impacts to residents of Hawai'i island. Following weeks of pressurization of the magmatic system from summit to the middle East Rift Zone, a collapse of Puʻu ʻŌʻō cone on 30 April coincided with a surge of magma into the lower East Rift Zone. On 1 May, the summit lava lake began to recede and the summit began to deflate steadily. On 2 May, ground cracking commenced in the lower East Rift Zone and on 3 May, lava broke the surface from three fissure vents in a subdivision. On 4 May, a damaging M6.9 earthquake occurred under the south flank followed by hundreds of aftershocks. Ongoing withdrawal of the summit lava lake and related deflation prompted seismicity that damaged roads and buildings including the Hawaiian Volcano Observatory.

As of this writing, more than 35 homes have been destroyed by lava, ground cracks continue to open, and additional lava outbreaks are likely. High levels of sulfur dioxide as emission have plagued residential areas downwind. Phreatic explosions from the evacuated conduit at the volcano's summit have produced near-vent ballistics approaching 60 cm in diameter and ash clouds reaching as high as 9 km ASL, with subsequent ashfall downwind. Thus far, the eruption at the summit strongly mimics events of Kīlauea Volcano's 1924 activity and the lower East Rift Zone eruption parallels similar eruptions in 1955 and 1960.

The US Geological Survey and colleagues have worked closely with Hawai'i County Civil Defense and other authorities to share information, assess changing hazard conditions, and prepare communities for impacts. Ash hazards are not familiar volcanic processes in Hawai'i, thus requiring much education and engagement to support effective response.

Rethinking volcanic hazards' communication: Lessons from using informal knowledge and experiences to permanent volcanic emissions from Masaya volcano, Nicaragua

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Building on results gathered from a multidisciplinary project involving volcanology, human geography, history and the visual arts, this paper argues for a need to reconsider the deficit model of risk communication dominating volcanic hazards management and Disaster Risk Reduction. By drawing on how rural communities living in the vicinity of Masaya volcano in Nicaragua have developed ways to deal with permanent volcanic emissions (PVEs), the paper highlights how 'informal' knowledge and experiences of PVEs seem to be excluded or ignored from mainstream DRR discourse and practices. This 'informal' knowledge is defined as ways of knowing, sensing, and experiencing hazards and risks, which are often underexplored and unreported in 'formal' scientific accounts of hazards and risks and yet, they are so vital to those living with PVEs in defining their daily activities and well-being. In an era in which anticipatory methods such as early warning systems (EWS) are defined as the most costs effective way to reduced impacts of hazards such as PVEs, the paper argues for a paradigmatic shift in risk communication that requires the development of risk instruments such as EWS to include and refer to 'informal knowledge'. Finally, our paper emphasises that risk communication through highly sophisticated techniques and methods such as EWS would profit from integrating plural understandings of hazards from those for whom risk messages are meant to be designed for. Finally, we conclude by providing a series of examples about how this kind of knowledge can be brought into the development of EWS through locally-tailored language and thus help the design of risk thresholds in which sensing and experiencing PVEs pollution (e.g. smell, sound) might be combined with different visualisation methods to convey risk messages.

Creating perspective archive of Volcanologist's activities in the society over the century-long history in Japan

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It is really regrettable that many Japanese honorable volcanologists had been passing away in the past decade, such as Prof. Yoshio Katsui (1926-2016) and Prof. Daisuke Shimozuru (1924-2014). On those occasions, we had started a systematic compilation of their social activities and contributions as a volcanologist. The compilation was expanded on the occasion of the 70th of Showa-Shinzan and the 40th 1977 Usu eruption.
At the time of writing, we had compiled over 2000 slides of personal histories in a form of ppt format on 20 key persons. The compilation was expanded for a few non volcanologists, such as Mr. Masao Mimatsu (a famous local post master known by "Mimatsu Diagram"), Mr. Sei-ichi Iida (the head of Muroran Police Station who conducted successful evacuation of 15,000 people before the 1910 Usu eruption with the knowledge learnt from Prof F. Omori), Mr. Saburo Mimatsu (the grand son in law of Mr. Masao Mimatsu, who functioned as an indispensable bridge between scientists and the society for the successful 2000 Usu management), and Mr. Shoji Koike (1935-2014, a newspaper editor who persistently issued 275 articles and published 3 popular books on volcanoes in Hokkaido, during the preceding 6 years to the 2000 Usu eruption). Original data sources were newspaper reports, TV/radio tape records, magazines and books, photo archive, and personal notes/letters. Major parts were the life-long collections by Prof Katsui, Mimatsu Museum and myself.
Recently social demands on "Home Doctor Service" by volcanologists became increasing clear in Japan. That is because transformation from University Observatory dominated monitoring to JMA's official monitoring/information scheme is facing serious troublesome, because of the lack of face-to-face effective communication. It seems to be a good chance looking back their history, searching how to educate and train young volcanologists, the present community needs.

S02.15 Poster

GUAYOTA: A weekly graphic chart on the volcanic activity of Tenerife Island

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One of the main goals of our institution is to communicate the level of volcanic activity on the island of Tenerife, as well as the alert level. Our method presents scientific work, using a clear educational and didactical point of view. We aim to communicate to people what an alert level means *and* the actual alert level for the island using clear, simple, and "easy- listening" language. All these goals are achieved through the weekly "bite-size" volcanic chart "Guayota". The name comes from the devil living inside the volcano according to the Guanches, aboriginals living on Tenerife before the Castillian conquest. This weekly chart visualises different parameters on the volcanic activity like seismicity, soil temperature, deformation or gas emission Each parameter uses a dimensionless scale since our focus is not on deep scientific discussions, but instead on an understandable display of data to let both locals and tourists know what´s going on with the volcanic activity. The reader quickly and easily gains an appreciation of how the past weeks' activity compares to what is normal. Tenerife hosts more than 5 million tourists every year, and is one of the most in-demand vacation spots in Eruope. For these reasons the Guayota weekly chart is released in eight different languages in order to reach the biggest audience possible. The Guayota is released for free at our website (www.involcan.org/guayota-tenerife/) and also through our Facebook page.

Geoetics and scientific analysis of the communication performed in the cities on volcanoes in Italy: the case histories of Ischia and Phlagrean Fields since 2013

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The paper is a scientific study - using the Communication Science tools - to analyse the “messages” appeared on the media, coming from various sources, in the various emergency or quite situations, such as the one that occurred with the earthquake of Ischia, on 21 August, 2017 and the situation of Phlagrean Fields, since 2013 (decreed yellow code) to date. The articles published in newspapers and on blogs are analyzed in details as address for the Civil Protection purposes, highlighting the positive and negative aspects of those who dedicate themselves to scientific communication, journalists, bloggers. Is considered in detail how the written texts and the scientific communication, that provides those who are involved in responding to the requests of the populations, rightly can be improved and customized for the Civil Protection purposed and for a better geoethic reliability. This can, indeed, be done homogeneously and consistently through press releases, videos, letters to newspapers and group of interviews. It is absolutely necessary to establish a priori how to handle possible errors, unfortunately always possible, to present correct and appropriate reviews, as soon as possible, always explaining in a transparent way the reasons for errors. Credibility is something irreversible if lost.

S02.15 Poster

Assessing warning confidence and perceptions of forecasting during volcanic crisis and unrest at Kīlauea and Mauna Loa volcanoes, Hawai'i

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The 2014-15 lava flow crisis at Kīlauea volcano, Hawaii and post-September 2015 elevated unrest at adjacent Mauna Loa volcano provided opportunities to assess households' psychological and behavioral responses to different levels of volcanic activity and uncertainty in regions of variable lava flow hazard. The Kīlauea sample was asked about their perceptions of lava flow forecasts and evacuations during the 2014-15 Kīlauea lava flow crisis, while the Mauna Loa sample was asked about perceptions of future forecasts and response to warnings and evacuations during the elevated period of unrest, which increased from Normal to Advisory in September 2015. We also examined how survey respondents perceived specific stakeholders i.e., themselves and their families, their peers, news media, elected officials, and government agencies, with respect to characteristics of hazard expertise, trustworthiness, and protection responsibility.

In general, we show that the relationship between respondents' confidence in factors important in decision-making during emergencies and evacuations, such as receiving accurate lava flow forecasts and having time to prepare to evacuate, were most significantly correlated with the respondents' past experience with lava forecasts. For example, the study found that residence in areas of high lava flow hazard correlated with increased perceptions of accurate lava flow forecasts that is, those in high hazard zones closest to the source of eruptions were more likely than their counterparts in areas of lower lava flow hazards to believe USGS would issue accurate lava forecasts.

Risk communication and evacuation planning. A study in S. Miguel, Azores (Portugal)

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In the case of a volcanic eruption, evacuation is a commonly adopted measure to safeguard life, reducing propriety losses and social disruption, favoring a positive recovery. An effective evacuation needs to be timely and gather the population's compliance. Therefore, understanding what attitudes citizens hold towards an evacuation and participative disaster planning and preparedness, who they trust most, what resources such as personal transportation and possible shelter people have, are important factors to explore, because they express behavioral tendencies with possible implications for the success of an evacuation.

This ongoing study aims to describe factors that can favor a successful evacuation of Vila Franca do Campo (São Miguel, Azores). Preliminary results point to the expectation of an evacuation in the case of an eruption, and immediate compliance with the alert. Most participants have personal transportation and possible shelter in other counties. Civil Protection is the most trusted entity by participants that consider it should be responsible for the evacuation alert. Participants also expressed willingness to collaborate on the creation of an evacuation plan for their county and to participate in simulations or exercises for an eruption. These results can help to integrate population's contribution to disaster management, inform risk communication, practices and policies.

S02.15 Poster

"Canary Islands, a volcanic window in the Atlantic Ocean": when the volcanoes go out to the street

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The Canary Islands are the only part of Spain which hosts active volcanism. Sixteen historical eruptions have occurred in this territory, the most recent one being the submarine eruption offshore of El Hierro Island on October 12, 2011. Since 2008, ITER and INVOLCAN have been performing a regular educational program focused on what the different volcanic hazards are, how to reduce risk from those hazards and the management of that risk in the Canary Islands, as well as the benefits of living in a volcanic territory. The outreach program aims to visit the 88 municipalities of the Canaries each year and it is given over 3 consecutive days; the first two days cover volcanic hazards and volcanic risk using the IAVCEI/UNESCO videos "Understanding Volcanic Hazards" and "Reducing Volcanic Risk", and the third day gives an overview of Canary Islands volcanism and volcanic risk management. During each day a questionnaire in the format of "Volcanic Trivia" is handed out. The audience has to answer the questions twice: before and after completion of every session. This data makes it possible to perform statistical analysis and to estimate the impact of the program. Across all municipalities, the most common audience questions focus on activity in the central Teide volcano complex. The age of attendees is dominantly over 35, which demonstrates that volcanic hazards are important to adult audiences. After the educational program is completed, the percentage of correct answers to the 'Volcanic Trivia' increases considerably. The ultimate goal of the program is a net improvement in the community's knowledge, therefore enabling people to reduce volcanic risk in the Canaries.

Data Collection and Management Challenges and Solutions for Generating the Smithsonian Institution-US Geological Survey Weekly Volcanic Activity Report

Sally Sennert. Michael Randall

USGS, United States Geological Survey, USA

Every Wednesday the Smithsonian Institution-US Geological Survey Weekly Volcanic Activity Report (WVAR) aims to provide a "snapshot" of worldwide volcanic activity, generated by summarizing data captured from a variety of sources during the previous week. Volcanic activity information is gathered from sources including volcano observatories, emergency management agencies, Volcanic Ash Advisory Centers (VAACs), meteorological agencies, and targeted social media. The data captured can range from simple (a text file from a VAAC) to complex (many reports, over many days, from many sources) but collectively results in a large amount of source data gathered each week. This extensive data collection is mostly accomplished manually and is consequently time consuming. Additional data-capture challenges include locating the latest volcanic activity reports on an observatory website or via social media, and translating non-English reports. Commonly informants use multiple channels to distribute volcanic activity information, including various social media platforms, making the messages difficult to find and fragmented, especially during a crisis. One solution to address these challenges is for informants to create a simple and concise volcanic activity report distribution strategy (VARDS) that can be simply a statement informing stakeholders about the location of the latest information.

To make the data-capture process more systematic and timely, USGS is developing an internal web-based tool that automatically scans and archives data from websites with volcanic activity information. During the pilot phase we have found that the tool easily captures simple text-based reports (e.g. VAAC notices), but is less useful for data in more complex formats, such as in a drop-down menus and text saved as images. To aid in data collection, in addition to creating VARDS, informants should organize their data in a predictable pattern, in a simple format, and with consistent terminology.

S02.15 Talk

Visual attention to volcanic crisis maps during evaluation and decision-making tasks: an eye-gaze tracking experiment

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Visualising volcanic hazard and risk information on maps can help trained specialists such as scientists and emergency officials understand the distribution of volcanic hazards, identify exposed assets, assess potentially at-risk areas, and plan risk management strategies. During a crisis, maps are also often used to exchange knowledge about a volcanic event with a wide range of potentially at-risk audiences, who may have a broad range of experience with maps and volcanic processes. These crisis maps can play an important communication role in a crisis, as affective responses, perceived risk, and inferences made from these maps may influence audience behaviour. Constructing meaning from maps is a complex information-processing experience that requires cognitive processing of the visual appearance, patterns, and relationships of representative shapes and symbols on the map. Eye-movements and visual attention to elements of a display have been shown to reflect cognition during problem-solving, and can allow insight into how people draw inferences from graphics such as charts and maps. Here, we present the results of a study with lay participants in New Zealand, which explores the application of eye-gaze tracking methods to assess how non-specialist audiences engage with volcanic hazard and risk content when shown on a map. Participant eye-movements were recorded as they read maps and responded to a series of questions and challenges based on the map content. We explore where people focus and shift their visual attention when reading and solving tasks with fictional volcanic crisis maps for two New Zealand volcanoes, address potential applications of eye-gaze tracking methods for understanding volcanic hazard and risk communication problems, and discuss implications for volcanic hazard and risk map design.

The imaginary eruption. An alternative approach to volcanic hazard education

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Outreach activities on volcanic hazards are usually based on the available knowledge of volcanic processes and their evolution. In theory, materials conveying these contents should suffice to provide an adequate information to citizen potentially threaten by the unrest of a volcano. However, communication is a complex process and is neither straightforward nor entirely rational: our efforts may fail because of pre-existing mental models and misconceptions. Recognition of existing biases may help overcoming the problem, but tracking down popular beliefs can be an elusive task. We present the preliminary results of our attempt to constrain and address how kids and youngster imagine the onset and impact of eruptive activity. Taking advantage of the long-term EDURISK project, established to offer training and education on natural risks to Italian schools, we selected a sample of ca. 30 classes (age 4 to 13), mostly from the Neapolitan area with a few more from non-volcanic regions for comparison.

Students were asked to draw a story in four panels, as a creative writing exercise with limited constraints. All stories had to include an initial quiet phase (1), then an unrest (2) that culminates in a volcanic eruption (3), and is followed by an epilogue (4). Characters and actual outcome of the eruption were left for the children to define. A careful analysis of the stories will provide us information on the collective imaginary and common expectations about volcanic eruptions. These stories will set the frame for a collective ‘tale of the eruption’ that, while incorporating characters and ideas from the students, will offer us a chance to introduce sound scientific concepts and address hazard mitigation issues.

The exercise is easily reproducible in different countries, and could provide a good opportunity for cultural exchanges.

S02.15 Talk

Volcano dormancy, historical memory and perception of volcanic threat in French volcanic areas

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Population's experience in volcanic eruptions and historical memory are factors often correlated with higher awareness and enhanced understanding of volcanic hazards -and linked with more appropriate responses to volcanic emergencies. Equally, it is commonly assumed that populations living close to dormant volcanoes tend to minimize the risk that they pose.

In this pilot study we explore the change in perception of the volcanic threat and awareness of hazards in French populations living around volcanoes that last erupted in different periods:

- Piton de la Fournaise, Reunion Islands, France – Last erupted in 2018.
- Soufrière, Guadeloupe, French Antilles, France- Last erupted 1977 (41 years ago).
- Montagne Pelée, Martinique, French Antilles, France- Last erupted 1932 (86 years ago).
- Chaîne des Puys, France- Last erupted ~ 6.500 years ago.

Through face to face questionnaires and interviews and online surveys we specifically examine their perceived knowledge and understanding of eruptions and eruptive processes, awareness of plans and emergency procedures, personal experience, attitude and perception of threat. We then compare the results between the different locations.

Zero tolerance? Official attitudes towards volcanic risk and implications for risk communication and management

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Policy makers responsible for disaster risk communication and management are faced with the difficult task of developing strategies that reflect the values and risk perceptions of wider society. Yet, as has been seen through numerous failed attempts to evacuate and resettle at-risk populations, public values are frequently at odds with those of policy makers. Living near an active volcano has obvious risks, but it also generates economic benefits for those that can tolerate those risks, such as high agricultural productivity; and many of these settlements have deep historical and cultural roots. These factors influence how people experience and perceive risk. This research examines risk behaviour close to active volcanoes - the dynamic nature of what people do and how DRM policies are adapted and applied by local authorities. The paper addresses the question of why (official) policies aimed at reducing risk in volcanic areas often fail. Part of the answer is in a lack of understanding of risk perceptions and behaviour. The authors define and compare levels of risk tolerance: the combined result of individual and social processes of risk prioritisation and normalisation, for those living close to active volcanoes and for the organisations with responsibilities for managing volcanic risk.

Research conducted in volcanic areas in Ecuador, Colombia and the Caribbean reveals these tensions and is of direct relevance to disaster risk management systems elsewhere and in different hazard contexts. Research findings suggest that volcanic risk communication and management needs to be co-produced by actors between and across scales of governance, so levels of risk tolerance can be articulated and better aligned. Lessons can be drawn from these experiences of adapting to volcanic risk to enhance risk management systems in the context of climatic and non-climatic hazards.

In the shadow of Vesuvius. What about eruption?

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Vesuvius (located near the city of Naples, in southern Italy) is an emblematic case of volcano that has not erupted for several generations. The 1906 event was preceded by over 1800 years of recorded volcanic history (79 CE eruption); it last erupted in 1944. Therefore, monitoring scientists or civil authorities have neither direct experience nor memory of responding to Vesuvius in eruption. If it's true that a good communication plays a key role in managing a volcanic emergency effectively (Tilling 1989; Solana et al. 2008; McGuire et al. 2009; Doyle et al. 2011), what does "good communication" mean in this particular situation? How can misunderstandings and dissonant behaviors be avoided? This contribute will try to highlight some implications of warning strategies which could satisfactorily match the expectations of a vulnerable community.

Focusing on the area of Parco Nazionale del Vesuvio (72,59 kmq/349.383 inhabitants), we will show the first results of an ongoing research, concerning: i) the structural characteristics of the territory exposed to the risk of eruption; ii) the implications related to the intense tourist flows that cross the area; iii) the perceptions/experiences of some local administrators.

We will also present the results of a pilotage phase of a questionnaire addressed to the population of two local municipalities, aimed in particular at capturing the levels of risk perception, the willingness to collaborate with the Civil protection, the main information channels used in the emergency, the memory (direct or indirect) of "spontaneous" behavior in response to danger. All elements (although not the only ones!) that, from our point of view, should be taken into due consideration in preparing warming strategies.

Keywords: Vesuvius; local communities; warming strategies.

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S02.16 - Volcanic ashfall & gas impacts existing and future resources in support of preparedness, assessment and mitigation

Continuous high degassing and strong ash discharge from Ibu volcano, Halmahera, Indonesia

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Ibu volcano located on Halmahera, Indonesia, maintains continuous eruptive activity since 1998 with regular ash column (every ~15 minutes) above the crater and an ongoing viscous lava extrusion (3200 m^3 per day). A once 200 meter depth crater is now filled by 0.08 km^3 of lava dome. Assuming a porosity of 19%, the corresponding dense (DRE) magma is 0.06 km3. Thermal infrared recording carried out in July 2015 has enabled estimation of ash mass release per eruption, which varies between 80 kg for less energetic discharges to 5000 kg for vigorous releases. Total of ~12 kt of ash has been ejected during nearly 2h of recording. Assuming that these values are representative then on a daily basis more than 140 kt of ash are ejected by Ibu, which may correspond to ~6000 m^3 of magma pulverized into the atmosphere, assuming a density of 2300 kg/m^3.
DOAS measurements carried out in July 2015 on the rim of Ibu indicate that Ibu volcano is releasing about 208 tons of SO_2 daily. Such figure emphasize that although Ibu is yet absent in the global volcanic degassing inventories, it is clearly a significant source of degassing than can be ranked 62 out of 91 volcanoes in the recent inventory. Multi-GAS recordings highlight molar ratios of 12, 0.8 and 2.2 for CO_2/SO_2, H_2S/SO_2 and H_2/SO_2 respectively. Using these ratios with the above SO_2 emission rate, we derive daily emission of 1772 tons of CO_2, 89 tons of H_2S and 14 tons of H_2.
These results indicate that although poorly known, this Ibu volcano merits further attention, not only for a potential dome collapse, but also for the impacts of recurrent strong ash release and continuous high degassing in respect to the 8500 inhabitants around.

Keywords: Ibu volcanic activity, Lava dome growth, ash and gas emission

Volcanic ash and gas:
a complex and dynamic relationship with affected communities

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We synthesise new research and experiences, which explore the impacts of volcanic emissions on society, including how they influence decision-making, livelihoods and wellbeing for communities in the vicinity of volcanoes. These impacts are felt at multiple scales and timescales, from the amplification of risk during immediate response to widespread and long-term deleterious impacts on human/environmental health.

In rural settings, and particularly in developing economies, impacts on crops and livestock generate considerable hardship, exacerbated by wider economic responses to these issues (lowered prices for damaged produce, and depressed values for livestock). In urban and peri-urban areas, impacts to business and services (sources of income, availability of food and schooling) are as important as direct impacts to households.

The continued difficulty in forecasting eruption length and style compound these issues: effective recovery and future preparedness significantly depend on the wider community and livelihood issues this generates. In some instances, the cumulative and longer term multi-faceted effects create considerable risk and prompt evacuation or relocation (or migration), simply due to reduced tolerability of these effects, or protracted loss of income. Living with ash and gas emissions for prolonged periods also stresses mental health, and interrupts attachment to place.

Nonetheless, there is considerable scope for improving how we respond and cope with these eruptions. There is much to learn from communities who have adapted to these threats, recently and in the historical past. Local adaptation measures include short-term forecasting of impacts, changes in agricultural practice (including livestock protection) and strategies for coping with degassing and ashfall on a daily basis, often learned through trial and error and by sharing information among local residents. This paper presents issues and opportunities from recent work in Ecuador, St Vincent, Hawaii, Vanuatu, Chile, Argentina and Indonesia.

Estimation of thickness of volcanic ash in upper area near the vent by LiDAR data measured on Sakurajima volcano, Japan

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In case volcanic ash deposits on a slope after a volcanic eruption, the risk of debris flow increases. It is necessary to research the deposition range and thickness of volcanic ash for ensuring warning evacuation against the debris flow after ash fall. In particular, the thickness on the upper area is important to estimate where debris flow occurs. However, it is difficult to observe directly, since installation of a measurement equipment near the vent is hard. Damage to the equipment is also assumed due to the plume. To estimate the thickness near the vent of active volcanoes, we used LiDAR data measured in Sakurajima volcano, Japan.

The thickness of volcanic ash is estimated by the difference of the altitude from LiDAR data measured every year from 2013 to 2016 in Sakurajima volcano. The relationship between the thickness and the distance from the vent was also investigated.

As a result, the elevation of the slope on the east side of the volcano increased every year. Since this value changed depending on the number of eruptions, the difference of the altitude was assumed to be caused by the deposition of volcanic ash accompanying the eruption. Through examining several longitudinal sectional views of the difference, the power law relationship or exponential relationship was confirmed between the thickness and the distance from the vent.

These results implicated the possibility of estimation of thickness of volcanic ash near the vent by the thickness measured in the foot of the mountain using the relationship between the thickness and the distance from the vent.

S02.16 Poster

"The drizzle burns my eyes and throat" – impacts of volcanic gas, aerosol and acid rain

Evgenia Ilyinskaya

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Even when volcanoes are not erupting ash or lava, their emissions of gases and aerosol can impact air quality, terrestrial and aquatic environments, climate, and health. This hazard can have a sudden onset, striking communities with no living memory of it (e.g. Laki and Holuhraun eruptions in Iceland); or be of a persistent nature, posing a chronic problem for decades or centuries (e.g. Kilauea in Hawaii, Masaya in Nicaragua).

While news coverage of disasters such as pyroclastic flows and lahars are always accompanied with spectacular images of destruction that emphasise their impact, volcanic gases are usually left in the shadow of attention, and are in many cases overlooked by Disaster Risk Reduction efforts. But this 'unseen' hazard can have significant societal consequences. Emissions from the Laki eruption (1783-1784) led to the loss of ~90% of Iceland's livestock, while ~20% of its population died from famine and disease. The persistent emissions from Masaya prevent subsistence farming and contribute to poverty in the area.

In terms of health hazards, asthma sufferers are particularly sensitive to even low levels of sulphur dioxide reacting with a rapid airways constriction. Links have been made between prolonged volcanogenic pollution and increased respiratory & dental problems, and elevated risk of cancer, although causal mechanisms remain unknown.

The emissions also impact water and soil quality and therefore can cause severe damage to agriculture and biodiversity. Rain becomes strongly acidic, resulting in vegetation kill zones and extremely fast corrosion of buildings and infrastructure: "Even our earrings, if you wear them for a couple of days, your skin will be stained by rust", remarks a local resident near Masaya. Conversely, some types of crops reportedly thrive better in gas-impacted areas; this is an important area for future research that could build resilience to this hazard.

S02.16 Talk

"The plume goes around like a snake": establishing a monitoring system for volcanic gas & aerosol pollution in Nicaragua

Evgenia Ilyinskaya[1], Sara Barsotti[2], Harold Rodriguez Bellanger[3], James O'Neill[1], Mark Richardson[1], Xochilt Hernandez Leiva[4], Sebastien Nobert[3,5], Hilary Francis[6], Wilfried Strauch[7], the UNRESP team[8]

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Masaya volcano in Nicaragua poses a low threat from ash or lava, but it is a significant source of volcanic air pollution (VAP) due to its persistent emission of gas and aerosol. The project UNRESP (http://unresp.com) is working with Nicaragua's natural hazards observatory INETER on developing an operational monitoring system for VAP. We present here the achieved advances and challenges of this ongoing work.

The new VAP monitoring system consists of a) instrumental monitoring by permanent and hand-held stations, b) citizen-science observations and c) plume dispersion forecasting. Here we present the instrumental monitoring and citizen science/community engagement. Presentation by Barsotti et al. will discuss the forecasting model.

The monitoring, operated since March 2017, provides real-time data in high temporal resolution on several key air pollutants (SO_2, NO, NO_2, O_3 and PM10, PM2.5 and PM1). In addition to the permanent stations, hand-held SO_2 monitors are provided to 'citizen observers' in communities exposed to VAP. The hand-held sensors are useful for monitoring specific locations which have vulnerable populations, such as schools and clinics, and can be used indoors and outdoors with ease.

A two-way communication system is being developed so that communities can inform INETER when they experience high pollution levels - similar principle to "Did you feel it?" citizen observation system used in many seismically active zones. This will have the double benefit of providing ground-truthing for the plume forecasting, and raising the awareness and involvement within the communities. Work is ongoing on creating public advisories which need to be tailored to the local setting and pre-existing practices in order to be able to intervene efficaciously.

To distinguish the volcanogenic air pollution from anthropogenic smoke (a significant problem in the area, too), we have introduced a new word, *vumo* - a combination of the Spanish words volcán (volcano) and humo (smoke).

S02.16 Poster

Tephra without borders: Building a global tephra data system across disciplines

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As stratigraphic and chronologic markers, tephra layers are a common link across multiple disciplines, including, but not limited to, volcanology, tephrochronology, archaeology, and paleolimnology. Tephra deposits reflect the magmatic, eruptive, dispersal, and depositional processes during their ejection and emplacement and can provide extensive time- stratigraphic marker beds across countries, across whole continents, and sometimes even across multiple continents and the intervening ocean basins. Tephras are also fundamental in understanding eruption history, frequency, hazards, and impact extent in volcanology.

THROUGHPUT is a collaborative project working to increase discoverability and access to tephra data across disciplines, improve integration between data types, and facilitate the use of digital tools. By incorporating data generated by scientists working in other disciplines, efforts by volcanologists to understand these aspects can be improved, especially with the advent of cryptotephra studies. With the addition of cryptotephra data, known ash distributions can be expanded and eruption volume estimates can be improved. However, data that have been collected over decades still lie fragmented in separate databases, publications, and unpublished datasets and in underutilized datasets produced by other disciplines. Best practices for tephra data capture, reporting, and storage also need to be developed and implemented across fields for everyone to benefit. For volcanologists, the resulting collaborative resource will provide a much more comprehensive dataset for impact and mitigation studies.

S02.16 Poster

The Current State of Knowledge of the Volcanic Ashfall Impacts Working Group

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The international Volcanic Ashfall Impacts Working Group, of the Cities and Volcanoes Commission of IAVCEI is dedicated to research focused on understanding and mitigating the impacts of volcanic ashfall. The Working Group is a consortium of multi-disciplinary expert geoscientists from government and academia working together to share experiences and research from eruptions across the globe with the goal of better preparing our own communities for ash eruptions. Overarching aims of the working group are: (1) more effective public ashfall warning messages, (2) standardization of protocols for ashfall data collection and analysis where possible, (3) checklists for the data on ashfall impacts to collect following eruptions, (4) creation of loss-damage functions due to ashfall for risk calculations, and (5) improving international ashfall impact data, image repository, and overall communications. Partnership with key IAVCEI commissions, such as the International Volcanic Health Hazard Network (IVHHN) and the Tephra Hazard Modelling commission, is key to ensure the most up to date and authoritative guidance on ashfall impacts and mitigation. Research areas include understanding impacts to buildings, transportation, power supply, health, agriculture, drinking water and wastewater, airports, communications and clean up and disposal.

The current state of knowledge of the Working Group includes: (1) the internationally collaborative volcanic ash website (http://volcanoes.usgs.gov/ash/) the authoritative global resource for ashfall preparedness and impact guidance, (2) posters on ashfall impacts a series of posters providing concise best-practice information for critical infrastructure and city managers to effectively prepare for, respond to, and recover from ash-producing eruptions, (3) case studies a series of field studies cataloging ashfall impacts from eruptions worldwide, (4) support in developing guidelines and resources for health hazards, (5) prototype checklists of impact data to collect after eruptions, and (6) support in developing guidelines for ash collection protocols.

Volcanic Ash Impacts to Infrastructure

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Volcanic ashfall can cause a range of direct and indirect impacts to infrastructure and agricultural production, which can lead to substantial societal impacts. Our knowledge of the likely impacts and ability to mitigate those impacts has progressed steadily over the past few decades. It is now relatively well established that ash impacts are complex, driven by: a) the broad range of potential ash characteristics, hazard intensities, durations, and the (potentially) complex interaction with other volcanic hazards and environmental factors, b) the vast array of infrastructure and agricultural elements exposed to ashfall hazards and their vulnerability or resilience, and c) the broad range of possible pre-, syn-, or post-event mitigation actions. These all create challenges for robust assessment of likely impacts/risks and identifying potentially credible and useable mitigation measures.

This presentation will 1) summarise recent developments in ash impacts to infrastructure and agriculture and potential mitigation measures through field and laboratory based assessment, and 2) efforts to translation and apply this knowledge in volcanic risk management approaches. It will also explore future challenges in this field and some of the exciting initiatives which will hopefully help address them.

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S02.17 - Mount Agung Eruption, 2017-18

Dyke intrusion between neighbouring arc-volcanoes responsible for 2017 unrest at Agung, Bali: insights from Sentinel-1 InSAR time series and 3D stress modelling

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On November 21st, 2017, Agung volcano, located in Bali, erupted, ending more than 50 years of quiescence. The previous eruption in 1963 (VEI 5) killed several thousand people, which underlines the potential large threat for the local population. The 2017 eruption was preceded by a strong seismic swarm from late August to mid-October, which led the Volcano Observatory (PVMBG) to increase the alert to its maximum level and to trigger the evacuation of over 150,000 people. Analysis of Sentinel-1 InSAR time series show a persistent 5 km radius uplift signal of 8-10 cm on the north flank of the edifice starting in late September 2017, in both ascending and descending tracks. Inversion of InSAR data using 3D Finite Element Model shows that the ground deformation signal is consistent with a deep sub-vertical magma intrusion located between Agung and its neighbour Batur caldera. Using stress modelling, we also confirm that the N129º strike of the inferred dyke is not consistent with regional tectonic stresses but instead it can be explained by the topographic load. Our interpretation is that the magma transport below Agung is controlled by the emplacement of deep mafic intrusions that likely propagate between Agung-Batur systems as tensile deviatoric stresses are highest. Later, in November, the dyke stopped propagating vertically before intersecting and mixing with a shallow, long-lived andesitic storage zone. Timescales of magma mixing usually range from days to few weeks, which explain the one-month delay between the end of the seismic swarm and the start of the 2017 eruption. For the first time, our geodetic observations revealed ongoing interactions between Agung and Batur, which have important implications for interpretation of distal seismicity, the links between magmatic systems of closely spaced arc volcanoes, and the potential for the occurrence of simultaneous eruptions at neighbour volcanoes.

S02.17 Talk

The role of local culture in volcano risk communication and coordination during the 2017 crisis of Mt. Agung

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Mt Agung (3014m), Bali is recognised its large eruption in 1963 which took 1148 casualties. Recently, the volcano reawakening was shown by swarms of volcano-related earthquakes recorded by the Agung-Batur monitoring network. The highest alert level (Level IV/Warning) issued on September 22, 2017 by the Center for Volcanology and Geological Hazard Mitigation and prompted the evacuation of more than 120,000 civilians. After 38 days without eruption, the activity was decreasing and the alert level was changed to Level III/Watch (October 29, 2017). The eruption started on November 21, 2017 and the intensity was increasing on November 25, 2017. Therefore the alert level was changed to Level IV/Warning (November 27, 2017). Since December 2017, the eruption intensity decreased and the alert level downgraded to Level III/Watch on February 10, 2018.

Communication and coordination related with hazard and risk of Mt Agung were carried out by multiple agencies and ministries involving authority leaders from village to national levels. These were done through direct and indirect communications (radio, telephone, WhatsApp group, MAGMA Indonesia application and text messages, social media and webpages).

Problems of communication in public official and community levels are associated with the understanding of hazard map, eruption experience, media interpretation related to culture, and involvement of external scientist who does not acknowledge exclusion zones.

Volcanic crisis is a critical time to build trust between government and community. External factors those disregard government recommendation and local culture affect public trust in the government. This nature also raises risks for the community. In contrast to be a disaster management official is a challenge and also bound by responsibility and law.

S02.17 Talk

Thermal model of lava in Mt. Agung during December 2017 episodes using Integrated SENTINEL 2A and ASTER remote sensing datasets

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In the beginning of December 2017, Mt. Agung eruption powered down to minor ash emissions and on the middle of December, aerial photographs of the crater were taken by Indonesia Centre of Volcanology and Geological Hazard Mitigation (PVMBG) showing a steadily growing lava occupying approximately one third of the crater. 3D digital elevation model (DEM) of crater were created by PVMBG during and before the eruption, corresponded to lava volume around 2 x 10^{-2} km^3 has been filled the crater. Here we present a method for deriving thermal model within the lava during eruption on 8 and 9 December 2017 using observations from multi infrared satellite SENTINEL 2A and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). We use Thermal eruption Index (TEI) based on the Shortwave infrared (SWIR) on SENTINEL 2A and Thermal Infrared (TIR bands) on ASTER, allowing us to differentiate thermal domain within the lava flow field. This study has successfully produced model of sub-pixel temperature (Th), radiant flux (Φrad) and crust thickness model of lava flow (Δh). The subpixel temperature and radiant flux during the eruption is in the range 655 to 975 ^{o}C and 179 MW respectively. The crust thickness model of the lava in the range of 7 to 14 m and the total volume of lava crust during this period is estimated at 3 x 10^{-3} km^3. The combination of infrared satellite remote sensing data shows a potential for fast and efficient classification of difference thermal domains and derive thermal model of lava.

Keywords: SENTINEL 2A, ASTER TIR, TEI, sub-pixel temperature, radiant flux, crust thickness.

Real-time magma flux quantization from GNSS during the 2017-2018 unrest at Mt. Agung (Bali, Indonesia)

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After the VEI 4+ deadly eruption in 1963 and 54 years of dormancy, Mt. Agung reawakened in September 2017 with a brutal and high energy seismic swarm which lasted about 40 days then progressively decreased. On November 21, 2017, a small explosive phreatomagmatic eruption began and subsequent explosive eruptions on 25-28 November had increased intensity with lava effusion began on November 26. Small deformations were recorded by a tiltmeter and 5 permanent GPS stations, with a maximum of 5 cm of displacements. In this paper we present a robust method to perform automatic source modeling from displacement trends, resulting in continuous time series of volume variations and source depths, as an efficient tool for real-time monitoring. An inflation period was detected from mid-August to mid-September, with a 12±2 km deep source and a maximum of +40±5 Mm3 volume variation. From mid-September to end of November, models show no significant large scale deformation. Sudden deflation began on November 28, 2 days after the magma reached the surface and started to fill in the crater. The subsidence lasted 14 days with a maximum of −36±4 Mm3 associated to 11±1 km deep source. Models and phenomenology suggest that a limited magma volume has supplied the shallow reservoir, followed by a fracturing episode towards the surface, then the filling of the crater associated with reservoir deflation of a similar volume amount. These results have been obtained during the crisis management, in December 2017, and have been used as phenomenological evidence in order to reduce the evacuation zone around Mt. Agung on January 4th, 2018.

S02.17 Talk

A critical shift in approaches to community respiratory protection during the Agung crisis

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The Health Interventions in Volcanic Eruptions (HIVE) consortium (http://community.dur.ac.uk/hive.consortium/) recently published research on the effectiveness of different forms of respiratory protection against volcanic ash (see presentation in Session 3.2). Key findings were disseminated on the IVHHN website (www.ivhhn.org), and to Bali-based Facebook groups, at the onset of the Agung crisis, to aid evidence-based decision making both at agency and community level. The take-home message from the studies was that industry-certified 'N95'-style masks offer the best protection against ash, even without fit training.

When a volcano erupts, agencies will often distribute facemasks which have already been stockpiled for public health emergencies (e.g., surgical masks for influenza pandemics, although the US and Iceland have stockpiled and distributed N95 masks). Until the HIVE project, there was little-to-no evidence of the effectiveness of any of these masks for ash in community settings.

The 2017 Agung crisis triggered a critical shift in the approach to community protection in volcanic emergencies resulting in the donation, stockpiling and distribution of tens-of- thousands of N95-style masks by a consortium of NGOs (Mt Agung Relief). This has not previously been observed in a volcanic crisis in a low-to-middle income country (LMIC). The fundamental difference between the preparedness for the Agung eruption, and that of previous LMIC volcanic crises, comes from a combination of changes in humanitarian practice at NGO level: the advent of crowdfunding platforms, greater coordination of grassroots response, and a move from the precautionary principle ('something is better than nothing') towards the principles of effectiveness (only providing proven interventions) and social justice (equality in public health provision). This ethical decision-making was aided by the HIVE project results. Mt Agung Relief also produced a series of informational products on facemask use, which incorporated further findings from the HIVE project, for example, on how to improve the fit of facemasks.

S02.17 Poster

Mitigation of a reawakening volcano: Lessons from the 2017-2018 unrest and eruptions of Mount Agung, Bali

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All eyes have been on Bali's Mount Agung during the final quarter of 2017 following an alarming earthquake swarm around the volcano, a notable increase in steam discharge and water expulsion in the summit crater hinting that the volcano might be awakening after 54 years of slumber. On September 22, the Indonesian Center for Volcanology and Geological Hazard Mitigation (CVGHM) raised the volcano alert to its highest level and the eventual eruptions started on November 21. The intense unrest and eruptions triggered evacuations of ~140,000 civilians, flight disruptions, and airport closures in Bali and Lombok islands resulting in ~US$800 million in economic loss.

Risk mitigation during the 2017-2018 unrest at Mount Agung became problematic for several reasons that include: (1) this volcano had slumbered for 54 years, yet it is one of only seven volcanoes around the world to experience consecutive VEI 5+ eruptions and the previous eruption in 1963 killed over 1000 people, (2) the volcano is a tourist attraction and the presence of important agricultural and aggregate resource areas on the flanks and upper slopes of Agung lured a large population to live within the hazard zones (~200,000), (3) the fact that Bali and its capital city (Denpasar, with its busy international airport) constitute the most-popular international and domestic tourist and business conference area of Indonesia, (4) lack of instrumental monitoring prior to previous eruptions meant that we had little historical basis for interpreting the unusual sequence of unrest, and (5) a relatively long run-up time (~8 weeks) between the highest volcano alert level declaration and magmatic eruption contributed to intense social pressures.

Here we discuss the unrest and eventual eruptions, provide a summary of actions taken by our group (CVGHM and VDAP-USGS), and identify problems and lessons learned from this crisis.

Agung 2017: an eruption through relaxing crust?

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Mount Agung, in Indonesia, erupted in November 2017 for the first time in 53 years. The eruption was preceded by at least four months of local volcano-tectonic (VT) seismicity. At volcanoes reawakening after long repose, VT events are commonly expected to show characteristic accelerations with time as crust is stretched and ruptured to allow magma ascent. In contrast, the VT events at Agung followed a pattern that ultimately favoured eruption during a decrease in VT event rate with time. Decreasing VT rates are empirically associated with a reduced likelihood of eruption. Here we attribute the apparent contradiction to the final stages before eruption being controlled by passive magma ascent through a relaxing crust.

Data provided by Indonesia's Centre for Volcanology and Geological Hazard Mitigation show three broad stages in Agung's VT behaviour: accelerating rates between July and 20 September; an approximately constant rate between 20 September and 20 October; and a general decay until eruption on 25 November. The accelerating stage is consistent with an increase in applied differential stress and consists of a sequence of exponential trends that reflect changes in mean deformation rate. Acceleration ended when the inferred ratio of applied differential stress to tensile strength reached 4-5.5, which indicates rupture in combined tension and shear. The steady rate that followed is consistent with opening of the rupture. The final decrease in rate suggests relaxation of stress in the crust. The elastic energy released favoured continued opening of the rupture and allowed magma to flow passively through the volcanic edifice. Passive magma ascent through relaxing crust is not inevitable, but requires a suitable geometry of the magmatic system. Identifying the geometry is essential for enhancing the reliability of eruption forecasts at volcanoes like Agung worldwide.

S02.17 Poster

Surface deformation associated with the 2017-2018 unrest of Mount Agung, Bali

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In 2012, Continuous Global Navigation Satellite System (GNSS) observation were deployed at 5 (five) locations around Mount Agung by the Indonesian Center for Volcanology and Geological Hazard Mitigation (CVGHM) and the Volcano Disaster Assistance Program of the US Geological Survey (VDAP-USGS) and 5 years later the volcano experienced an intense unrest and eruptions. In August 2017, a series of volcano-tectonic earthquakes were observed northwest of the volcano. Seismic rates and amplitudes increased rapidly between September 15 and 22 from tens of events per day to >800 events per day. After September 22, seismic rate has continued to fluctuate at high levels meanwhile seismic amplitude has decreased. On October 20, seismic rates decreased rapidly while seismic amplitudes began to re-increased in early November. On November 21, Mount Agung erupted for the first time in 54 years.

Here we analyze the GNSS observation data from October 2017 to January 2018 and used the L1 and L2 GPS frequency bands with sampling intervals every 1 (one) second. GAMIT/GLOBK ver. 6.1 was used to get precise daily coordinates in reference to the ITRF2008 and baseline solutions. The temporal change in slope distance between all stations in the period October 2017 – January 2018 show correlations with changes in volcanic activity. Starting October 26, the extension started with 1-2 cm increase in baseline length. On November 27, all baselines began to contract rapidly along with the series of eruptive events. The rapid contraction occurred until November 30, after which the baseline continued to experience low-rate shortening. The GNSS measurements show significant changes a month prior to the eruption, during the series of eruption series, and thereafter.

Absorption of magmatic volatiles into large cold springs at Mt. Agung, Bali, Indonesia

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After 54 years of dormancy, Mt. Agung entered a period of unrest in early August 2017, followed by eventual eruption on November 21. Agung lacks hot springs but has many large cold springs located on its southern flank. According to the unpublished hydrogeologic map of Agung, there are over 30 springs that emerge from the SW to E flank at elevations ranging from 200 to 600 masl, with spring locations clearly linked to discrete stratigraphic horizons.

From 10/17 to 1/18, we collected waters from 11 springs and local rain. Estimated spring flows varied between ~1 to as high as 500 L/s. Balian, Petung, Dusun Kahang and Tirta Gangga had flow rates >100 L/s. Solute content of springs were greatly enhanced compared with local rain waters. Springs with high discharge had high flouride (0.1 to 0.37 mg/L), sulfate (15 -123 mg/L) and chloride (3 to 15 mg/L) contents compared with rain waters, low flow rate (<15 L/s) springs, and a large spring on Mount Bratan (an extinct volcano in western Bali). The local rain waters had <0.01 mg/L F, and < 1 mg/L SO_4 and Cl. Tirta Gangga was the most concetrated spring we sampled on Agung, consistent with values from the literature.

Large springs were also depleted in O and H isotopes compared with small springs and rain waters (generally 1-2 per mil in $d^{18}O$ and ~10 per mil in dD). This implies that the waters are sourced much higher than their discharge elevations. A HCO_3-Cl-SO_4 ternary diagram suggests that most springs are peripheral waters (ground water) mixed with some steam- heated and hydrothermal-water compositions. Anomalies in SO_4, Cl, and F are consistent with absorption of magmatic volatiles by the massive cold spring system which is sustained by high precipitation (generally >3000 mm of annual precipitation on the south flank of Agung).

S02.17 Poster

The use of global data and analog eruptions during the 2017–2018 Agung eruption

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During the 2017-2018 unrest and eruption at Mount Agung, Indonesia, VDAP and CVGHM used global data from analog eruptions to help assess the unrest, develop a conceptual model, and populate event trees.

Global data proved useful during the unrest and eruption for a wide range of topics. For example, global data helped to assess: 1) the probability of large explosions at different time intervals after the eruption start; 2) the relationship between the timing of lava effusion and explosions; 3) the most appropriate input parameters for pyroclastic flow modeling; 4) the relationship between VEI and ballistic impact range; 5) the percent volume distribution between explosive columns and fountain-collapse pyroclastic flows; and 6) the avulsion of pyroclastic surges and lahars.

It was, however, challenging to compile a list of close analogs to Agung, perhaps due to an initial over-emphasis in our searches on two unique aspects of previous Agung eruptions: the occurrence of lava flow effusion followed by large explosions and a propensity for large VEI 4 explosions. Further review of the longer eruptive history of Agung from Fontijn et al. (2015) indicated that while Agung does have a prevalence for large VEI eruptions, smaller (VEI 2-3) eruptions are still the most common style of activity.

Additionally, many questions arose during the crisis that were difficult or impossible to answer with current databases. In particular, datasets that could address the delay between peaks in seismicity and eruption onset and the timing between first phreatic and first magmatic explosions would have been very useful.

This submission seeks to describe how global data from analog eruptions helped during a recent volcanic crisis, to describe some key challenges in selecting analogs, and to highlight some open questions we would like to answer with global datasets.

Ash time series from the 2017 eruption of Mount Agung, Bali

Oktory Prambada

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Ministry of Energy and Mineral Resources of Indonesia

After more than 50 years of repose, Mount Agung in Bali erupted explosively on November 21st 2017. The subsequent explosive eruptions on 25-27 November 2017 had increase intensity. Ash deposits on the southeast flank and northeast sides of the volcano were sampled respectively on 21, 25 and 27 November 2017. We analyzed two grams of each sample by using SEM (FEI Quanta series FEG-650) in order to classify particles into lithologic and textural categories (components). We find differences in compisitions and morphological characteristic of the ash particles. The ash sample from the initial eruption on November 21st was dominated by hydrothermal altered rock (>90%) with a smaller portion of juvenile material (<5%) suggesting a phreatomagmatic explosive mechanism i.e. rising magma came in contact with hydrothermal altered rock. The November 25th and 27th volcanic ash samples showed larger portions of juvenile (< 40%) and lithic (<55%). Ash samples contain glass with a few primary crystals covered by a lot of secondary minerals. Widely varying clast vesicularities reflect complex variations in the relative timing of vesiculation and water-induced fragmentation and become more uniformly in the range of 70% regardless of magma viscosity. We also analyzed the ash composition using the WDXRF PANalytical Axiosmax PW4400. The silica content varies during the 21-29 November 2017 eruption period from 55.43% (basaltic-andesite) to 59.56% (andesite), consistent with a change in erupted componentry. Our analysis indicates that the componentry of ash evolved as the eruption progressed, with increasing amounts of juvenile material and a decrease in hydrothermally altered material.

Keywords: Agung volcano, eruption, volcanic ash, phreatomagmatic, juvenile, lithic, bubble wall.

SO_2 emission rates and gas plume composition of Agung volcano, Bali during the crisis of October 2017 to February 2018

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Unrest at Agung volcano started in September 2017, since its 1963 eruption. The SO_2 emission rate was measured using mobile DOAS between October 1 and November 14; twelve detailed measurements all failed to detect SO_2.
We successfully deployed a fixed-wing sUAS (small Unmanned Aerial System; Aeroterrascan model Ai450) with a mini-multiGAS at 08:21 AM (UTC +8) on November 21, 2017 and detected a large CO_2 anomaly in the plume (ΔCO_2= 35 ppmv); $SO_2$was below 0.05 ppmv. Approximately 9 hours later, the first eruption occurred. Ground-based DOAS measurement yielded 660 t/d of SO_2 on November 22, 2017. Three sUAS flights on November 23 and 24 found large CO_2 anomalies (ΔCO_2= 50-90 ppmv), very low SO_2 ($SO_{2,\ Max}$ = 0.60 ppmv on November 23; 0.05 ppmv on November 24), no detectable H_2S, and average molar CO_2/SO_2 ratios increased dramatically from 80 to 800 prior to a magmatic explosion at 17:20 on November 25.

The highest SO_2 emission was measured on November 26 (5,500 t/d) but quickly fell to 180 t/d on December 1, 2017 and highly variable during December, 2017 (SO_2= 130-1500 t/d; median = 380 t/d, n = 14). An sUAS flight on December 19 yielded H_2O/CO_2= 21, CO_2/SO_2= 3.2, and $SO_{2,\ Max}$ = 26.9 ppmv. The DOAS measurements on November 26, picked up very low ratio of BrO/SO_2 (3e-5). Subsequent data revealed higher ratios of BrO/SO_2= 1.8 and 1.9E-4 on December 17 and 18, respectively. Overall, low SO_2 values prior to the first eruption and high CO_2/SO_2 appear to reflect scrubbing of SO_2 by the large groundwater system at Agung. Whereas, high SO_2 values correspond to Agung's first explosive eruptions in November 2017.

Seismic velocity changes associated with the 2017-2018 activity of Mount Agung, Bali as inferred from cross-correlations of ambient seismic noise

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Seismic records are one of the most important monitoring parameters used in estimating and evaluating the activities of Mount Agung during the crisis of 2017-2018. A rapid increase in seismicity was observed around Mount Agung between 15 and 22 September 2017. Seismicity continued to fluctuate at high levels for 4 weeks before suddenly declining on October 20. In early November, seismic rates continued at low level while seismic amplitudes began to increase. On November 21, Mount Agung erupted without preceded by seismic rate increases.

Here we analyze the cross-correlations of ambient seismic noise around Mount Agung from April 2017 to February 2018 using the vertical component signals of three short-period seismometers located on the flanks of Mount Agung and its neighbour Mount Batur (18 km NW of Agung). We use two pairs of stations (BTR-PSAG and PSAG-TMKS) to compute the relative seismic velocity changes. The first pair represents seismic velocities of an area between Agung and Batur volcanoes (Batur-Agung area) while the latter is in the southern slope of Agung volcano (Agung area). In late May 2017, following a short-lived earthquake swarm located at around 32 km in the northwest of Agung, seismic velocity abruptly decreased in Batur-Agung area while no changes observed in Agung area. In July 2017, seismic velocity in Batur-Agung area displayed a gradual recovery. In mid-September 2017, seismic velocities in Agung area increased along with the increased seismic rates. On October 10, 2017, seismic velocities in Agung area continued to decrease through the eruption onset on November 21, while no changes observed in Batur-Agung area. Seismic velocity in Agung area did not recover until the end of observation period. We suggest that seismic velocity changes in Agung area may be related to stresses changes induced by over- pressurization of the magma reservoir within the Agung volcano plumbing system.

Using a mobile application (MAGMA Indonesia) to disseminate volcano early warnings and information: An example from the 2017-2018 unrest of Mount Agung, Bali

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Mount Agung reawakened in the era of smartphones when people rely more on mobile applications in their life. In September 2017, an alarming earthquake swarm northwest of Mount Agung prompted the Indonesian Center for Volcanology and Geological Hazard Mitigation (CVGHM) to raise the volcano's alert level. False information spread rapidly through online media, and exaggerated news reports resulted in confusion and even fear throughout the community. The 1963 eruption that caused over 1000 casualties was still within the public' memory and instilled the perception that Mount Agung is a “killer volcano”. The dissemination of official information to the public, media, local and central government officials and other related agencies became crucial.

Here we present the use of a mobile application (MAGMA Indonesia - Multiplatform Application for Geohazard Mitigation and Assessment in Indonesia) to disseminate volcano early warnings and information during the course of the crisis at Mount Agung. The application is accessible on the web (https://magma.vsi.esdm.go.id) or through an Android app available on the Google Play Store. The app provides different types of notifications to address specific information needs: (1) Volcanic Activity Report (VAR) - a scheduled update on monitoring data summary, alert level, and recommendation (once every six hours during alert level 3 or 4, and once a day during alert level 1 or 2), (2) Press Release - a special update during significant volcanic events, ongoing unrest or eruptions, and (3) Volcano Observatory Notice for Aviation (VONA) - a specific report for the aviation sector. The app provides access to hazard maps, rapidly estimates the distance between users' and hazards' locations and allows users to report significant events around them.

We find that a mobile application makes volcano early warnings and information dissemination simpler, faster, more reliable, and widely accessible and could potentially contribute to volcanic disaster risk reduction.

S02.17 Poster

Evidence for rain-induced tremor during lava effusion at the summit of Mt. Agung

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After the emplacement of a low viscosity lava dome at the summit of Mt. Agung on 25 November 2017, there were 39 explosion-like tremor signals between 27 November and 4 April 2018. In the time domain, these tremor signals appear to be similar to explosive ash eruptions recorded at other volcanoes, but several lines of evidence suggest these tremor signals are associated with heavy rainfall events at the summit. (1) These tremor events mostly occur in the afternoon hours when storm cells typically develop in the tropics, (2) the tremor only occurs on days that rainfall is thought to occur at the summit (based on webcam images and World Wide Lightning Location Network data), (3) the tremor signals lack significant energy below 1 Hz as would be expected for an explosion signal, and (4) none of the tremor signals are associated with visual observations or satellite detections of an ash plume. One possible mechanism for these events is a process similar to what was observed at Mount St. Helens between 1989 and 1991 (Mastin, 1994) in which the tremor occurs when rain water falls on hot rocks at the surface, accelerates cooling fractures, and allows small amounts of gas to escape as a small steam emission. Due to a lack of visual observations for these events it is difficult to say more about the tremor source mechanism, but the correlation between rain and tremor episodes suggests the process is surficial. Recognizing these events, based on their timing and spectral properties, is important for accurately identifying or not identifying hazardous ash explosions.

Insight into the evolution of pre- and co- eruptive seismicity at Mount Agung based on retrospective cross-correlation analysis with RedPy

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During the vigorous pre-eruptive swarm of thousands of volcano-tectonic (VT) earthquakes at Mount Agung, Indonesia from August to October 2017, analysts for the Center for Volcanology and Geologic Hazard Mitigation (CVGHM) tracked earthquake types, magnitudes, and locations manually from digital records. After the fact, we re-analyzed all earthquakes using the RedPy software (Hotovec-Ellis and Jeffries, 2016) in order to describe the evolution of different earthquake clusters prior to and during the eruption. The results highlight two seismic episodes, noted by real-time analysts, that were associated with dramatic shifts in both seismicity and the state of the volcanic system, as gas and fluid pathways and the state of stress in the crust evolved.

Before 12 November, almost all earthquakes grouped into one of ~40 VT clusters that located mostly NW of Agung. On this date, a series of large low-frequency (LF) and tremor events occurred proximal to the volcano's summit that were unlike previous activity and highly concerning. Subsequently a new cluster of LF events and three new clusters of proximal VT events appeared. Simultaneously, almost all pre-existing distal VT clusters ceased to persist. Together these observations suggest that the gas/fluid pathways and distribution of stress in the crust changed fundamentally on 12 November. Seismicity then remained relatively quiet leading up to the first phreatomagmatic eruption on 21 November. On 25 November, a brief, subtle episode of proximal LF events that were larger than most previous LFs occurred hours before the onset of magmatic explosions and lava effusion. The swarm of LF events on 25 November also belonged to a new, unique cluster of events and introduced a new regime of co-eruptive seismicity at Agung. All subsequent earthquakes grouped into clusters that had not existed prior to the onset of the magmatic phase.

Use of event trees at Agung volcano 2017-2018.

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Probabilistic event trees were created 8 times during the Agung crisis, including 20 September, 23 September, 2 October, 17 October, 15 November, 11 December, 24 January, and 12 March. Event trees were based on the expert-elicitation process used by the VDAP and CVGHM team, using procedures similar to those in Newhall and Pallister (2014) and Wright et al. (2018). Trees were constructed by VDAP and communicated to CVGHM, Indonesia in order to address hazards issues relevant for their discussions with emergency managers. Expert elicitation included group discussion, with the addition of individual assessment via online polls. All short-term event tree forecasts covered a period of two weeks, because this relatively short time interval was of most importance to the emergency managers.

Early event-tree eruption forecasts (late September and early October) relied heavily on seismic data, remote sensing observations, analysis of past eruptive periods at Agung, and comparisons with analog volcanoes and analog seismic progressions. As the crisis continued (mid-October to November), additional monitoring streams aided short term forecasting efforts, including GPS data retrieved in early to mid-October and initial InSAR data that was processed, corrected, and interpreted by mid-November. Forecast probabilities decreased with time since peak seismicity; however the eruption occurred almost 2 months after this peak. This raises the question of whether delay times between seismic peaks and eruptions would better determine the duration of short-term forecasts in general?

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S03.02 - Health hazards of volcanic eruptions towards improved preparedness and resilience and reduced impact

Microscopic Monitoring of Laboratory Based Physical Disintegration Ratio of Fibrous Zeolite Crystals from Cappadocian Altered Ignimbrites (Turkey)

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Cappadocian explosive volcanism are represented by 10 distinct ignimbrites, which extend over 20000 km^2 forming spectacular landforms. Weathering and physical disintegration result in various erosional morphologies on ignimbrites as deep valleys, channels and, fairy chimneys which are controlled by welding degree of the units. Although, alteration of volcanic glass increases the welding degree, microscopic or mesoscopic disintegration can be occur. Hydrothermal alteration of Cappadocian ignimbrites are represented by secondary clay and zeolite group of minerals. Erionite, has been listed by International Agency of Research on Cancer (IARC) as Group-1 carcinogen, is one of the main alteration mineral species in some localities. Disintegration and transportation via airborne of carcinogen zeolite group minerals are the one of the important reason of mesothelioma epidemic around the some distinct villages.

This study aims to quantify the disintegration ratio of fibrous zeolites by weathering experiments. Freezing-thawing and wetting-drying experiments have been applied on core samples (diameter: 3cm, height: 10 ± 3cm) of highly zeolitized ignimbrites. Throughout the experiments, proportions of disintegrated fragments were calculated after each cycle using optical phase contrast microscope (PCM), scanning electron microscope (SEM) and X-Ray micro-computed tomography (Micro-CT). Although, fibrous erionite crystals formed as radial/prismatic bundles from volcanic glass, erionites are able to disintegrate as individual crystals (approx. 100 ±30μ max size.) after the approx. 3 months of weathering processes. Quantitative ratio of individual erionite crystals were measured by using correlative 2D and 3D image analysis techniques. Consequently, quantitative spatial extension and exact surface area of altered (erionite bearing) ignimbrites have a crucial importance to make realistic calculations in terms of separated erionite crystals or other mineral species that related environmental health problems.

S03.02 Talk

Revisiting the health impact of the degassing at Masaya, Nicaragua

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Mount St Helens erupting in 1980 opened the door to multidisciplinary collaboration over volcanic impacts and mitigation measures. In 1981, Stoiber and Williams proposed a collaborative study at Masaya volcano, Nicaragua, to investigate the degassing plume and its human and environmental impacts, a concept ahead of its time. Strong degassing that began many decades ago has continued since 1981, except for a brief period in 1994. Revisiting Masaya in 2017, the multidisciplinary UNRESP project has built on advances in air pollution science and air monitoring since 1981, which have made health risk assessments for communities at Masaya and other degassing volcanoes more feasible than before. Sulphur dioxide (SO_2) remains the dominant hazard for asthma and COPD sufferers, but international exposure guidelines and air quality indices devised for ambient air pollution are applicable for this gas in the fumigated settlements and tourist viewpoints. Ready access to the health care system is available, but health surveillance in communities exposed to the gas plume (a.k.a. VUMO to distinguish it from the smoke from wood burning for cooking - itself a significant respiratory health hazard), is still non-existent and routine statistics are limited. The acid gases, hydrogen chloride and hydrogen fluoride, contaminate rainwater making it acid and fluoride rich: subsistence crops can no longer be cultivated, though rainwater catchment in large cisterns is now provided by pipes and tankers, eliminating a major source of fluoride in the dietary intake of people and livestock. Probabilistic plume modelling incorporating SO_2 flux measurements is helping to map the population at risk and in siting innovative mobile air monitors to provide warnings of future increases in SO_2 and to identify areas for mitigation measures, such as gas proofing schools and refuge spaces in homes.

Volcanic fatalities: threat to life with distance and victim classification

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Volcanoes produce a variety of potentially lethal hazards, which can have significant impacts over tens or even hundreds of kilometres, both during and between eruptions. With around a tenth of the world's population now living within the potential footprint of volcanic hazards, it is unsurprising that lives are regularly lost in eruptions, and volcanic fatalities are recorded in 18 of the last 20 years. A volcanic fatalities database for the period 1500 AD to 2017 has been updated and expanded to include data on the location of the fatal incident and classification of the victim, based on their activities at the time of impact. Around 280,000 fatalities are recorded. Populations living on or near volcanoes are the most frequently killed, but tourists, volcanologists, members of the media and emergency responders are also identified as common victims. Whilst pyroclastic density currents are responsible for the largest number of fatalities overall, the dominant fatal cause varies with distance. The new location data are used to characterise volcanic threat with distance, as a function of eruption size and hazard type. Victim classification aids the understanding of how certain activities increase exposure and the likelihood of death. The database provides empirical data on which to forecast impacts and support evidence-based eruption planning and preparedness.

It ain't over till it's over: A latent health impact of an Icelandic large fissure eruption (Holuhraun 2014-2015) through exposure to mature, sulphate-rich, volcanic cloud

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Large volcanic fissure eruptions with massive emissions of suphur dioxide (SO_2) are rare, but an opportunity to study the health impacts from air pollution of this type of eruption in Iceland did not present itself until the 2014-15 Holuhraun event.

Public health advisories were issued in Iceland for air pollution events caused by the grounding of the SO_2 plume that occurred on a daily basis around Iceland according to the prevailing wind direction. However, the volcanic plume also impacted air quality after it matured chemically to an SO_2-poor, acid sulphate-rich composition, but this was not recognised in real-time monitoring or public advisories.

Using population-based registers in the Icelandic capital area (population 210,000) we found that exposure to the chemically mature plume was associated with increased health care utilisation for all age groups, but particularly in children under 18 years. The number of dispensed asthma medications was significantly increased (18.7%) on the day of the exposure (lag 0) when all age groups were considered together; and being highest (28.5%) in children. For all age groups, primary care contacts were increased by 22.7% at lag 0; and hospital emergency department (HED) visits by 15.6% on days 2 and 3 after exposure (lag 2-3). For children, the increase in HED visits was also significant at lag 0 (27.3%).

Our recommendation for future eruptions, in Iceland and elsewhere, is that ambient air monitoring and forecasting of health associated air pollution events should also include the mature, aerosol-rich plume.

The effectiveness of facemasks for protection against volcanic ash: overview and results of the HIVE project

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During volcanic eruptions, and their aftermath, communities may be concerned about inhaling ash. The Health Interventions in Volcanic Eruptions (HIVE) project (http://community.dur.ac.uk/hive.consortium/) aimed to build the first evidence base on the effectiveness of common materials used to protect communities in volcanic crises from ash inhalation including cloth, surgical and industry-certified masks. Mostly, agencies distribute surgical masks, or basic, single-layer, non-woven masks.

This presentation gives a synopsis of the results of this transdisciplinary project which incorporated laboratory analyses, on the filtration efficiency and fit of 17 forms of respiratory protection (RP), with psychological (questionnaire-based) and anthropological (interview-based) social surveys in Mexico, Japan and Indonesia. Our results show that the most effective form of RP is the industry-certified mask, even where no training in proper usage is given. Cloth materials performed poorly and, whilst surgical masks have excellent filtration efficiency against $PM_{2.5}$ particles in ash, their poor fit compromises their overall effectiveness. The social surveys highlighted context-specific perspectives and behaviors in the different locations, and the importance of multiple sources of authority which influence whether people will consider wearing RP.

In addition, the HIVE project has assessed the potential for conducting health impact assessments in volcanic crises and is developing standardized protocols for rapid epidemiological studies in eruptions. Additional to the main HIVE project, we are also reviewing the ethical considerations of facemask recommendation and distribution by agencies.
The presentation will also briefly present new outreach products being developed in association with IVHHN, PAHO (WHO regional office of the Americas) and local agencies and communities in the locations in which we have worked.

A full presentation of the project findings will be given at the HIVE workshop on Tuesday night, which we hope you will attend: **W.7** | Effective respiratory protection for volcanic ash exposure reduction: results of the HIVE project https://www.citiesonvolcanoes10.com/w-7/

S03.02 Talk

The use of affordable technology to mitigate community concerns of volcanic emissions

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Sulphur Springs Park (SSP) on Saint Lucia in the West Indies is an active hydrothermal area and major tourist attraction. Since 2015, networks of low-cost monitoring devices (active samplers and sensors) have been deployed to test their potential for monitoring the exposure to volcanic gases of SSP officials and visitors, and for establishing a citizen-science network to raise awareness of the volcano's activity. Initial measurements focussed on SO_2 emissions. SSP staff were trained in the field sampling required for a ten-month campaign using active samplers. Measurements were extended in 2017 to include bespoke low-cost technology to monitor ambient and soil CO_2 flux. Ambient sensors were installed along pathways with the highest foot traffic around the site, whilst units measuring soil flux were deployed in areas of diffuse fumarolic activity. The sensors performed well and, compared with traditional gas-monitoring instruments, the CO_2 sensors in particular are smaller, require lower maintenance and are significantly less expensive.

SSP staff recorded data and maintained the network. In addition to monitoring, the results were beneficial as a tool for promoting volcanic-hazards education and enhancing communication and understanding between geoscientists and the community they serve. Information for the public was disseminated on posters and brochures, in local newspapers and via phone-ins on public radio. It was also shared among SSP staff and government stakeholders in dedicated workshops. The principal obstacles to maintaining the networks have been time constraints on SSP staff and the lack of local resources for resupplying sampling materials. In spite of these challenges, the results have enhanced awareness of the volcano and provide a template for developing citizen-science programmes across neighbouring volcanoes in the Caribbean.

Distribution of volcanogenic elements in Vanuatu: Impacts to health and agriculture from volcanic degassing and deposition

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Vanuatu is home to some of the most active volcanoes in the world, with extensive degassing, significant ashfall and geothermal activity. The majority of the population relies on rainwater-harvesting or groundwater springs for potable water sources and live a subsistence lifestyle. The volcanic landscape can therefore present a number of risks to the inhabitants from ingestion of elevated concentrations of volcanogenic elements; inhalation of particulates; damage and pollution of crops; risks to livestock from ingestion of polluted water sources and forage; and dermal contact with ash and polluted rainfall. Analyses have been carried out on samples of fresh volcanic ash, rain-harvested drinking water supplies, freshwater resources, surface soils (<600mm) and crops/vegetation collected from islands in Vanuatu. Cation analyses were carried out utilising Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) and anion analyses are currently underway using Ion Chromatography (IC). Initial results show a number of elements (e.g. zinc, arsenic, magnesium) at or above Minimal Risk Levels (MRLs) for human health assessment, indicating a potential health risk from consumption of volcanically-polluted waters and inhalation of volcanic ash and soil particulates. A number of samples exceed phytotoxic screening values such that between root uptake and physical damage (weight of ash deposition, corrosion from acid rain) there is a significant risk to agricultural resources. Distribution of some volcanogenic elements shows a strong correlation with concentration and distance up/down wind of the plume (e.g. Selenium r^2=0.75, Aluminium r^2=0.86, Iron r^2=0.9), where concentration in soils increases with distance in both directions, indicating variation in the form of exposure risk dependent on location of the population in relation to the volcanoes. This research aims to utilise these data to bring together a multitude of exposure scenarios for local populations to provide a thorough assessment of the risks presented to communities living in proximity to active volcanoes.

Environmental health consequences of the 2017-ongoing Ambae eruption, Vanuatu

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In addition to causing immediate threats to life safety, volcanic eruptions can also affect the habitability of nearby communities, including aspects such as contamination of drinking- water supplies, degradation of both outdoor and indoor air quality, damage to property, changes to soil fertility, crop damage and food security. These aspects of environmental health can be important drivers of evacuation decisions, particularly if impacts are ongoing. The 2017-ongoing eruption of Ambae volcano, Vanuatu triggered an evacuation of the entire population of the island, in October 2017. Following a period of relative quiescence and repatriation, renewed ash and gas emissions from mid-January 2018 onwards began to cause substantial impacts in downwind communities, particularly in the west and south of the island. Environmental health consequences have been assessed through visits from multi-agency field teams and assistance from local agency staff and community members as well as analyses of ash, soil and drinking water samples and preliminary air quality measurements. There was considerable concern among local residents about contamination of water supplies by volcanic ash and gas, so a comprehensive sampling program was set up, including setting up sentinel tanks for repeat sampling over time. The resulting data set has been used as a basis for key messages distributed to residents, and endorsed by a wide range of agencies. Ashfall deposits all contained <10% by volume of particles smaller than 10 µm, although many had substantial proportions in the 10-100 µm size range. Preliminary air quality monitoring indicated that airborne ash concentrations (PM_{10} and $PM_{2.5}$) were generally low, although measurements were made on a calm day with low windspeed. As the dry season sets in, further measurements would be worthwhile, especially during windy conditions and both indoors and outdoors, as thick ash deposits may dry out and become resuspended by wind.

S03.02 Talk

Characterising the three-way interactions between people, domestic animals, and hazards from Popocatépetl volcano, Mexico: What are the implications for human health and resilience?

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Animal ownership is highly prevalent in Mexico, including within populations living at risk from one of its most active volcanoes, Popocatépetl, which is a source of multiple physical hazards including regular ash emissions. Despite recent inclusion of animals within official evacuation plans, the context-specific influences of human-animal interactions upon perceptions and responses to volcanic hazards, and their implications for health and resilience in this setting, are poorly understood.

The human communities in rural and urban regions at risk from Popocatépetl are heterogenous, and perspectives on human and animal health and wellbeing vary significantly. Within the closest rural communities at risk, economic and working animal species remain central to human livelihoods and identity as well as historical evacuation refusals, despite low prioritisation of animals' health and welfare status from a western perspective. Within regional urban populations, however, the human-animal relationship has shifted dramatically towards a 'pet' culture, with increasing animal health awareness and veterinary services engagement.

We are presenting the results of a thematic analysis of qualitative, semi-structured interviews undertaken as initial doctoral fieldwork between March-June 2018. Interviewees include residents, veterinarians, and hazard and disaster stakeholders involved with rural communities living on the slopes of Popocatépetl volcano, and nearby Cholula town and Puebla city, that have all been affected by ashfall. Drawing upon multidisciplinary perspectives, including the 'One Health' paradigm and assemblage theory, this analysis characterises the three-way interactions between volcanic hazards, people, and their animals, within the following themes: i) Hazard perceptions; ii) Human and animal health impacts; iii) Hazard response and disaster resilience.

This analysis provides a novel perspective for considering volcanic health impacts within a dynamic human population living in a complex, long-term risk environment. We identify key points to explore in this region of Mexico through further quantitative health and social science research, to drive future evidence-based resilience measures.

S03.02 Poster

The impact of in-plume ash-gas interactions on the respiratory health hazard of volcanic ash: an in vitro study

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Volcanic plumes are complex environments composed of gases, aerosols and ash particles, where various chemical and physical processes occur in different temperature and compositional regimes. By gas adsorption onto the surface of ash particles and subsequent chemical reactions, volatiles such as sulphur dioxide (SO_2) and hydrogen chloride (HCl) are scavenged, *i.e.*, removed from the atmosphere, and dispersed into the environment, commonly in the forms of sulphate and chloride soluble salts that grow on the ash surfaces. Human exposure to respirable volcanic ash particles following an eruption is a health concern, but the impact of gas-ash interactions on ash toxicity is hitherto unknown. Here, we investigate, for the first time, whether the presence of salt coatings may influence volcanic ash toxicity.

A sophisticated 3D multicellular *in vitro* human lung model was exposed to isolated respirable ash which was either salt-laden or pristine. To emplace surface sulphate salts via replication of chemical reactions that occur between pristine ash surfaces and volcanic gas, analogue substrates (powdered synthetic volcanic glass and natural pumice) were exposed to SO_2 at 500 °C, in a novel Advanced Gas-Ash Reactor (AGAR). The *in vitro* lung model was then exposed to each particle type for a period of 24 hours. Cell cultures were subsequently assessed for adverse biological endpoints, including cytotoxicity, oxidative stress and (pro)-inflammatory responses. Overall, results indicate that the toxicity of salt-laden ash does not differ significantly from pristine ash, both of which were minimally reactive. Based on dissolution modelling, > 80% of the sulphate salt coatings dissolved from the ash surfaces within 10 minutes. In the lung, this would imply dissolution into lung lining fluid, prior to cellular uptake.

The findings of this study advance the understanding of the overall hazard posed by volcanic ash through consideration of aspects of in-plume processing on ash toxicity.

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S03.05 - Protected Volcanic Landscapes and their Geo-cultural Heritage Opportunities for education, management, and scientific research

Archaeotrekking in the excavations of the Roman Villas of Stabiae (Campania, Southern Italy): a multidisciplinary volcanological and archeological approach towards the Plinian 79 AD Somma-Vesuvius eruption understanding

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A multidisciplinary scientific event was organized by the authors on October 21, 2017, for the Fifth Edition of 'The Week of Planet Earth', with the purpose of promoting a valuable and not well known archaeological site, excavations of the Stabiae Roman Villas (Campania, Southern Italy), and through this site, improving comprehension of the Plinian 79 AD Somma-Vesuvius eruption.

The event consisted in three phases, where earth scientists and archaeologist worked together, both explaining and taking people to the field.

The archaeotrekking began with a meeting on the eruptive history of Vesuvius and its effects on the territory, man, and on the Roman cities destroyed by the 79 AD eruption. The conference was conceived for understanding the complexity of Vesuvius activity, through traces of its eruptions visible in archaeological excavations of the buried cities, like Stabiae.

The second phase took place in the Stabiae excavations, which played a strategic role since the eighth century BC, and until the 79 AD Vesuvius eruption; in Stabiae numerous villae were in a wonderful position, designed for residential purposes, with porticos and nymphaeum beautifully decorated. We visited three 'villae' not yet fully investigated: 'Villa
S. Marco', one of the largest Roman villas; 'Villa Arianna', the most ancient; the 'Second complex' of the Varano hill. At the end, we moved to a valuable exhibition hosted in the Royal Palace of Quisisana and named 'From Dark to Light. The exibition presented excellent finds from both the rustic villas and from the luxurious domus built on the hill of Varano, explored and buried again in the eighteenth century.

Finally, we believe that similar scientific events represent unique opportunity to enrich knowledge about our Roman towns like Stabiae, but also to stimulate the awareness of the active volcanic area in which people participating to the archaeotrekking live.

S03.05 Talk

Cultural Ecological Knowledge in Governing a Volcanic River Basin. Case of Opak Sub-Basin originated at Mt. Merapi, Yogyakarta.

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The cultural ecological knowledge (CEK) is defined as all forms of knowledge (in/tangible) in the human-nature relationship passed down through generations, either written or orally transmitted. Meanwhile, the volcanic river basin (VRB) is a catchment originated at an active volcano.

This study uses the Opak Sub-Basin, Post-2010 Mt. Merapi eruption as the baseline case study. The focus of this paper is to answer: “What types of CEK existed and utilized in a VRB management?” The theoretical framework connects the concepts of CEK to the water-lahar- volcano management. This research uses the qualitative methodology, purposive sampling with 57 in-depth interviews within two fieldwork observations. The data are coded using the Atlas.ti with axial codes based on the indicators from the theoretical framework.

The results explain that the CEK exists at three levels of governance: policy setting, managerial context, and interaction attempts. In each level, the national, regional and municipal hierarchies are also taking place.

The managerial context is divided into VRB management styles: Normal (no volcanic activities), Eruption (onset volcanic activities), and Normal+ (no volcanic activities, lahar sedimentation, sand mining). The findings indicate all types of CEKs can be found in each style, mostly utilized in Normal and Eruption, but not being heeded in Normal+. Meanwhile, for the interaction attempts: the Normal and Normal+ are clustered together and themed as ‘general development’ and ‘water’, while the Eruption as ‘disaster’ attempts. In the last two attempts, where boundary spanning activities exist between CEK and the governance in informal attempts, this resulted in a higher integration of sectors.

The study indicates boundary spanning activities as the process for CEK utilized in the multi-levels of VRB governance. It also shares the experience of rediscovering CEK in a VRB to improve resiliency in a developing country, which can be used in other similar cases.

The Global Volcanic Estate: Conserving the world's volcanic landscapes

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Volcanic landscapes are among the most recognizable protected areas of the World Heritage Program, the Man in the Biosphere program, and the UNESCO Global Geopark Network. These landscapes are identified for their geological, biological, and cultural values to communities and societies across every continent. Despite global recognition for these landscapes, important questions remain. Are the world's most significant and important volcanic landscapes recognized and properly protected? What are the challenges in the management of volcanic world heritage properties in the future? Are the various regions of the globe properly represented in these programs?

To address these questions, the International Union for the Conservation of Nature (IUCN) has undertaken a revision of its *Volcano Thematic Study on World Heritage Volcanoes* to examine not only World Heritage properties, but also properties in the Man in the Biosphere program as well as in the UNESCO Global Geopark Network. Preliminary evaluation of the properties through May 2018 show that for World Heritage sites, 80 of 1073 (7.4%) have volcanic features; for Biosphere Reserves, 58 of 669 (8.7%) have volcanic features; and for UNESCO Global Geoparks, 35 of 140 (25%) have volcanic features.

We have identified significant gaps in the inclusion of volcanic sites in the World Heritage list where, of the 80 volcanic sites, only 27 are inscribed for outstanding universal value for their geological attributes under criterion viii (the geological criterion). This is not surprising as in addition to their geoscience story, volcanoes provide one on Nature's most dynamic stages which have their expressions in the great biodiversity found in volcanic landscapes, the cultural connections between people and their environment, and as a record of human developments.

Andean cosmovision and volcanism in Colombia

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The Andean cosmogony strongly underlies the culture of the *peasants* and indigenous people of Colombia, South America, including those occupying the active volcanic regions. The local knowledge contains remarkable information on the social behavior developed throughout millennia to co-exist with natural phenomena, including volcanism. This knowledge emerges from their daily activities and cultural practices in their vital environment, and has been transmitted and preserved through oral tradition. Without political and academic will to embrace such knowledge, communication breakdowns between agencies responsible for volcanic risk management and local communities will persist.

In the Colombian Andes, it is crucial to understand concepts that describe the "quality" of nature, such as (i) "the hot", (ii) "the cold", (iii) "the tamed", and (iv) "the angry". Through cultural practices, including agriculture, human beings have tamed much of the earth's surface, while the natural components that cannot be controlled by humans are referred as "the world of the angry". The world of the tamed contains little energy, it is cold, and releases heat. The world of the angry is charged with energy, is hot, and it takes energy. According to the Andean vision, the energetic gradient existing between the angry and the tamed allows the flow of vital energy. Hence, both are essential to life. Volcanoes communicate both worlds, and therefore, must remain free of human intervention.

In this context, and excluding the circumstances of forced displacement in Colombia, the local knowledge has resulted in a particular way of inhabiting the territory. For example, to consider vents and proximal areas as sacred has intended to protect biodiversity and water resources, and simultaneously, to restrict the access to dangerous areas. Understanding such approaches would help stakeholders to be able to design participative strategies of more efficient and effective volcanic-risk management with local communities.

S03.05 Poster

Ruiz Volcanic Geopark project, a strategy of social appropiation of geoscientific knowledge and volcanic risk management

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The technical cooperation offered by the government of Japan to Colombia through “JICA” has allowed Colombian volcanologists to participate in the program, “Prevention and management of volcanic disasters for the countries of Central and South America”. Among the most significant findings is that lessons of the eruption of the Nevado del Ruiz volcano on November 13, 1985 and the resulting Armero disaster can advance prevention strategies in Japan. Lessons from past eruptions are highlighted to help prepare for future eruptions. These lessons include the importance of preventative education by utilizing and preserving the ruins of eruptive disasters, the importance of visiting, enjoying and learning from active volcanoes, and the importance of generating trusting relationships between the volcanologists, the public, and authorities of the territory. Motivated by what we observed in the Toya-Usu UNESCO Global Geopark in Japan and with a goal to multiply the knowledge acquired in Japan for the benefit of the country, we proposed that the Nevado del Ruiz volcano as the first Geopark in Colombia. This park would have the great responsibility to spread the lessons from the 1985 diasater to the country and the world. The project is a regional integration strategy that seeks socio-economic and sustainable development through conservation of geological, cultural and natural heritage. The proposed polygon has an extent of 2287 km^2, includes 4 Departments (Caldas, Tolima, Risaralda and Quindío), and represents a typical volcanic environment that will favor learning about science, nature, history and culture. Socio-economic and cultural development projects will be carried out at a local level, following the principles of geo-conservation, geotourism and geo-education. The Ruiz Volcanic Geopark will contribute to the knowledge of the territory and the social appropriation and management of volcanic risk.

The Vesuvius Observatory, an invaluable scientific, historical and naturalistic geosite in the framework of the most famous volcano in the world

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The Vesuvius Observatory is the first volcanological observatory in the world. Since its foundation in 1841 and thanks to the approval of King Ferdinand II of Bourbon, in this site began the systematic study of Vesuvius and its eruptive activity.

The Observatory site must be considered among the most representative geosites of the Vesuvius surroundings, due to the geological setting of the area and its historical and scientific value.

In the nineteenth century volcanologists based much of their research on the direct observation of the volcanoes, so it was decided to found the Observatory not far from the Vesuvius crater. The choice could seem hazardous, but actually it never was. In fact at that time the Vesuvius activity was only characterized by effusive or low-energy explosive eruptions, and the site was always only lapped by lava flows, as reported in the first volcanological map of Vesuvius, by Johnston Lavis (1888).

Names of distinguished scientists, who have dedicated their entire lives to the study of the volcano, are the flagship of the Vesuvius Observatory since its foundation. Many of them have directed it, thus linking their name to this site as well as to important discoveries in both volcanological and seismological fields.

At present the historical site of the Vesuvius Observatory hosts a permanent exhibition, in which collections of great scientific, artistic and cultural value - unique for their abundance and variety - tells the story of this institution. The exhibition also introduces the visitors to volcanism and related hazards, the forecasting of volcanic eruptions and the monitoring systems of active volcanoes, proposing itself as an invaluable instrument of risk mitigation, by increasing the population awareness about the threat posed by these volcanoes and generating the conditions for a correct land-planning and management, and a sustainable development of the territory.

Towards the Vesuvius Geopark:
a unique jurney throughout a living natural history museum

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Vesuvius is unique in the world for many aspects, ranging from geology to volcanology, natural sciences and archeology. It includes contexts in which all these disciplines show peculiar aspects even in a single site. It is the place where the modern studies of volcanology begun, leading in 1841 to the foundation of the Vesuvius Observatory, the oldest volcanological observatory in the World.

Vesuvius exhibits a wide range of eruption styles that spans from effusive to Plinian eruptions, which produced disastrous effects on the communities that over time inhabited the surrounding areas.

The oldest traces of human settlements date back to the Neolithic times, while the most recent were covered by the 1944 eruption deposits. The most famous archaeological remnants are by far those buried by the deposits of the AD 79 eruption of Pompeii.

However, not less important are the traces of many past eruptions over ancient plowed fields, prehistoric villages and small rural villages in the Campania plain. All the past traces of life have been sealed repeatedly by eruptions through time, and the stratigraphic record still retains all evidence of both environmental and human resilience.

It is mandatory for us to make this important patrimony accessible to everybody, respecting its high level of fragility, typical of a geologically “young” territory.

Presently, despite the very large number of tourists and scientists that visit this volcano and its National Park, only a limited number of sites of great geologic, naturalistic and cultural interest is accessible.

One of the main goals of the Vesuvius National Park, acting together with the INGV, is to promote a series of educational and outreach activities aimed at a full and compatible fruition of the park environment as a whole, creating the background for the candidacy of this territory to the European and global network of geoparks.

S03.05 Poster

Geoheritage in protected volcanic landscapes in Tenerife, Canary Islands, Spain

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Tenerife constitutes the largest (2034 km^2) and highest (3718 m a.s.l.) island of the Canary Islands Archipelago, Spain. It has been built up as a result of the accumulation of different volcanic materials during a period of time > 12 million years. The aim of this abstract is to communicate a study of the geoheritage in protected volcanic landscapes in Tenerife (PVL). The methodology is based on field work and calculations of volcanic geoheritage based on the identification of geomorphosites according to Serrano and Trueba (2006), and to compute for each their scientific and cultural values, as well as use and management values. Tenerife has forty-three protected volcanic landscapes that consist over 48% of the surface of the island. On the Island, there is one National Park (Las Cañadas del Teide), ten Natural Reserves, one Natural Park (Corona Forestal), two Rural Parks (Anaga and Teno), fourteen Natural Monuments, nine Protected Landscapes and six Sites of scientific interest. The main volcanic geoheritage in the protected landcapes of Tenerife are: volcanic shields (Anaga and Teno massifs), Las Cañadas caldera, two stratovolcanoes (Teide and Pico Viejo), 297 cinder or scoria cones, lava fields (pahoehoe, aa and blocks), petrificated lava lakes, lava tubes (e.g. Cueva del Viento) ravines, cliffs, alluvial and colluvial deposits and black beaches. In general, the index of geoheritage for PVL of the island shows scientific values lower than the cultural values. Only in concrete cases scientific values are over the cultural values (e.g. Teide and Pico Viejo stratovolcanoes). These data imply that the geodiversity and volcanic geoheritage of the protected volcanic landscapes of Tenerife are the opportunities for education, management, and scientific research.

S03.05 Talk

Volcanic geoheritage values of Bodrum peninsula, Muğla, Turkey

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Bodrum (Halicarnassos in ancient times) is a well-known touristic destination for its cultural and archeological values such as the amphitheater and resting on blocks of the famous Mausoleum, the medieval castle (on the UNESCO World heritage tentative list) hosting the Museum of Underwater Archeology, the antique cities of Pedasa, Aspat (Strobilos), Myndos, or the more modern windmills. Therefore, Bodrum attracts thousands of tourists annually. Bodrum also represents the remnants of an Upper Miocene caldera volcanism with block and ash flows from domes, welded and non-welded ignimbrites (namely Kale and Akvaryum ignimbrites) that form spectacular pyroclastic series, columnar jointed trachybasaltic flows, numerous ultrapotassic and trachytic dykes cutting through the volcanic sequence, monzonitic intrusions and related hydrothermal alteration in places.

In addition to this older in-situ volcanism situated adjacent to the easternmost tip of the South Aegean Active Volcanic Arc, distal deposits of the Kos-Nisyros-Yali volcanic system (namely the rhyolitic Kos Plateau tuff, 161ka) can be observed in several locations on the Bodrum peninsula. We plan to advertise these volcanic features as info-boards along the hiking trails and also mobile applications throughout the region to add an extra geotourism value to an already touristic and well-known destination.

A geopark for the Somma Vesuvius volcanic complex as a synthesis between conservation of nature and a sustainable development model

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Vesuvian area presents an exceptional geological and naturalistic value, and it is precisely because of this value that a large part of it, with the D.P.R. of June 5, 1995, became a protected area pursuant to Law No. 319/91.

Somma-Vesuvius complex is one of the most studied volcanoes of the World, not only for what concerns the strictly volcanological aspects, for which it represented and represents the cradle of this discipline, but also for the related naturalistic aspects. The main botanical and zoological aspects of the Park's biodiversity, without rhetoric, can be considered a treasure of inestimable biological treasures, embellished by the characteristic volcanic environment and by the historical and anthropological framework that makes it an extraordinary unique for the entire planet.

The immense cultural value of Vesuvius is dominated by the presence of archaeological sites of international importance which annually record a considerable number of tourists (Pompeii over 2,000,000, Herculaneum 300,000 and the Gran Cono 650,000), of historical villages and agglomerates of "Villae", of "Masserie" and of minor historical-architectural edifices that cover a high symbolic and ritual value, as constitutive elements of Vesuvian identity.

Vesuvius National Park Authority has the protection and conservation of environmental and landscape values, as well as their promotion and enhancement, including research activities. The main aim is the development of geological knowledge that combines environmental conservation with the fruition of land and of an irreproducible geological heritage.
In this context, the Park Authority has initiated a scientific collaboration with INGV-OV in order to structure a path that should lead to the nomination of this volcano in the European and global network of Geoparks. In this context tourism could become the driving force of the Vesuvian economy, capable of triggering a process of development that reverses the current trend towards degradation and madcap exploitation of the territory.

S03.05 Poster

Campo de Calatrava European Volcanoes' Night as a didactic experience for children

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Campo de Calatrava is a volcanic region belonging to European Intraplate Volcanism. From 2014 to 2017, on the initiative of the research group of Castilla-La Mancha University, "Geomorphology, Territory and Landscape in Volcanic Regions" GEOVOL, four editions of European Volcanoes Night have been developed. This activity takes place in European cities on last Friday of September, coinciding with the European Night of the Researchers, aims to unite science, geotourism and didactic activities, aimed to introducing primary and secondary students to the world of volcanology and learn to know, respect and protect its landscape. In short: encouraging scientific divulgation and learning in a festive atmosphere. Throughout these four years most of the localities that in the region have a volcano in their territory, have been involved in the volcanic related activities. These activities have directly involved more than 2,500 schoolchildren accompanied by their teachers and thousands of adult inhabitants of such cities and towns. The activities developed have ranged from scientific-informative lectures, routes along the emblematic volcanoes of the region and musealized spaces, to activities in the classroom: competitions of drawing, painting and photography about volcanoes, their meaning and their landscape, documentary screenings and discussions with scientists. The positive result of this experience, which has the financial and logistical support of the local and provincial administrations, becomes clear when each edition exceeds the number of locations, schools, students and inhabitants linked to the proposed programs. The knowledge of the volcanic territory and its assessment constitutes the main objective proposed and achieved. The society has understood that the beauty of the landscape does not lie exclusively in its grandeur but in its peculiarity, and in our case this new conception is implying an awareness and an institutional support to the request of the geopark figure for the Campo de Calatrava.

S03.05 Poster

The cultural and geoheritage of Chaiten, Patagonian Chile

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In May 2008, the Chaiten volcano erupted, prompting the largest evacuation in Chile's history. Resettlement of the town is still ongoing. The Chaiten municipality is trying to protect a complex of rock art filled caves as well as use them as a draw for tourism. As part of a transdisciplinary project to examine the caves, our team created a geoheritage site inventory for tourist maps and municipal conservation of the larger volcanic landscape and additional sites that merit protection. A cultural foundation, ProCultura, is currently building a site museum within an area of destroyed/conserved houses that is intended to commemorate the volcanic disaster and disseminate information about the volcano. Our data and interpretations will be housed there. New houses are under construction now alongside the conserved houses and museum, making a striking visual image of community resilience but also vulnerability to future disaster events. We seek to share the work we've done and invite comment and suggestions for the ongoing project.

S03.05 Talk

Geology makes the World go round!

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As Richard Fortey wrote: “ Geology underlies everything, landscapes, agriculture, character of villages and it is such a collective unconscious of the World…” Well, this is clearly undeniable for Vesuvio and its surrounding area, a protected one since 1995.

The Association “Scintille”, founded by Official Guides of Vesuvio National Park, geologist and Science Communicators, since many years works to improve the knowledge of Vesuvio geological and natural features and, above all, to make clearer the relationship between the volcano, our culture and our everyday life too.

For this purpose the Association Scintille organizes different activities on field, such as original path through Volcanic features of the last lava flows and the oldest Vesuvian winery (Walk and Wine) or special trail through Geology and History (Walking with Kings and Queens) , but also scholar activities and kids lab about Neapolitan Volcanoes in which their Volcanological history is retraced from their actual shape. Further ore some considerations are suggested about vernacular and Volcanological terms: Lava, for example!

A special activity is about “Urban Geology” in which is possible to discover the geological roots of houses streets and monuments.

Volcanic geoheritage of the SW Pacific: key for sustainable development programs associated with indigenous knowledge

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The SW Pacific is the home of many Quaternary volcanoes, most of which have associated rich oral traditions, legends, cultural practices and textbook type geological features. Many of the SW Pacific's volcanic islands have great geodiversity in spite of the limited landmasses they represent. Geodiversity in most of these islands is linked to the volcanic geoheritage of the islands, where well exposed and accessible geosites are abundant. The geoheritage aspects of many of the SW Pacific's volcanic islands are underutilized due to either the limited information accessible for the local communities or the lack of coherent research programs to develop geosite inventories. The economy of the SW Pacific volcanic islands is generally based on subsidence agriculture, strong links to diaspora work in developed countries and a growing sector of tourism. The tourism sector is particularly advanced in Fiji, Samoa and Vanuatu; however, there is very limited visible attempts even in these countries to utilize their geoheritage values to promote geotourism. On a global scale, there is a clear trend towards developing geopark projects to harvest geoheritage information in order to develop sustainable geotourism that can be a catalyst for local economic growth; however, the concept of geoheritage sites is not well developed in the SW Pacific. A partial explanation behind this situation is that there is a rift between traditional (indigenous) knowledge and western scientific knowledge, and an absence of successful frameworks to run such geoheritage programs. Geoheritage reflects the heritage component of a geological site and is reflected through the cultural activity around it. Geopark projects, such as the Samoa Geopark Project, can be triggered through workshops mixing traditional and western knowledge. Geoparks can also be part of a broader geoconservation-geopark strategy of the region and therefore can be designed together with local NGOs and Government Offices.

S03.05 Talk

A GIS-based evaluation method of geoheritage resources in the Auckland Volcanic Field

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The study area, located in urban Auckland, New Zealand, have been the scene of a series of eruptions as result of coastal intracontinental volcanism. At least 53 eruption centre form a distinguished volcanic landscape composed of scoria cones, maar craters, tuff cones, tuff rings, lava flows and lava caves. The case of assigning heritage status to the most representative sites of the Auckland Volcanic Field has been proposed recently expressing the outstanding universal value of the relationship between the features of the diverse monogenetic volcanic field and the Maori cultural landscape. Due to the ever increasing number of volcanic heritage nomination, the evaluation system used needs to be advanced further to signify the rich and diverse geoheritage the volcanic landscape possesses. The issue that is first addressed by the study lies in the nature of geoheritage assessment that involves multiple objectives along with constraints on what combinations of those objectives are attainable. The main aim of this work is to carry out the evaluation of the study area with the advantage of geographic information system (GIS) tools for a multi-objective spatial analysis. Application of geostatistic models (e.g. Multi-Criteria Decision Analysis) in GIS creates an objective, multidimensional and dynamic map for a heightened viewpoint of analysis from more possible perspectives, assuring the most adequate criterion assigned to the studied volcanic features. The combination and harmonization of landscape and social information models and scientific value related static data plotted on one map drives better insights and inevitably better decision-makings by all stakeholders. The assessment could serve as a guideline for sustainable planning and management where GIS platform provides the public administration with interfacing and sharing of data and an effortless incorporation of geoconservation tasks in the public agenda.

Nominating a tectonic landscape on the World Heritage List, what teachings?

Cecile Olive-Garcia

Local Council of the Puy-de-Dome, World Heritage department, Clermont-Ferrand, France

After a 11 year experience in setting up and defending a UNESCO World Heritage geological nomination, this presentation aims to give an empirical feedback and analysis of this international process and the differential use of science, aesthetic perception and politics. At the time of the conference, a final decision will have been adopted by the World heritage Committee after three submissions by the French State: 2014, 2016 and 2018. The last attempt was based on new protocols tested with the international bodies in order to improve the technical dialogue, accountability and understanding between the different parties. These are the French State, the local stakeholders, the IUCN, the scientific community, and UNESCO itself. Our proposal was the Chaîne des Puys - Limagne fault tectonic arena, which illustrates a complete rifting process through its different morphologies. The project's essence was a conjunction of inseparable geological processes, underpinned by continental rifting. We had proposed a combined approach, where a property is seen in its entirety, and the constituent features seen as interlinked elements reflecting the joint underlying phenomena. While scientific assessment methods are developing rapidly, our challenge was to find the right balance between sound science and World Heritage language, being able to determine what this concept of heritage refers to in terms of geological features and values in a context of reinforced requirements. It also tackles the question of how to boost the links and dialog between geological organizations and the heritage and nature conservation bodies.

Enhancing social resilience through the fruition of geological heritage in the Vesuvio National Park

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Cultural heritage highly contributes to social resilience, providing communities with a sense of belonging to the place that can improve the response of citizens to adverse natural events, positively influence city creativity, innovation and vitality of the entrepreneurial environment, indirectly enhancing the economy. Geoheritage, which consists of both geomorphological and geological components, with other types of natural heritage has been recently integrated in the cultural heritage considering that landforms or geological features through a perceptual process can deservedly become heritage elements. The Vesuvio National Park, established in June 1995, is the green area closest to Napoli megacity that suffers absence of urban green spaces, and could hence offer to inhabitants the opportunity to enjoy the peculiar geoheritage represented by the landscape of an active volcano. We here propose two trails with several stops, named the Ancient Railway Track and the Valle dell' Inferno Trail. They start from two opposite sectors of Somma-Vesuvius, namely from the Southern (Ottaviano town) and the north-western side (San Sebastiano al Vesuvio town) and are both directed towards the Gran Cono. Along both trails the visitors can enjoy several volcanic forms and products (the Somma caldera rim, dykes, lava domes, ropy lava flows, pyroclastic fall deposits) together with historical remains, as the Cook Railway track, and natural features, as the Mediterranean bush typical botanic association. The stops were illustrated by panels describing in detail both geological and landscape characteristics with pictures and simple text boxes, clear and engaging for a wide set of visitors of different age and cultural background. We evaluated the contribution of the project of popularization and fruition of green spaces in an active volcanic area here proposed to promote healthy living and wellbeing, at the ultimate aim of achieving a better level of resilience for society in a high volcanic risk area.

S03.05 Talk

Which eruption did see Cristobal Colón in Tenerife (Canary, Spain)?

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The very first written references about volcanic activity in Tenerife island comes from the period before the conquest of the island, in 1497 (Alonso de Plasencia 1490-91, Cristóbal Colón 1492 and Andrés de Bernáldez 1495). On August 24 1492, when Cristóbal Colón was travelling from La Gomera to Gran Canaria, and was passing by the Island of Tenerife, he indicated "*…y pasó aquella noche cerca de Tenerife, de cuya cumbre… se veían salir grandísimas llamaradas... explicó el fundamento y la causa de tal fuego, aduciendo al respecto el ejemplo del monte Etna en Sicilia…*". Absolute dating with ^{14}C of volcanic lavas in Boca Cangrejo volcano with age between 1430 and 1660 AD, has led Carracedo *et al*., (2007) to point out that this volcano is the one that Colón observed. There is a chronicle from 1779-1780 that mentions the existence of an eruption produced after the conquest and refers to Boca Cangrejo volcano (Romero *et al*., 2009). This fact convers this eruption in the first historic eruption of Tenerife but, obviously posterior to the one that Cristobal Colón has seen. The cinder cone Boca Cangrejo is a volcanic protected landscape and is an excellent example of the Canarian forests' colonization after suffering a volcanic eruption in leeward sides of Tenerife. The monogenetic volcano possesses great value for geoturistic interests, as the first historic eruption of Tenerife, and localized within 4 km of the eruptions of 1706 and 1909. To this we must add the diversity of landscapes created by extended lava flows that expands from 1500 m of altitude, with open pinewood forest until almost the coast with xeric scrubs. The volcanic and geo-cultural heritage of Boca Cangrejo cinder cone possess high educative values and creates a place with opportunities for management, scientific research and geoturism.

S03.05 Poster

The (Dark) Geocultural Heritage of Volcanoes

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Volcanologists are increasingly including social scientific methods in their research, especially when the aim is to not only understand the physical characteristics of a volcanic system, but to reduce the vulnerability of people living at risk (Donovan, 2010; Barclay *et al*., 2015). Donovan (2010), for instance, reflects on how to 'do social volcanology' and it has been argued that understanding the culture of populations at risk is crucial for reducing vulnerability (Mercer *et al*., 2012). This argument has subsequently extended to include past volcanism and how it articulates with historical and archaeological understandings of culture, i.e. geocultural heritage (Riede, 2015). Notably, in cultural heritage research, it is well established that people draw a great deal of individual and collective identity from their past (e.g. Sommer, 2000) – and, importantly, this identity construction also motivates action. Based on field and archival work, we here develop the geocultural notion of 'co-volcanic' societies where people co-exist (more or less sustainably) with nearby volcanoes. We extend this perspective into the deep past by conducting three comparative case studies: La Soufrière/Soufrière Hills (Lesser Antilles), Vesuvius (Italy), and the Laacher See (Germany). Each of these volcanoes represents a major threat, but the ways in which they articulate with their surrounding communities are very different. In bringing together historical/social volcanology and geoheritage, we bring ideas from cultural heritage studies – especially dark heritage and dark tourism (McAtackney, 2014; Strange and Kempa, 2003) – into play to explore how the combination of cultural and geological histories can provide an improved platform for outreach, sustainable and safe tourism, and for disaster risk reduction.

Prepardness and recovery of local communities following the 2012 eruption of Mount Tongariro situated in the dual World Heritage Tongariro National Park

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Ngāti Tūwharetoa have resided at the foot of their sacred mountain Tongariro since their eponymous ancestor Ngatoroirangi first ascended the volcanoes 30 generations ago. Their cultural framework is interwoven with deep admiration for the natural world, where historic events such as eruptions are revered. That deep sense of attachment to nature can be tested when volcanic unrest is detected and the need to ensure safety becomes paramount. After the increased activity of Te Maari Crater was identified in July 2012, Ngāti Tūwharetoa became closely involved in management. The safety of local families and hikers on the popular Tongariro Alpine Crossing nearby were priorities.

Here we review the development of an effective messaging system established with scientists, governmental authorities, police, fire services, power companies and transport agencies. We discuss the effectiveness of a preparedness plan instigated by locals in late July outlining how they would cope with an eruption whereby they would need to prioritise the needs of the most vulnerable. This plan included the management of water supplies, animals and safety of homes.

On August 6 2012, a debris avalanche preceded a phreatic eruption with PDCs and fallout. The eruption was witnessed by locals who raised the initial alarm. Their plan to self- evacuate the vulnerable to a nearby Marae was instigated while the remaining people kept in close contact with neighbours until the morning. Recovery began two days later. Locals were involved with clean-up and in important roles with the Crossing, local agencies and scientific work. Cultural protocols were invoked to minimise impacts and help ensure the safety public. These included a Rahui and installation of an early warning system. Other hazards included respiratory issues, stock welfare, equipment corrosion and protection of water supplies with beneficial soil nutrition effects recognised as early as one year after the eruption.

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S03.06 - Volcanoes and Human History

Conflicting accounts of the 1902 VEI 6 eruption of Santa María volcano, Guatemala; an investigation into how natural, social and political factors impacted the validity of eruption reporting

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Few large volcanic eruptions have occurred in recent history; those with eyewitness accounts provide vital case studies that enhance our understanding of large events. Here we examine accounts from the 24th October eruption of Santa María volcano, Guatemala, in 1902. Although it was one of the largest eruptions of the 20th century, few studies have examined accounts of the eruption and its impacts. 1902 had abnormally high rates of seismicity and volcanism in Central America. Significant earthquakes in January, April and September along with volcanic eruptions in May (La Soufrière, St. Vincent; Mount Pelée, Martinique) and October (Santa María) caused numerous fatalities and widespread damage. The devastation caused by the eruption of Mount Pelée, however, has dominated studies of the volcanic events of this year.

Here we use contemporary accounts from Guatemala to assess communication about the Santa María eruption within and outside of the country. First, the response to the event was complicated by a damaging *Ms* 7.5 earthquake in April. Second, the timing of the eruption – after the earthquake and during a national festival – led to a cover-up whereby the president Estrada Cabrera and his government attempted to minimise the reporting of the eruption. For example, telegrams issued by the government declared that the damage was minimal and that there were no fatalities. In contrast, newspapers, scientific articles and eyewitness testimonies provide numerous reports of significant devastation in Guatemala caused by the eruption. We approach these contrasting reports, in particular, using the daily record provided by the Guatemalan newspaper '*Diario de Centro-América'* and accounts from elsewhere in the region. Compiling a corroborated account of the eruption and its impacts will provide an insight into how social factors in general, and "fake news", specifically, can influence our understanding of large magnitude volcanic eruptions.

“We used to grow more crops here; now we can only grow pineapples and dragon fruit”: historical evidence for impacts of persistent volcanic degassing from Masaya volcano in Nicaragua

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Masaya volcano in Nicaragua is a long-term source of persistent gas emissions evidenced by written records dating back to the 16th century. Through research of historical archives (from mid-19th century onwards) and oral interviews with the local communities we investigated how people perceived the threat from volcanic gases and what steps were taken to avoid or minimise their impact.

Documents demonstrate that the current problems faced by the local communities have deep historical roots: documents from the Somoza-era refer to the poverty of these communities, a result of two key burdens: first, inadequate access to water, and second, the impact of the volcano’s gases. There is substantial evidence for the impact of Masaya’s emissions on agriculture, with much preoccupation on coffee. In the late 1920s a special tax was levied to pay for (highly innovative) schemes to stop the volcano’s emissions. The impact on the economy from coffee loss was such that President Somoza advocated dropping a bomb into the Masaya volcano in order to seal it up. In comparison, health impacts do not appear to be an area of concern for the authorities.

We also found evidence of local initiatives to combat the negative effect of volcanic gases on agriculture. In the 1970s local farmers began collecting wild-growing pitahaya (dragon fruit) from close to the volcano’s crater. These plants, and their descendants, were particularly well-suited to local conditions, and helped to develop the local pitahaya industry. Similarly, farmers began experimenting in the 1990s with ‘living filters’, using resilient plants to shield coffee.

We demonstrate that the local, seemingly simple, initiatives have in many cases been more successful than ‘parachuting-in’ of experts. Even in challenging conditions, some crops thrive well on the volcano and these naturally resilient crops are an exciting area for future research.

Physical impacts of the AD 1600 Huaynaputina VEI 6 eruption on habitat and infrastructure, southern Perù: Geophysical insights from the Huayruro project

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The Huayruro project aims at better understanding the physical and socio-economic impacts of the CE 1600 Plinian eruption of Huaynaputina in south Peru (VEI 6, 11-14 km^3). Despite its global climatic impact, its regional consequences on the Inca population and constructions have been scarcely studied. In particular, the location of ten to fifteen settlements buried by the erupted deposits is not accurately known. Finizola et al. (2018) identified several buried settlements and ruins during several archeological and geophysical surveys during the 2014-2017 period within a 16 km radius of the crater (Coporaque, Calicanto, and Chimpapampa). Extending their work in May 2018, we used ground- penetrating radar at 400 et 200 MHz, magnetic gradiometry, multi-frequency conductivimetry and Structure from Motion (SfM) photogrammetry with multi-view stereo to further explore the sites of Coporaque (12 km WSW of the crater), Estagagache (16 km SSE) and San Juan de Dios (17 km SW), affected by fallout deposits 2.6, 1.5 and 0.4 m thick, respectively.

The present study provides spatial constraints for mapping buried house walls, cultivated terraces, rural infrastructure such as grain storage areas, contributing therefore to delineate the extent of the damaged villages. Such geophysical surveys combined with aerial imagery, high-spatial resolution DEMs and tephra studies help to focus on adequate sites for future archeological excavations and assess physical impacts of thick tephras and PDCs deposits on pre-Conquest constructions. The ultimate goal of the Huayruro project is to disseminate volcanic risk knowledge and help create one in situ museum to be built up on the site of Calicanto.

Study of Local knowledge from experience and individual responses during Mayon Volcano eruptions: A Phenomenological Approach

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In this study, the focus is on the value of Mayon Volcano eruption stories as far back as 1968 as told by eyewitnesses, to gain in-depth understanding of shared lived experiences. In phenomenological approach, meanings of events are deduced from the eyewitnesses' descriptions. Eruptions are characterized from the point of view of those who had first-hand experience of the events. In the stories shared, the three dimensions of the eyewitnesses' views of their eruption experiences- as seen, as heard and as felt were used. Through the years, eyewitnesses have developed shared meanings of the Mayon Volcano eruptive events that took place. The eyewitnesses have shared meaning structures and view eruptions as gradational. This gradational view of eruption characteristics provides patterns to the way individuals behaved when faced with volcanic events and when translated into action, contributed to decision-making of whether to evacuate or not.

S03.06 Poster

THE ANGER OF GODS.
Mt. Cameroon traditional beliefs among Bakweri and Bakossi ethnic groups

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The case of the Mt Cameroon communities is very explanatory for the perfect symbiosis with animistic deities and the complexity of those cultural mechanisms that lead to risk mitigation through paths based on the intangible economy.
The strong interaction between the ancient traditions and the dynamic capability for self- repair to cope with hazards belongs to a deep knowledge of their cognitive space.
In Buea and surroundings, two different layers of social resilience are applied in case of disaster: the current government law application by the Cameroon Civil Protection (MINATD) and the local mythology, psychologically more efficient among those communities traditionally based.
From 2009 to 2011, within the FP7 MIA-VITA [Mitigate and assess risk from volcanic impact on terrain and human activities] project we have tried to focus the multidisciplinary aspects of volcanic threat assessment and management from prevention to crisis management recovery.
The ethno-anthropological information belonging to Bakweri and Bakossi ethnic groups were analyzed to focus the cultural interaction between Mt. Cameroon and its residents.
One of the outstanding results from the study was the cultural beliefs that supernatural forces, as the god of the Mountain called Epasamoto and the god of the sea called Nyangonamuna, play a great role in the causation and controlling of natural hazards.
Since the social group is always in debt to the gods, because of its deceptive behavior, it must remedy calming the wrath of the gods by offerings and rites.
These propitiatory rites are managed by the “Paramount Chief” and few selected representatives of the communities involved in the practice, whose rituals are dedicated to keeping under control the Genius Loci negative reactions.

The present work will examine in detail the influence of these supernatural forces in the perception of risk and its prevention in the region.

S03.06 Talk

Lateral facies variations in the 79 AD deposits at Pompeii

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The 79 AD eruption destroyed Pompeii and buried the town under almost six metres of pyroclastic materials. Pompeii was excavated in the last 270 years and most of the volcanic material was removed without any geological descriptions. For this reason, most of the recent (last 30 years) illustrations of the tephra succession refer to outcrops located outside the town walls. Almost one-third of the Pompeii area is still unexcavated. The boundary between excavated and unexcavated areas cut throughout the town and a 2.5 km thick front looms over the unburied buildings. To secure the excavation front a re-profiling of this front with gentle slopes is in progress. Excavations in the Regio V exposed several new astonishingly well preserved stratigraphic successions of the 79 AD deposits. Most of these logs are ephemeral and last few days to allow archaeologists to exhume roman artefacts. A systematic survey of all exposed pyroclastic sequence allowed us to study in detail the distribution and lateral facies variations of the different 79 AD stratigraphic units. The basal lapilli fall deposit shows a remarkable thickness variation ranging from 2.7 m to 4.5 m. Local overthickening are observed where pumice lapilli rolled on sloping roofs and accumulated in the alleys around the buildings. Even more pronounced lateral variations are observed in the upper part of the sequence, a mainly pyroclastic density current (PDC), stratified ash deposit, that ranges in thickness from few tens of centimetres to two metres. In this case thin, massive ash layers can be traced laterally into thick, poorly sorted, ash and lapilli layers, with well-developed sedimentary structures. Lateral facies distribution of the PDC deposits within Pompeii are influenced by urban structures (e.g. height, direction).

Legends and traditions: Laguna Caliente, Poás Volcano, Costa Rica

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This study compiles known information on the history, legends and traditions regarding Laguna Caliente of Poás volcano. We describe the evolution since the first ascends in the 16th century, until the massive incurrence of touristic activities. We include the exciting "Legend of Rualdo" on a bird that sacrificed its sweet song to save its pretty maiden, who was going to be sacrificed to stop the fury of the volcano. The "Legend of Rualdo" narrates supernatural facts and explains the formation of Laguna Caliente thanks to a pact between a bird and the powerful volcano. Moreover, the origin of the yearly tradition of climbing Poás volcano on March 19th, the day of the patron Saint of San José, is documented. Legends and traditions can be useful tools to decipher past activity of volcanoes, in this case Poás.

It is a mistake to ignore the lessons of the ancestral towns. The historical memory of the different societies is a fundamental tool to possibly reconstruct volcanic activity. We must study this information carefully because behind the legends, myths and traditions it is possible to find useful tracks to understand the behavior of active volcanoes.

S03.06 Poster

New Excavations and Researches: the second life of Pompeii

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The archaeological research started in Pompeii in 2017 in an area in the north-eastern of the city, the regio V, and along the excavation fronts are the privileged field of observation of interactions between archeology and geology: the ability to read synchronically such levels makes the case of Pompeii unique. Currently the reviewing of the most famous Vesuvian eruption passes through a renewed interest for the accurate reconstruction of its phases, the understanding of the eruptive dynamics, the succession of events from 79 AD up to the modern age, finally a detailed analysis of the actions that gradually characterized the area of the Civita, the plateau below which Pompei was hiding.

The discovery of Pompeii took place in 1748, when the Bourbon engineers focused their attention on this deposit, attracted by the highest structures already emerged and were clearly visible from the royal road. The excavations followed the information collected and depended on the availability of the owners of the farms. Removing the few meters of volcanic ash, it proceeded to open air in trenches or with tunnels.

The excavations underway in the regio V not only allow to tell the life of Pompeii before the eruptive event gutted it. They also allow to reconstruct the history of the excavations after the discovery: from the tunnels, the trenches and the deep open-air cables, to the routes beaten by the workers of the late ‘800 and the modern discharges. This phase, which can be placed between the second half of the eighteenth and the beginning of the twentieth century, is closely intertwined with the succession of Vesuvian eruptions, which seal and specify the actions of the first excavators: only a joint reading of the double level, archaeological and geological, can increase the knowledge of the complex history of the site.

Volcanology and Archaeology for Better Understanding the History of Campi Flegrei: Post-NYT Bradyseisms and More Rapid Deformation

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The Campi Flegrei volcanic district includes insular (Ischia and Procida Islands) and peninsular volcanic activity (Campi Flegrei volcanic field) with the link to older activity till Ponza Island. The history of this area has been studied in detail since the eruption of the Campanian Ignimbrite (CI, age: 39 ky BP, volume: 200 - 300 km^3), which makes this one of the most powerful eruptions in Europe. The Neapolitan Yellow Tuff (NYT: age: 15.0 ky BP, volume: 50 km^3) is another powerful eruption occurred. Activity younger than the NYT can be subdivided in three epochs which include 70 recognized ephemeral eruptions. The volume of these individual eruptions is between 0.4 and 1 km3 (DRE). Probably, the long- lasting magma reservoirs (i.e., CI and NYT) represent eruptions that are fed by deep magma reservoirs. In deep reservoirs >10 km), magmas stagnate, differentiate and are probably modified by crustal components (Hercynian basement). The long-lasting reservoirs are also the ones that feed the ephemeral shallow magmatic system (2 - 5 km) that gave rise to the post-caldera magmatic epochs. However, the magmas of the post-caldera epochs are isotopically heterogeneous and made by several components (i.e., least evolved (as an example the Minopoli eruption, 9500 y BP), CI, and NYT components). Mixing between ephemeral shallow reservoirs occurs. Mixing of long lasting reservoirs also occurs; and also during explosive eruptions. The concentration of earthquakes and the deformation history suggest that Campi Flegrei could erupt again with an ephemeral eruption, especially if the uplift will reach 5 - 6 m like Monte Nuovo eruption, given existing uplift of 1970-72 and 1983-84.

PAGES: Pleistocene Archaeology, Geochronology and Environment of the Southern Caucasus

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The Southern Caucasus forms part of a land bridge between Africa and Eurasia and is the location of archaeological sites where the earliest human fossils outside Africa (Dmanisi, Georgia) [1, 2] and the earliest evidence for advanced human behaviour (Nor Geghi 1, Armenia) [3] have been found, transforming understanding of the relationship between the European and African Palaeolithic. However, it is presently unclear what mechanisms drove *Homo* sp. dispersal to geographic regions beyond Africa and how technological innovations (i.e. stone tools) and ecological adaptations developed along the way.

The interdisciplinary PAGES project aims to build a geochronological framework for the Pleistocene of the Southern Caucasus, specifically focussed on the Hrazdan and Debed gorges in Armenia. These areas comprise volcanic deposits and intercalated alluvial, lacustrine and aeolian sediments. Detailed geological mapping, $^{40}Ar/^{39}Ar$ geochronology, tephrochronology and geochemical/ petrological characterization of the volcanic deposits, are hence able to provide a stratigraphic link between archaeological sites in the region. The data are used in conjunction with palaeoenvironmental and climate records from sediments in order to enhance understanding of human habitation and dispersal in the region and to contribute to a high-resolution model of early human evolution.

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Geoarchaeological perspectives on the human impacts of the Laacher See Eruption at some distance

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Using calibrated radiocarbon dates, Bayesian modelling and the exclusive spatial relation between the distal tephra fallout of the Laacher See eruption (~13ka BP) and the Late Pleistocene so-called ‘Bromme culture’ of southern Scandinavia, it has been suggested that the eruption event had a substantial impact on contemporaneous human communities. Loss of life in the proximal area has not been documented and abandonment and migration may have been more pronounced responses. This short paper reviews some of the previous investigations into potential impact mechanisms linking the tephra fall to these archaeologically observed changes with a particular focus on the changing hazards from proximal to distal. In reviewing already known sites in Central Europe with relevant archaeological remains and Laacher See tephra, the hypothesis of Laacher See impact also predicted the abandonment or at least substantial changes in land-use under the north- eastern fallout lobe in the wake of the eruption. I present our current approach for testing this prediction by locating sites containing both Final Palaeolithic archaeology and Laacher See tephra in the region some 150 km north-east of the Laacher See using legacy datasets integrated into a predictive model within a GIS environment. Excavations at four carefully selected sites will be underway at the time of the CoV meeting and I will present our latest finds and results.

Recent excavations at Pompeii: new findings and their volcanological implications

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Detailed descriptions of the effects of Plinian explosive eruptions on urban settlements are rare. For this reason, volcanologists spent considerable time studing the destruction of the roman towns around Vesuvius occurred during the 79 AD eruption. At Pompeii, during the eruption accumulated about three metres of pumice lapilli from the eruptive cloud and successively one to three metres of stratified ash aggraded from pyroclastic currents. Both phases caused hundreds of victims. All reconstructions followed the chronology of Pliny the Younger, who witnessed the eruption and wrote two famous epistulae to the historian Tacitus. In these letters the eruption is described as a continuous event that lasted about nineteen hours. New stratigraphic data collected during recent excavations in the Schola Armaturarum, a famous building located in the central part of the Pompeii archaeological site, seems to contradict the never discussed before continuity of the eruption. Inside this building a large quantity of debris from walls and roofs was found lying through the whole pyroclastic sequence. Roofing tiles were found in the lapilli fall deposits, while east-west trending walls were partly demolished in the ashy deposit accumulated during the flowage of the pyroclastic currents. A relevant observation is the presence of an erosive surface, 55 cm depth and 320 cm wide, covered with a few cm thick lens of reworked material cut into the middle part of the pyroclastic succession. The finding of this structure suggests a time gap in the eruptive phenomena affecting the city of Pompeii; this pause could have pushed the inhabitants, recovered indoor during the fallout phase, to leave their homes trying to reach safer places.

Beyond Social Volcanology: The teachings of Merapi and Popocatépetl in regards to health, authority and protection

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This presentation explores how people living near Popocatépetl (Mexico) and Merapi (Indonesia) volcanoes perceive and enact forms of protection from volcanic ash, based on the findings of a qualitative study. We critically develop the budding premises of 'social volcanology' which, drawing from Science and Technology Studies (STS), engages with the topic of how expertise in volcanology is produced and, at times, awards the status of 'objectivity' to scientific knowledge, and to other practices the status of 'cultural beliefs'. In light of this, one could explain the adoption of protective practices, such wearing masks, as a cultural shift provoked by a loss of faith in 'traditional religious beliefs' and ritual experts, and concomitant rise of new local leaders that endorse science as a better way to deal with volcanic hazards. While this answer can be found in the literature exploring vulnerability and culture around volcanoes, our research produced material that prompts us in another direction. Our findings show that it is not a distinction between ritual and science - or substitution of incorrect knowledge with enlightened evidence - which have brought about new protective practices. Local practices incorporate distribution of respiratory protection and education into existing volunteer-led monitoring networks near Merapi, and the enactment of care and authority influence protective practices in Mexico. Knowledge and protective practices that might appear seemingly incommensurable, cross-fertilise in order to take care of health. In a departure from social volcanology, we provide a context-specific and holistic anthropological approach to the investigation of local perceptions and practices of non-scientists who claim to have privileged access to the environment and/or the spirits regulating the cosmos. These plural knowledges cannot be reduced to ideological, contextual, or cultural reflections in the encounter with science but, instead, need to be recognised and understood on an equal footing with scientific knowledge.

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S03.07 - Forensic analysis of volcanic impact as a support for better preparedness and recovery process

Livelihoods and the risk to life during volcanic eruption

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Forensic analysis of fatalities and displacements from recent volcanic eruptions provides insights into factors that influence actions to protect life in high risk environments. Global analysis reveals that although there have been > 4000 fatalities since 1985, 20% have involved <5 casualties and 35% indirect activity such as lahars or landslides. For the remaining 45% of events, fatalities only amount to around 0.1% of the affected population. For many events warnings were in place, and ~ 85% of fatalities were from individuals who lived in the evacuated area acting against those warnings, perhaps to protect their assets and livelihoods in the face of hazardous volcanic activity.

Our detailed analysis of two case studies (St. Vincent and Tungurahua, Ecuador) shows that the timeframes, forecasting uncertainties and rapid landscape change associated with volcanic eruptions mean that the physical and social vulnerability of populations change significantly during the course of an eruptive episode. This dynamic, associated with push (e.g. shelter conditions) and pull factors (e.g. protecting assets, place attachment) for wellbeing and human security, can lead to the tendency for evacuees to return during high- risk periods or decisions not to evacuate for people who have previous experience of volcanic hazards and evacuation. These push/pull motivations are part of the implicit risk 'calculations' that people make; their decisions do not necessarily imply a lack of knowledge. However, the result can be subsequent exposure to hazard events that are beyond previous experience (and therefore beyond people's risk calculation capability).

This means that considerations of time play a key role in shaping protection of life, particularly for people with insecure livelihoods. In this context time implies the dynamic relationship between hazard experience and action; timescales of hazard escalation and warning and the timescale over which evacuate conditions are tolerable (to livelihood,asset preservation and wellbeing) in shelters.

Impact assessment framework applied to critical infrastructures: an innovative forensic strategy

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Volcanic eruptions are a complex natural phenomenon capable of producing a large variability of processes and products at different time and space scales. As a result, a broad range of consequences can be expected over the systems exposed to volcanic hazards. Volcanic eruptions are rare, consequently there are relatively few opportunities to observe, integrate and assess the potential impacts associated with these phenomena. On the other hand, the inherent vulnerability of the different elements exposed encompasses not only their physical features but also systemic (e.g. systems interdependency) and socio-economic aspects. Therefore, the interconnections between impacts and multidimensional vulnerabilities due to volcanic hazards remain still ambiguous. We present an integrative impact assessment framework of critical infrastructures (e.g. power, water, telecommunication systems) based on a post-event analysis of the consequences of primary tephra fallout associated with the 2011-2012 Cordon Caulle eruption (Chile). We make use of forensic strategies to unravel the impact root causes and enchained consequences, usually known as cascade effect. The proposed framework includes: i) identify the impacted elements; ii) disentangle the root causes; iii) analyse the subsequent consequences and iv) classify and restructure the impact within 4 causal orders. First order refers to the *physical damage* of a system element; second order refers to the *loss of functionality* due to a physical damage; third order is associated with the *systemic* vulnerability due to the interdependency and connectivity among the different critical infrastructures systems; and fourth order comprises the induced impact on the economic and social sectors that can activate an overall damage to the global economy of the country or countries affected. The final goal of this framework is to depict and prioritize the critical areas where mitigating measures might be implemented in order to reduce vulnerability and to establish response priorities in case of future volcanic events.

S03.07 Talk

Forensic Analysis for better planning, preparedness, and recovery from volcanic eruptions

Sue Loughlin, Melanie Duncan

British Geological Survey, The Lyell Centre, Edinburgh, UK

Forensic investigations into the causes of losses, damage and disruption are essential if lessons are to be learned and volcanic disaster risk is to be understood, effectively managed and reduced. Volcanic unrest and eruptions are multi-hazardous events with consequences that unfold over weeks to years in a wide variety of social, cultural, environmental and political contexts worldwide. Globally there are tens of eruptions per year, some from volcanoes that are frequently active and some from volcanoes that only erupt infrequently but they all have consequences and cascading effects that are rarely fully documented and investigated. Even small volcanic events can have devastating impacts on communities in situations where vulnerability and exposure are high. The dynamic aspects of hazards, vulnerability and exposure over time are key factors that must be addressed when investigating volcanic disasters. If major loss of life may have been avoided, an event still merits investigation to establish the causes of any positive outcome. Such events can nevertheless involve significant losses and disruption (e.g. to livelihoods, critical infrastructure, education, health etc) which can cause long-term impacts for a society.

In this talk we will review forensic investigations that have been carried out since 1985, highlight key documented issues around the causes of disasters in a volcano context and draw attention to knowledge gaps where scientists can contribute to building evidence and knowledge through research and practice. We will also consider progress in building a strong interdisciplinary capacity in young researchers, an objective of the FORIN project.

S03.07 Talk

Forensic investigation of disasters to improve risk models and to support resilient recovery

Scira Menoni

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Forensic investigation refers to a variety of methods to identify causes and root drivers of damage consequent to hazardous events. The term used to refer to investigations conducted mainly by engineers and geologists to support judicial determination of responsibilities when losses and harm can be attributed to neglected safety rules and procedures. An extended understanding of this field of practices as intended in our proposal seeks to clearly identify how and to what degree risk factors, namely hazard, exposure and vulnerability have concurred to provoke damage in a given context affected by a natural extreme. A more recent understanding of forensic investigation has been proposed by IRDR in the Forin project, where besides technical and hard facts, also the social and political drivers of risk are considered important to elicit. Interestingly the latter approach has been taken also in the insurance setting with the PERC method. All the mentioned methods share the requirement to dig into the disastrous event to learn lessons that can be used to improve the understanding of disaster mechanisms and therefore risk assessment models, plan for a more resilient recovery in which pre-event vulnerabilities are diminished and major weaknesses in preparedness and in the built environment are addressed. The proposed presentation aims at illustrating how forensic investigation can be applied to disasters due to volcanic eruptions with examples taken from a study on the 1999 MC eruption. The proposed method aims at structuring damage and loss data according to the sector that has sustained them, considering relevant spatial scales and at different time stages in order to account also for the so called indirect and longer term damage. Such data structuring permits to conduct in depth analysis of events extracting knowledge relevant for the case under examination as well as for similar ones.

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S03.09 - Gateways to different perceptions and engagement of volcanoes the role of art/science collaborations

MUSO: Drawing on Improvised Opera to Communicate Volcano Hazards and Foster Public Engagement

Chiara Ambrosio, Carina Fearnley

University College London, Department of Science and Technology Studies, UK

In this talk we present some reflections on MUSO, a co-production between the UCL Department of Science and Technology Studies, the Grant Museum of Zoology and Comparative Anatomy and Impropera, possibly the first (and only) improvised opera company in the world. The talk will showcase one of the project's performances, specifically revolving around communicating volcano hazards to a non-academic audience. As part of the performance 'the volcanologist' incorporated historic paintings of Mt. Vesuvius and Campi Flegrei, and Mt. Fuji from the UCL Art Museum Collection, alongside fossils to tell stories about volcanic hazards communication to a public audience. From Pliny the Elder, to Japanese folklore, to stories of mass extinctions, the materials inspired the opera singers to improvise various songs that brought great comedy.

We will show how this new and highly interactive form of engagement produces a genuine form of engagement: one in which all the participants - performers, academics, audiences and curators, contribute to the final making of an unrepeatable emotional and transformative experience. Along with being a uniquely innovative experiment in public engagement, MUSO is an experiment in relinquishing the kind of control that is so typical of academic research, embracing the unknown, and taking pleasure in finding out what happens as a result. We will argue that this element of unpredictability, so thoroughly explored by performers working with improvisation and so attractive to audiences, has a huge potential to expand the scope and effectiveness of academic engagement, and potentially academic research as well.

Imaginary Explosions: media and measurement of volcanism as cultural imaginaries of planetary plasticity

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As a visual artist, I approach volcanism to observe how the measurement, monitoring, and exploitation of global volcanic activity contribute to visual cultures and knowledge production in modeling planetary systems. I define my approach as "pseudo-science fiction", employing ethnographic observation to speculative fiction in artistic practice. It is a method to inhabit technoscientific imaginations as they contribute to new epistemologies of seeing and sensing.

Treatise on Imaginary Explosions is an episodic video series that follows an affiliation of transfeminist scientists as they operate in communication with the desires of the mineral earth for radical, planetary transformation. The scientists investigate volcanoes, remote- sensing laboratories, and geological survey sites across the world, conspiring to erupt all of Earth's volcanoes simultaneously. The series encounters embodied time-scales of geological metamorphosis alongside human traumas over generational time. The series parallels interpersonal violence as a slow violence under patriarchy, with the corrosive structural violence of global warming. Collaboration and intersectional transfeminism are foregrounded as political strategies of social cohesion and generational change.

For *Cities on Volcanoes 10*, I will share excerpts from video episodes shot at active volcanic sites in Iceland and Chile and describe methodologies of collaboration with scientists and scholars. How can visual cultures of modeling, scale, and computational photography enable us to grapple with interconnected webs of global warming, extractive capitalism, and patriarchal power? This project is an exercise in literacy, analysis, and imagination.

Assembling volcanoes: Paektusan in Korean art and architecture

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This paper analyses paintings, mosaics, maps and architectural carvings to understand the cultural significance of Mount Paektu (Changbaishan) on the Korean Peninsula. It focusses on interpretations of the volcano in the Democratic People's Republic of Korea (DPRK), which is a "sacred mountain" to the Korean people, and which also sits across the border between DPRK and China. Paektusan has considerable cultural importance to Koreans – both presently and historically. It associated with struggles against imperialism and with stories of origins. Its depiction in art and architecture resonates with these stories, but also demonstrates the broader assembling of the volcano not only as a material feature of the landscape but as an idea and as a form of cultural heritage. Paektusan is important to Koreans just as many other volcanoes - including Vesuvio - are important to cultures elsewhere in the world. This cultural significance has to be understood if we are to engage with populations.

Using this example, the paper argues more broadly that understanding volcanoes through art and literature, as well as through a scientific gaze (social and physical), can significantly contribute towards understanding volcanic risk (another lens through which we can view volcanoes) more holistically. It can also aid interpretation of the complexity of population relationships with volcanoes and therefore their ambivalence about risks that they might face. Volcanoes are ultimately assemblages of ideas, materialities and experiences – of encounters with a volatile, energetic earth. Separating scientific interpretations from these wider, historical and cultural interpretations is counter-productive in managing risk.

Geologic Intimacy: Collaborative possibilities between Art and Geology

Ilana Halperin

Royal Scottish Academy, UK

Almost half of my life ago in New York I was walking down the street near the now unrecognizable Bowery. There was a man selling old books on the sidewalk, laid out on a sheet. One caught my attention, a book called Volcano about volcanoes from around the world. There were volcanoes from Iceland, Hawaii, Italy, Scotland. In retrospect, every project I have ever undertaken can be traced to a picture in this book. It features the places I have gone to meet volcanoes (alive, dormant and extinct), to understand what it means to be human and rock and both at the same time.

For over twenty years my work has explored the relationship between geology and daily life. I spend time with earth scientists and in natural history collections, in my studio and working in remote geological field environments. Within my work, I have celebrated my birthday with a volcano born the same year; boiled milk in a 100 degree Celsius sulphur spring; talked with geologists inside a lava tube inhabited by life-affirming bacteria; spent time with geology collections formed inside the body; and held the Allende Meteorite, the oldest known object in the solar system, in my hands.

To articulate a corporeal sense of geological time, I form sculptures with natural geological processes which change within our own lifespans – from high velocity calcifying springs in France to geothermal pools in Japan. My hope is that through merging a more daily and geological sense of time, we may begin to understand ourselves as part of a deep time continuum. For COV 10, my presentation will focus on the 1973 Eldfell eruption on Heimaey, on sharing the same age as a volcano; and on a recent international geological art collaboration in the geothermal city of Beppu, in Kyushu, Japan.

Prehistoric art, contemporary imagination, and the disaster museum of Chaiten, Chile

Karen Holmberg

New York University, USA

A cave complex near the Chaiten volcano contains dozens of red painted designs as well as excised motifs identified archaeologically as vulvas. The remains of a child were found inside along with deep shell middens. Our archaeological excavation recovered an array of materials, including obsidian and a piece of pumice modified into a crude sculpture. While protected from the tephra fall elsewhere in the Chaiten area that indicates roughly 18,000 years of continual eruptions, the caves and their long period of human use intersect deeply with the volcanic landscape. Drone imagery, photogrammetry, and 3D modeling of the caves for VR were interwoven into our archaeological and volcanological fieldwork as was the filming of an episodic science fiction artwork, Imaginary Explosions. When presented in the Chaiten site museum currently under construction, the site data will only be translatable to tourists and local residents effectively through creative, interpretive display. The scientific study of the rock art and volcanic context has led to more art as well as science which will be conveyed through art. They cannot be disentangled from one another or the volcanic landscape.

S03.09 Talk

From VOG to VUMO: Science communication and the role of socio- technical interrelations in the adoption of new volcanic realities

Dave Lynch[1], Pete Eyres[2], Christophe de Bezenac[1], Evgenia Ilyinskaya[2] and the UNRESP team

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Words are thinking tools that can alter the ways that we conceive the world, but how do new terms become meaningful? This paper proposes novel science communication methods informed by artistic practice. It traces the factors that contributed to the adoption of the term “vog” as a descriptor of air pollution from volcanic emissions into the ambient atmosphere. The word is a portmanteau of “volcano” and “fog”. Since the 1980s, the term routinely describes the impact of volcanic activity of Hawaii residents, with its inclusion in real-time forecasts. (http://ivhhn.org/vog/content/vog-). In this paper, we explore the possibilities of introducing “vumo” (a combination of the Spanish word for smoke “humo” and volcano “volcán”) – a novel term to differentiate between the gaseous emissions from the Masaya volcano and smoke hazards from solid fuel fires. The aim is to engage affected populations in mitigation and warning systems developed by the UNRESP project team (https://unresp.wordpress.com/). In December 2017, this new term vumo and a numerical forecasting model was presented to the local community of El Panama, situated 2km from the Masaya volcano using posters, videos, oral presentations and novel use of video-mapping onto a 3D model of Masaya volcano. The outreach materials were designed using methodologies derived from the community’s descriptions of firsthand experiences, such as “The breeze burns my eyes and throat”. More general thoughts regarding the potential of arts-science collaboration to engage target audiences will also be explored.

Pompeii of the North, in Art and Science

Gisli Palsson

University of Iceland, Iceland

Drawing upon the concepts of "geologic intimacy" (Halperin 2013) and "geosociality" (Palsson and Swanson 2016) – emphasizing the geologic sensibilities of humans and the irreducible mingling of geos and social life – this paper discusses the eruption on Heimaey, Iceland, in 1973. I shall focus on the erupting volcano "Holy Mountain" (Helgafell), scientific understandings of this historic events, local perceptions of the risks and threats posed by quakes and lava, the culturing of lava during the eruption by means of intensive cooling, and the representation of the volcano and the island terrain before and after the event in the visual arts, notably the works of Guðni Hermansen, a local painter, and Ilana Halperin, an American artist and theorist based in Glasgow.

Flaming fields: ecocritical art practice and history

Andrew Patrizio

University of Edinburgh, UK

This paper will be a counter-intuitive essay on volcanology and flatness in visual art practice and history. The ideas come partly from my new book (*The Ecological Eye: assembling an ecocritical art history*, Manchester UP 2018) particularly around the book's central trope - 'non-hierarchy'. This plays out in various ways: politically, it draws on egalitarian notions developed within social ecology and anarchist thinking; in eco-critical terms, using the flattened ontologies of posthumanism and new materialism. Art history is thus flattened and repurposed for an environmental, posthumanities future.

I will translate some of these broad disciplinary and interdisciplinary concerns into a 'levelling' or plateauing of the volcano and the visual culture around them, picking out some key practices from the past and present. I will discuss a number of works by Ilana Halperin*,* an artist inspired by volcanologist Jim Luhr. As Halperin writes: 'Jim said to me, a volcano buries itself. It perpetually erases its own history. A volcanologist explained the nature of love to me. He said, you love what you get to know, what you pay attention to and therefore become more aware of. This is not a passive form of love.' This paean to forms of attention - with ethical and aesthetic imperatives – also impels the kind of future art history we also need.

I will discuss Halperin's etching series *Emergent landmass* and sculpture *The Library*, comparing it with the photography and screen-based practices of artist Tacita Dean, specifically the photo-etching *Vesuvio* (2001) and film *Antigone* (2018).

As Timothy Clark put it in *Ecocriticism on the Edge*, we need a perspective that 'does not deepen so much as flatten'. Out of these eco-critical artistic practices, a rich lineage of the flat and planar can be run through the visual culture of volcanology.

Pompeii's Ashes: The Presence of Absence

Helena Petersen

Artist

Photography offers infinite possibilities to depict moments of transition in society and nature that lead to irreversible changes. Through photographic processes, fleeting moments are made visible.

Analogous to a photograph, the volcanic eruption of Vesuvius in 79 AD halted life in Pompeii in just a matter of seconds - freezing a moment in history. Pyroclastic flows, buried the city and its inhabitants, preserving their final instants for almost 2000 years. Past excavations exposed cavities with the reminiscence of bones inside, and in 1860, archaeologists, for the first time, poured plaster into these cavities. The process created moulds revealing imprints of human bodies, a three-dimensional photograph of the fatal incident. Over time, excavations brought more layers of Pompeii's final moments to life. Moments that were, until now, buried by the dark concealment of ash.

The ash performs here the same function as a negative in photography. It captures a moment in time and space which would otherwise disappear unrecorded, but today's earth- coloured ash hills surrounding the archaeological sites are an inconspicuous backdrop to the devastation that lies beneath.

In the series 'Cinis' (Latin for ash), mainly using camera-less techniques, further possibilities of visualizing a transient moment are explored.

Through our collaboration we transform the ash into the photographic process: high magmatic temperatures bring the ash to new life in the state of a mobile glowing melt. Melt drops flow, connect and generate new patterns and cavities. Rapid cooling, in turn, coagulates the melt recreating translucent volcanic glass pervaded by rapidly evolving fractures. Only with the light of a slide projector the molten ash is visible as an image.

Turning ash into melt and glass, we recreate images of this historical incident which has not become less of a threat today.

Unconventional science communication. Exploring different ways to share information about volcanic processes

Micol Todesco

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The development of outreach programs has become an impelling necessity, especially when dealing with natural hazard and its mitigation. The widespread demand for outreach materials and activities poses a variety of problems to scientific institutions: from the availability of trained staff, to the choice of relevant scientific contents; from setting up appropriate venues and outreach occasions, to fine-tuning the languages and approaches for a diversified audience. The European Researchers Night (ERN) proved to be a great incubator and an excellent workspace to practice new approaches. This presentation will illustrate some of the outreach activities proposed in the last few years (at ERN and elsewhere) to explore different settings, targets and languages. Outreach programs included cracking party poppers, invading modern art museums, drawing imaginary eruptions, and telling volcano stories at a theatre festival. All of the activities were possible thanks to the availability and expertise of a number of collaborators, including anthropologists, visual thinkers, historians, IT staff, designers and painters, teachers and educators. The main principle behind all these different approaches is to shuffle the cards and mix seemingly incompatible elements and contexts. Looking at the same subject from different perspectives and cultural backgrounds offers a wider, more detailed representation with unexpected interpretation keys. At this time, a formal measure of the efficacy of these activities is missing. However, direct feedbacks from the participants suggest that unusual locations and atypical languages (literature, theatre or arts) stirs the public attention and widen the potential audience.

S03.09 Talk

Art, geology and volcanoes in Argentina

Florencia Torres Barthe[1], Lucía Bellusci[3], Marcela Montemurro[1,4], Carlos Legname[1], Elizabeth I. Rovere[1,2,3]

[1]*Galería Torres Barthe, Argentina*
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[3]*Espacio Cultural Circe, Argentina*
[4]*Profesorado De Arte Leopoldo Marechal, Argentina*

We define the concept of Art as a symbolic value of the communication and expression of human beings. It is from this starting point that we develop a project that links Geoscience - Community - Art. The representation in visual format of the different geological manifestations adopts a mission of concrete transformation on the social reality and at the same time is formative and pedagogical in relation to the statements posited by science today. We address in our work the impact of recent volcanic activities (Hudson, Chaitén, Puyehue-Cordón Caulle, Calbuco and Copahue volcanoes) in their socio-environmental context. We develop artistic languages as an essential complement between technical- scientific research and the receiving environment. The interaction between the artists, the scientific community and the affected populations are a priority axis for the development of the work. An expressive and sensitive contribution to the specific issues of impacted areas by volcanic eruptions is the subject of treatment. Different artistic disciplines: Painting- Engraving-Drawing-Sculpture-Installation-Collage, determine a new look on the problem allowing to recompose links and elaborate alternative social conclusions in the face of possible catastrophes or complex situations. The use of different plastic resources and the use of different materials for the construction of the works give us a bonus to the presentation of the proposal, facilitating the understanding of the subject and the awareness of possible volcanic eruption future events. The reuse of native (volcanic-pyroclastic) materials within the framework of a new project is presented as an alternative of structural and social resilience associated with information and prevention against geological hazards (earthquakes, mass removal, floods, volcanic eruptions, fires and lightning). This is how a group of artists takes volcanic activity as its theme, with the objective of transforming through aesthetic and artistic proposals, often-complex realities, returning to a new starting point.

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S03.10 - Pedagogy of Volcanology

Experiential learning exercises in small communities: the example of the elementary school of Vulcano Island, Italy

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Experiential learning exercises are effective educational tools for school-age children that can be easily implemented at the local level. Since 2011, we have been carrying out an educational activity with the elementary school students of Vulcano Island, Italy, with a permanent population of about 800. The last eruption of La Fossa, the main volcanic structure of Vulcano, occurred in 1888-1890 and areas that are now densely populated are located on the deposits from the eruption. The proximity of residents and visitors on the island to hazards associated with an eruption exacerbate the risk to both people and property. In our work with the elementary school of Vulcano, students experience a mix of laboratory and theatrical activities, in order become learning facilitators for the entire community. We involve about 15 to 22 children between 8 and 11 years old that play the role of key stakeholders managing the hypothetical emergency situation on their island, including volcanologists, Italian Civil Protection and media. The exercise has been carried out as part of the Specialization Certificate in Geological and Climate-related Risk (CERGC) of the University of Geneva. On one hand, the exercise raises awareness of volcano and emergency management issues among the island's young generation, and on the other hand it inspires international practitioners and graduate students participating in the CERG-C on the effective use of educational strategies in a volcanic context. The CERG-C program has already trained more than 400 practitioners and graduate students from some 85 countries and many of them have been largely inspired by the Vulcano exercise to carry out similar educational activities in their countries. In addition, Vulcano school children are always very open to interaction with the CERGC participants and have learned to value their territory even more thanks to the international interest raised by their volcano.

S03.10 Talk

Alaska Volcano Observatory Historically Active Volcanoes of Alaska Reference Card Deck

Cheryl Cameron

Alaska Volcano Observatory, Alaska Division of Geological & Geophysical Surveys, Fairbanks, AK, USA

In 2009, AVO developed a set of criteria to establish whether a volcano was "active" – essentially, whether there were indicators of magma under the volcano capable of erupting. These criteria included: historical eruption, possible historical eruption, long-lived boiling point (or possible boiling point, for those without temperature measurements) fumaroles, deformation caused by magma movement, and seismic swarm caused by magma movement. If a volcano had one or more characteristics, it was added to the "active" list. The list initially totaled 52 volcanoes – a perfect card deck, with one volcano per card. We printed our first version of this card deck in late 2009, and eventually sold nearly 7,000 decks. Further geologic study in recent years resulted in the addition of two more volcanoes to the deck, so we updated the card deck to include jokers, and printed a new version in 2017.

The 2017 version has several improvements over the 2009 version: we've replaced colored dots (which were a problem for colorblind individuals) with different-shape icons to show a volcano's historical activity; we show the volcano's location on a map instead of listing the coordinates; all photos are oriented in landscape mode; we opted to put caption information on a website instead of printing separate inserts; and volcanoes are more rigorously ordered into different suites on the basis of their geochemistry: calcalkaline vs. tholeiitic. These card decks have been a useful outreach tool, especially as they are relatively cheap, compact, and people can use them to play games they already know.

3D models of Aeolian Islands to educate students at Vulcano and Stromboli INGV Centres

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Vulcano and Stromboli are the most active volcanoes of the Aeolian Islands. Vulcano is quiescent since 1888-90, but it underwent several unrests. Stromboli is characterized by a permanent mild explosive activity, episodically interrupted by major explosions, lava effusions, or paroxystic explosive events. In order to reduce the risk, a Volcanological Information Centre has been established on each island (on 1990 at Vulcano and on 1997 at Stromboli), by INGV in cooperation with Civil Protection and local authorities. Visitors receive information on volcanic history and hazards of the two islands, on volcano monitoring systems and preparedness plans. Booklets and posters are distributed. During summer, volcanology students of several Italian universities, coordinated by senior researchers, are involved in the tourist educational/information activity in the visitor centres. In the school opening-period, activity is mostly dedicated to local students. In order to improve the educational involvement of students we carried out a project on modeling raster data for spatial analysis and 3D printing starting from a DTM. The considered area covers the whole archipelago of the Aeolian Islands and three different procedures have been applied with two types of software: ArcMap by ESRI and QGIS. The final result is a 3D- puzzle consisting of the seven Aeolian Islands and surrounding sea, at the scale 1:35,000. Students will have to play with the pieces of the puzzle, in order to correctly assemble the archipelago. Its shape will help to understand the structure and nature of a “volcanic arc”, and the morphological characteristics of each island (e.g. cone, crater, depression, lava flows, caldera) will help teachers to explain its volcanological features and students will handle the islands applying their three different senses (hearing, sight and touch).

S03.10 Poster

Public dissemination of science and its language: test and school reports to improve the mutual comprehension between scientists and people

Gianfilippo De Astis, Federica La Longa, Massimo Crescimbene

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Roma1, Italy

Public awareness of science, public understanding of scientific language or public engagement with science and technology are activities related to the attitudes, behaviours, opinions that involve the relationships between people (or society as a whole) and scientific knowledge as well as research organisation. It is a comparatively new approach aimed to explore the multitude of channels and links interplaying among science, technology, innovation and the general public. To explore that particular aspect of these topics related to the “technical” language used by researchers and scientists, we carried out a study that investigated the readability and comprehension of some texts of scientific divulgation. We selected two texts of volcanological topics using the GULPEASE index to check the readability of a calibrated text in Italian. For our survey we used one text with a medium- high Gulpease value (addressed to primary school), and one text with a medium-low Gulpease value (addressed to an audience with a higher education level). We have created a questionnaire to evaluate understanding and the attitude of the public in relation to the proposed volcanological dissemination texts. In particular, we investigated five dimensions: how the title is; how the text is; how the information contained in the text are, diffusion to other people; desire to deepen the topic of the text. Here, we present the results of the survey conducted between 2017 and 2018, in collaboration with the students of scientific high-school (Liceo Peano, Rome), as part of project “Gulpease and beyond”. We think that this type of work should become a routine activity to bring scientific knowledge as close as possible to the life of conscious citizens. This is particularly true when dealing with great social impacts issues such as hazard and risk in active volcanic territories where citizens’ decisions play a paramount role in reducing natural risks.

S03.10 Poster

How could hand laboratory games will improve acknowledgement to the correct volcanic risk perception?

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Earth Science study has been considered marginal especially in Italy in which environmental calamities occurred frequently. The purpose of this work is to improve the acknowledgement of the Earth in order to achieve the correct risk perception in the children aged between 3 and 5 years old. The experience has been conducted on 15 classes for a number of more than 300 children in schools of Rome. Theoretical-practical laboratories on volcanoes have been carried out in order to diffuse the bases of the Earth Science. To improve the comprehension of this young age children the new strategies included readjustment of techniques already used for 6 years old children. The laboratories have been achieved using food and natural stuff. Volcanoes laboratories are made by building two volcanoes modeling sand around plastic bottles. The effusive eruption is made by inserting flour and bicarbonate powder in the bottle and the vinegar as reactant. The explosive is made by only inserting bicarbonate and vinegar and using a cork to plug the bottle.

Before and after the laboratory, questionnaire skills were administered to the children, while only after laboratories different questionnaire were administered to teachers. Results obtained from children questionnaires show how volcanic laboratory improve the acknowledgement to the correct volcanic risk perception especially during the explosive simulation. The teachers questionnaire took over the importance of an expert doing these laboratories.

S03.10 Poster

The best of both worlds: Multidisciplinary collaborative initiatives for the improvement of volcanology higher education

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Globally, there is a wealth of education knowledge and expertise that supports evidence- based learning and teaching practice across disciplines, levels (i.e., primary, secondary, tertiary), and settings (i.e., informal and formal education). Within the earth sciences, there is a vibrant community of discipline-based education researchers who specialise in how we learn and teach about the Earth. Our team has worked to increase the application of evidence-based pedagogies through meaningful partnerships between education researchers and volcanologists. We found that experts in volcanology bring tacit and volcanological content knowledge, technical and cognitive capabilities, learning objectives and outcomes, and history of the discipline. While education specialists bring knowledge of how people learn, improving and maintaining student engagement, motivations for learning, pedagogies that address common learning barriers and supports and strategies for incorporating technology in the classroom and field.

Here, we highlight initiatives from the Geoscience Education Research Group (University of Canterbury, New Zealand). We include examples of successful curricula grounded in education and volcano expertise (e.g., eruption simulations, volcanology and journalism, volcanic hazards and emergency management). For example, our work with eruption simulations has led to increased graduate competency and experience in communication skills who now hold roles in national science agencies and emergency management sectors. Additionally, several key learning experiences have helped to forge strong relationships between media, journalists, our staff and graduates. In this way, we have developed a strong volcanology learning and teaching community at our institution and those of our affiliated partners, which has resulted in educational grants, teaching awards, and the convening of national and international symposia in geoscience education. Through these examples, and others, we highlight the value of an evidence-based approach to teaching and how crossing disciplinary boundaries has enhanced our learning and teaching practice and contributed to academic and public communities here in New Zealand.

Connecting with Generation Z - Strategies for engaging Caribbean secondary school students in volcanology

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The University of the West Indies Seismic Research Centre, Trinidad & Tobago

The University of the West Indies Seismic Research Centre (SRC) monitors and conducts research on earthquakes, volcanoes and tsunamis in the English-speaking Eastern Caribbean. We also operate a dynamic education and outreach programme, which seeks to mitigate against these hazards. Students, at all levels, are one of our primary target groups and for more than a decade we have adopted a myriad of approaches aimed at conveying important volcanic hazard and impact information while simultaneously fostering an interest in the geo-sciences as a career choice. Secondary school students have consistently proven to be a difficult group to reach thereby leading to continuous review, assessment and updates of our pedagogical approaches when working with this group.

In addition to the developmental challenges that the natural process of adolescence may pose for teaching this group, the current generation of secondary students, so-called Generation Z[1], broadly share characteristics which may significantly challenge the effectiveness of conventional pedagogy. Generation Z students are global, technology- driven; they have shorter attention spans and thrive in active learning settings, compelling educators – formal and informal – to re-think instruction delivery.

We provide an overview of some of the strategies and activities used for teaching secondary school students and share our experiences on successes and lessons learned.

[1]Generally categorized as people born between 1995-2012.

Teaching Volcanology in Italy

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Teaching procedures and methods are shaped deeply in the culture they perform and are usually the subject of specific studies. This presentation investigates in specific the way volcanology is present in the curricula of Italian first, secondary and tertiary public education and how such presence is (or not) relevant to the perception of volcanic complexity in the public opinion. The exploration of different pedagogical approaches should rely on explicit studies of what is the expected role of education in the context of reducing volcanic risk as well as in developing understanding and care for the volcanic territory people live in. We find that academia has dedicated little to no attention to this topic, leaving a huge gap to be filled in terms of literature on the didactics of volcanology that may inform and shape Ministerial curricula.

S03.10 Poster

Are you prepared to live near an active Volcano?

Teresita Gravina

Associazione Nazionale Insegnanti di Scienze Naturali, Napoli, Italy

Italian high schools aim at helping students in acquiring knowledges and competences as basis for a lifelong learning (MIUR and INDIRE, 2014). Knowledges and competences are organized into four cultural areas, one of which is represented by Science-Technology and include Biology and Earth Sciences. Compulsory Science curricula was revised in 2011 by the Ministry of Education, University and Research (MIUR), differences in deepening are possible due to high school Science teachers different backgrounds (Biology, Chemistry, Geology, Natural and Environmental Science degrees). Volcanology represent only a small part of the Science curricula, sufficient for future citizens Science background, but is not effective for students living in the surrounding of volcanic areas. These students needs supplementary skills in order to deal with emergency situations due to volcanic phenomena.

In order to investigate the Italian high school student's background in Volcanology I analyzed the results of Italian Earth Science Olympiad, which is held annually by the Italian National Association of Science Teachers (ANISN) and involve Italian high school students between 16-19 years old (Gravina et al., 2018 in press). During the 2017 edition one of the test proposed to students focused on pyroclastic flows, a phenomena capable of producing high value of volcanic hazard. Results were analyzed in order to compare: students performance in Volcanology in contrast to other Earth Science topics and the preparedness of students that lives in Campania, an active volcanic area, in comparison to the general Italian high school population. These results could provide some thought to the relevance of Volcanology in Italian high school Science curricula, in particular in active volcanic areas.

Fair of Science & Volcanoes: when they become your high school classmate

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The Fair of Science and Volcanoes is an educational project funded by Tenerife *Innova* Program 2016-2021, that coordinates the Tenerife Area 2030 of the Cabildo of Tenerife, Canary Islands, Spain. The objective was to invite 3rd and 4th level students of Secondary Education as well as 1st and 2nd level students of High School, who are studying in Tenerife, during the 2016-2017 school year, to develop scientific projects related to volcanic phenomenon and/or volcanic risk. Fields of study range across experimental and social sciences, as well as in the field of audio-visual arts. The projects were supervised by the teaching staff of the educational centres with the technical-scientific support of INVOLCAN and were disseminated during the celebration of The Fair of Science and Volcanoes as oral presentations. The first edition of this educational project was held in September 2015. During the third edition held on November 23, 2017, 700 schoolchildren from 16 educational centres participated. The results of a total of 11 projects (4 experimental + 4 social + 3 audio-visual) were presented and a Volcanic Olympiad was celebrated with 12 different school teams of four students each. For each team, students bore the names of 12 volcanoes that are part of the list of the 16 Volcanoes of the Decade. This project has made it possible for schoolchildren to learn how to conduct science by promoting cooperation as a method of work, and participating in the different phases involved in carrying out a scientific project. The Fair of Science and Volcanoes has brought the students closer to the geological reality of the Canaries, the volcanoes, informing and educating them about their risks and their numerous benefits, promoting interest in the advancement of knowledge as an essential element to contribute to the development sustainable of volcanically active regions

Learning about "VUMO": pedagogic lessons from interdisciplinary research dissemination on persistent volcanic hazards in rural Nicaragua

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Children worldwide often learn about volcanoes through accounts and pictures of dramatic eruptions. However, many communities have been experiencing 'latent' volcanic activity which is not featured in school curricula and thus neither represents these experiences nor conveys relevant knowledge for times of crisis. This presentation is based on a pedagogic reflection about the dissemination activities of an interdisciplinary pilot research project looking at the human and social impacts of Persistent Volcanic Emissions (PVE) of gases in a rural community in Nicaragua. The dissemination of project results included materials designed to integrate social experiences and perceptions with vulcanological measurements taken at the site and a short documentary film recording these experiences along with inhabitants' daily routines. The materials and film were presented to the community on two occasions, one event open to all community members in December 2017 and one for students and teachers from the local school in April 2018. Both activities followed a participatory logic and opened and informal education space that featured facilitated moments in which participants shared their experiences with the volcano and its emissions, and "new" information about this latent hazard, including the new word "vumo" (a collation of Spanish words *volcán*and *humo*) which aims at linguistically differencing PVEs from smoke. The resulting discussions and interventions, along with the reflections shared by participants provide new possibilities to re-think science and hazard education in rural contexts and the value of different bodies of knowledge in it. A participatory pedagogy framework is proposed to integrate the very diverse and rich experiences of children and their families living with persistent volcanic emissions to foster meaningful and relevant learning about volcanos, hazards and science that can contribute to better communicating the vumo hazard to the public.

Virtually drilling into Icelandic volcanic hazards

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Fieldwork is a critical learning experience for learners across the natural sciences. Virtual fieldtrips (VFT) and games are being increasingly considered effective forms of teaching, especially with the rise of new technologies and the increasing desire for inclusive classroom environments. As part of the outreach for Krafla Magma Testbed, we have designed virtual Iceland fieldtrip experiences for primary, secondary and university learners; designed to achieve learning objectives around volcanic hazards associated with different Icelandic volcanoes, geothermal energy, and societal impacts. Various pedagogical aspects of the virtual fieldtrip and game will be measured through interviews, observations and surveys. Both activities, including the hazards and volcanological content, are designed to align to New Zealand curriculum, but are intentionally flexible to encourage international participation. The web-based material can be delivered as a purely online activity, group laboratory, or classroom activities at any level. Our web platform presents key components, including: a) videos of teacher-led interviews with experts in Iceland, b) teacher diaries of the trip, with the opportunity to send a school mascot to Iceland, c) background volcanic hazards material, and d) interactive 3D hand samples and outcrops with online peer learning assessment. The trip and content are designed to run synchronously or asynchronously with a classroom experience, allowing live video web conferences with experts and teachers whilst in Iceland. As part of the trip we have developed a *Magma Drillers Save Planet Earth* game that allows learners to role-play volcanologists, hazard scientists, and engineers as a team to generate clean and safe geothermal power. Learners watch videos to learn about their roles to inform drilling decisions. As a team decisions on drilling are made and drilling results are visualized in 3D. As such, we are sharing the learning materials online for free, and we are looking for opportunities to reach international audiences.

S03.10 Poster

'Hazagora: Will you survive the next geohazards?' Lessons learned from the development, adaptation and outcomes of a serious game on volcanic risk reduction

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Hazagora is an educational board game aimed at raising awareness about geohazards and disaster risk reduction strategies. During the game, the players develop communities with contrasted livelihoods on an island exposed to a range of geohazards (lava flow, tephra fall, tsunami, earthquake). Each player aims at fulfilling the basic needs of its community while strengthening their resilience to disaster with preparedness measures. The game initially targets secondary school students and citizens to induce a better understanding of geo- disasters they witness in the media. It was also played with scientists and stakeholders involved in risk management in developing countries with the objective to generate discussions about risk management strategies. The learning outcome of the game was tested using a survey questionnaire completed by players before and after the game session. Hazagora game appears to positively enhance the players' insights into processes involved in disasters, while being fun to play and generating the active engagement of the player. As such, the game is an efficient learning tool to introduce participants to the concepts of geohazards and disasters, and to generate discussion.

In this contribution, we report about five years of experience of developing and testing the game with a range of users. The game was made publicly available for download in three languages, together with education material and videos, and is used by a range of institutions. It has been adapted to various contexts by modifying the geographical setting and the types of hazards simulated. Based on the feedback from over 10 different users from different countries in schools, museums and scientific institutions, we reflect on the advantages and limitations of serious games to communicate about geological risk. We also identify relevant lessons for the development and the adaptation of such a tool according to the targeted public and the learning outcome.

S03.10 Poster

The Omaira Sanchez commemorative park: a new approach in the social appropriation of geoscientific knowledge of volcanic areas in Colombia

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The eruption of the Nevado del Ruiz Volcano in November 1985, which produced a lahar that destroyed the city of Armero in the department of Tolima and devastated the population of Chinchiná in the department of Caldas, highlighted both the need for the formal study of the volcanoes in Colombia, and the need for different communication strategies by scientific staff of the then INGEOMINAS today GEOLOGICAL SURVEY OF COLOMBIA (SGC), to reach the communities in areas of volcanic risk. For many years the SGC has developed many different activities for social appropriation of geoscientific knowledge through its three volcano observatories located in the cities of Manizales, Popayán and Pasto. The primary outreach activities include publically open observatories, in which through games, experiments and presentations the technical and scientific staff encourage closeness with the community to better facilitate the exchange of experiences and knowledge; Likewise, the SGC is developing an improved volcanic risk communication strategy in Colombia in conjunction with the National Disaster Risk Management Unit, the Observatory of Science and Technology, and the Nevado del Ruiz Volcanic Geopark project, among other strategies.

As a part of this strategy, the SGC as an institute of science and technology is innovating new technological outreach tools, including augmented reality (AR), mixed reality (MR) and virtual reality (RV), that aim to reach a different type of audience, to better educate the public about Colombian volcanoes and their volcanic phenomena. These tools are being developed in conjunction with didactic experiments and games which help us with scientific studies, education, and comprehensive volcanic risk management.

Take-home volcanoes and miniature eruptions: Applications of 3D-printed volcano models

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Communication of scientific insights to general audiences is a crucial part of research. Volcanologists face particular challenges, since effective communication of sometimes complex scientific findings to local communities can save lives during volcanic crises. We have explored 3D-printed models of Popocatépetl volcano, Mexico (Popo), as a hazard communication tool aimed at children, both in schools close to Popo, and in Europe.

Our printed models have dimensions of ~20 x 30 cm, and they have been crafted to serve both as a 3D map and as a mold. In Mexico, we used the models to produce plaster casts with school children living in communities close to Popo. They then located themselves on their own models, and simulated different types of volcanic eruptions. In the UK and Europe, we modified one of our printed models to include a summit and flank vent, which can produce miniature explosive and effusive eruptions using household ingredients. With reasonable resources, major volcanic hazards can thus be illustrated, such as pyroclastic flows, lava flows with different viscosities, ashfall and lahars. This activity has proved popular amongst children and forms an integral part of our educational activity on volcanism in the UK and Europe.

These examples show the potential of 3D-printed volcano models as an affordable and versatile tool to communicate volcanic hazards, both in communities close to active volcanoes, and as a STEM activity in regions without volcano-related risks.

One Way Scientists Are Introducing Volcanology and Other Geoscience Topics to Underrepresented Students

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In the United States, only 2.8% of all students in the science, technology, engineering, and math (STEM) fields study geoscience and only a small percentage of them will choose a career in volcanology. Additionally, the geosciences has the lowest number of racial minority students of all of the STEM fields. The USGS is partnering with George Mason University to address this issue by leveraging partnerships among other DC-based geoscience-related agencies and universities in the metropolitan Washington DC. We are promoting the geosciences to youth in this urban area via a program called DC Rocks. Both the need in Washington DC and the potential for lasting impact are great since 89% of students in DC public schools are minorities; there is no dedicated geoscience curriculum in DC, and there are several groups in the region that deal with geoscience-related issues. DC Rocks aims to give these students early exposure to the earth sciences, and encourage them to consider careers in the field. DC Rocks works with partner agencies to apply several methods recommended by researchers to increase the participation of minority students in the geosciences. Some of these methods include providing profoundly positive experiences that spark interest in the geosciences (Levine et al., 2007); increasing students' sense of belonging in the geosciences (Huntoon, et al, 2016); and place-based teaching practices emphasizing the study of local sites (Semken, 2005). These methods and lessons learned from developing DC Rocks can be applied in a variety of locations and do not require significant resources. The DC Rocks model can be used to educate youth about the hazards and risks posed by the volcano in their backyard, and ultimately can lead to adults ranging from educated stakeholders who can make informed decisions to those who may choose a career path in volcanology.

"Life among Volcanoes" is an Educational Project about volcanic active areas, by the Teófilo Pérez Primary School, Tegueste, Canary Islands, Spain.

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In the volcanic areas where the eruptions are spaced over times, it is produced over population a forgetting phenomenon of volcanic risks. Because of this, Educational Administrations must guarantee the teaching of contents related to Nature on volcanic areas through Compulsory Education. This allows us, our students' knowledge would be transmitted to their families naturally. Therefore, a trained population will always react better towards emergency volcanic situations.

The Educational project "Life among Volcanoes" of Teófilo Pérez Public School have been carried out successfully among our students either as Early Childhood as Primary Education. We have worked this topic from several subjects in a globalized way. First at all, teachers were trained on volcanic phenomenon thanks to the Volcanes de Canarias Association. Then, the teachers designed some activities to develop in their class so that our students can learn dynamics of the eruptions through scale models of volcanoes in an experiential way, made with their families. Moreover, students had to investigate volcanoes around the world using TICs and they share what they learnt about volcanoes. Likewise, cookers of our school canteen also collaborated making a special dish inspired in volcanoes.

Both students and families participated actively in this project, showing a lot of interest in the volcanic phenomenon. This allows an integral education in our students helping them to know their territory and being conscious of where they live. On the other hand, TICs help students to know the geography of our planet, helping them to discover for themselves information of other volcanic territories and to know how they live in those places.

This project will include the creation of an Earth Observatory. It will be initially composed of an educational seismograph and a weather station. This way the students will be able to follow the terrestrial natural phenomena.

S03.10 Talk

Polystyrene 3D Volcano Models with projected geological information as a tool to teach communities about geohazard

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The Chilean Andes range is characterized by 95 active volcanoes where various cities have been established nearby, exposing the population to possible volcanic hazards. Though these volcanoes have been studied, it is necessary to convey the information to the communities that may be affected to raise awareness in case of emergency. Creating 3D polystyrene models represents an innovative way to show information that has been conventionally displayed in bidimensional maps. In these models, hazards such as lahars and pyroclastic flows can be better understood as they are closely related to the geomorphology of the area. Due to the white of the material, it is possible to project different layers over the volcano, as satellite images, geological maps and hazard maps, which visualize the information in a creative way. A DEM is necessary to build the volcano, where a better resolution of the DEM translates to a finer detail in the results. Using *3D Leapfrog* software, it is possible to adjust the design to the Router CNC (computer numeric control) specifications that cut the polystyrene. Amongst the advantages of the procedure are the low cost of the materials and light weight of the model, it is simple, not time- consuming and that it can be made at different scales and dimensions. A 3D model of the Nevados de Chillán volcano will be shown in the city of Chillán at the next Volcanic Divulgation Exhibition, which is organized by the National Volcanic Surveillance Network to educate the community about the volcano in an interactive and visual way. Results will assess if these mockups are a suitable method for explaining risks to communities. This project responds to the need to engage people with geo-science and raising awareness about potential volcanic risks to reduce vulnerability in possible emergency situations.

S03.10 Poster

Global perspectives of volcanic geoheritage values of monogenetic volcanic fields and their suitability for holistic geoeducational programs

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Monogenetic volcanoes are commonly defined as erupting only once during their eruptive history through distinct eruptive phases. Systematically or randomly changing magma discharge rates, fluctuation of external versus internal influences on the eruption styles, and magmatic versus phreatomagmatic fragmentation can produce a great range of volcano types. Such volcanic processes make monogenetic volcanoes unique but their "human-scale" volcanic features make them relatively easy to utilize to demonstrate volcanic processes and hazards. Monogenetic volcanic fields carry high geoheritage value especially if a) their eruptions influenced human society, b) they have high aesthetic value, or c) they are used as reference areas to describe unique volcanic processes. These three criteria for geoheritage values reflect the current geosite evaluation methodology (GAM) that is applied to evaluate geoheritage value. The difficulty is, however, to demonstrate the outstanding universal value (OUV) of monogenetic volcanoes, since they are the most common volcano type on Earth. There are "simple" low geodiversity and "complex" high geodiversity volcanic fields. Hence geodiversity could be used as a strong argument to define a monogenetic volcanic field's OUV. As monogenetic volcanoes are human-scale and diverse, they naturally offer systematic classification schemes and embedded educational aspects, where pedagogical methods, such as the Montessori Method, can be applied for geoeducational purposes for addressing volcanism to the general public, a formal educational system or disseminating volcanic hazard knowledge to various sectors of society. Here we present examples of monogenetic fields from Saudi Arabia, Central Europe, Argentina, Japan and Samoa to exemplify simple and complex fields in various scales.

S03.10 Poster

Educational program with innovative seismic instrumentation for volcanic risk reduction in Canary Island Spain and Chichon Volcano Mexico

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Volcanic risk management in long period recurence volcanic areas relates to two important issues: the lack of risk perception in population towards a possible eruption, and the lack of resources in monitoring and educational programs to reduce the volcanic risk effects. Under these circumstances, it is necessary to develop educational-oriented programs to spread and improve the knowledge related to volcanic activity, including the use of new technologies to make it more attractive for young people. This type of educative program was initiated in Tenerife in 2001, among others, with SOCRATES-COMENIUS European project in which several schools from different countries exchange data and knowledge about volcanic activity (Canary Island, Azores and Sicily). This initiative was also driven and supported by the Didactic Guide for Volcanic Risk, published by the National Civil Defense of Spain in 2004. The new educative program presented here takes into account the installation of a seismometer in a school located in an active volcanic area. The seismometer is developed and the software compiled by low-cost modules and systems (ARDUINO and RASPBERRY), supported by educative activities as the construction of a seismic sensor combined with a commercial 4.5 Hz (~60€) short-period geophone or a LEGO module. Seismic data will be registered, analyzed and discussed by the students, who will also exchange results with other students placed regionally or from other countries. The seismic station will be the first of other scientific modules for data acquisition as CO2, thermometer, etc. Other parallel activities will be conducted, such as field trips, development of self-protection and family emergency plan, visit interesting places, etc. We also explain how these affordable instruments are also being implemented at Observatori Fabra in Barcelona to digitize old seismometers and other newer educational sensors for both professional and divulgation projects.

S03.10 Poster

How is the perception of risk due to infrequent volcanic hazards affected by the occurrence of non-volcanic hazard events?

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Understanding a person's or a community's perception of a hazardous events can helps understand their motivation for reacting to events as they occur. Their perception of such events, through experience or education, helps people understand the risk faced. Here we ask if the experience of being affected by one type of event has a longer term effect upon people's perceptions of other less frequent but higher impact types of event? Is this effect positive, with events of one type sensitizing the affected population to the possibility of other types of hazard, or negative, with the rare event types being pushed to the back of peoples' minds as they cope with the consequences of the events that have occurred?

To address these questions, we present results from the years of a 5-year longitudinal or time-series study in Dominica that span the occurrences of Tropical Storm Erika (August 2015) and Hurricane Maria (2017). This study has followed the changes in the perceptions of personal risk due to different hazards among secondary school students in the Roseau Valley area of Dominica, enabling us to consider the effects of these recent hydro- meteorological events upon the students' perceptions of volcanic hazards such as pyroclastic density currents that have affected the Roseau valley in the geological past. Our results show the potentially large changes in perceptions caused by such hydro- meteorological events on lower frequency events, such as volcanic hazards.

This study highlights the importance of undertaking long term perception studies. It shows that in a multi-hazard environment the effects of experience of hazard events of one type can, if not carefully considered in the context of hazard education, have a lasting impact on the longer term perceptions of other less frequent and potentially higher magnitude events, such as volcanic eruptions.

S03.10 Poster

Assessing the effectiveness of educational methods to change hazard perception, improve learning and enable disaster mitigation in secondary school students located in a multi-hazard environment in Roseau, Dominica

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We present results from a 5-year longitudinal or time-series study to assess the effectiveness of different teaching methods about volcanic and other natural hazards in and around Roseau on the island of Dominica, Lesser Antilles. The students involved are a cohort of Secondary School students, who entered the schools at age 11 and are now about to leave school at age 15-16 years. They have been taught through different methods between October 2014 and April 2018, whilst experiencing different hazard events, in particular Tropical Storm Erika (August 2015) and Hurricane Maria (September 2017).

The study has utilized various teaching methods and materials, to assess which were effective in shaping the students' knowledge. Different approaches to teaching have included talks, question and answer sessions, thinking and decision making activities, mapping and fieldwork. The assessment of the effectiveness of these teaching methods has used the PRISM method. PRISM uses spatial positions of moveable markers ("object") on a board, relative to a fixed marker that represents the subject ("self") as a visual metaphor for the importance of the object to the subject. Three separate PRISM exercises have been used to assess the changes in each student's perceptions of hazards, hazard information and personal mitigation strategies , and have been carried out before and after each teaching period through the five years of the study.

This study highlights the importance of using different teaching methods to maximise understanding; of the involvement of trained and experienced educators in hazard awareness and disaster mitigation education, and of assessment of teaching methods to monitor their effectiveness over time. These points are particularly important when the students have also experienced disasters that also have affected the students' perceptions both of the hazards that triggered those disasters, and of the hazards that they have not experienced.

S03.10 Talk

Using Games for Engagement and Entertainment

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The 'Strengthening Resilience in Volcanic Areas' project, STREVA, opened up multiple opportunities for sharing our learnings both inwards - across the project, with our collaborators, and across in-country settings – and outwards: with audiences remote from volcanoes, in the UK. Both sets of opportunities were engaging and enriching, either as they opened up channels for communication, and sharing of stories; or through the opportunities they provided opportunities for 'learning while doing'.

Two examples of spin-off activities that emerged from STREVA were *Volcanoes Top Trumps*, and a related set of role-playing scenario activities. Volcanoes Top Trumps is a 'categories' card game, in which players use numerical data (eruption size, volcano height, etc) to try and beat an opponent's cards. Tops Trumps is popular among children; and Volcano Top Trumps has proved readily adaptable for educational settings – where it offers a fast and fun introduction to volcanoes around the world.

We have also developed a role playing game called *Monitor, Evacuate, Plan* to explore decision making during a volcanic crisis. This was inspired by the 'serious games' used by the Red Cross and Red Crescent to explore climate adaptation with local communities, and involves groups of people working together as a volcanic scenario unfolds behind them. In the role play, groups each represent local community leaders; while the stochastic nature of the volcanic events and their impacts are simulated by rolling dice. Having used this first in a community setting in Ecuador, as an ice-breaker, we have now adapted the game for use with school groups of all ages. This scenario game actively promotes engagement and discussion, and can be used to help participants with the challenges of responding to natural hazard events and their impacts on communities.

S03.10 Poster

Living with a volcano:
A role-play scenario-based game focused on Soufrière Hills Volcano, Montserrat

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Communicating the concept of volcanic hazard and risk to communities and schools can be a challenge. The complexity of decision making during a volcanic crisis can be difficult to convey. One approach in presenting this complexity is through role-play, where participants act out a role in a developing volcanic crisis. In this role-play scenario-based game the participants choose a role based on the main stakeholders on the Island of Montserrat during the 1997 activity of Soufrière Hills Volcano. They can choose from roles such as Farmers, Scientists, Government Officials, and Shelter Occupants. The groups are presented with the overall situation at Soufrière Hills Volcano in 1997, and then given an individual scenario. They talk about this within their group and then split up to enable cross- communication with members of the other groups. They are asked to decide what they would do next and then share their decision with the rest of the participants. After they have shared their decision with the other participants the "What happened next" is revealed and they explore the reasons why they chose that specific course of action. Participants need little background knowledge of volcanoes as all the necessary information is presented during the introduction section. The game has been successfully played in schools with students of ages 12 and up, and at university level with both undergraduate and graduate students. The game is especially effective at getting the participants to think about risk and responsibility, and to understand that for volcanic crises (like many natural hazard situations) there is complexity to the decision-making process.

Teaching activity for the classroom: Volcanic activity and monitoring of Puʻu ʻŌʻō, Kilauea volcano, Hawaii

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A teaching activity was developed in 2010 as part of the Volcano Exploration Project: Puʻu ʻŌʻō (VEPP), a project initiated by the USGS Hawaiian Volcano Observatory (HVO), NASA, and the University of Hawai'i, Mānoa, to develop accessible geoscience datasets that could be used for coursework, activities, and workshops. The specific activity presented here is a 10-week project that has been used six times as part of a Volcanic Hazards elective course for undergraduate and graduate Geology students at the University of Puerto Rico. The project consists of the analysis of real-time or near real-time monitoring data from Puʻu ʻŌʻō, which was downloaded until 2015 directly from a web site developed by HVO. On 2015, the VEPP project ended and since then data have been available through collaboration with volcanologists at the USGS. The activity has therefore evolved through time to include data from different events or different periods of time, instead of real-time data. For the project the students separate in 3 expert groups, each assigned to work on seismic (RSAM) and deformation (GPS or tilt) monitoring data. They present progress reports and complete the exercise with written and oral reports. The last task consists of a wrap-up exercise in which students discuss and report on the future of Kilauea's eruption based on their findings. The activity allows the students to immerse themselves in pseudo-real-life volcano monitoring jobs. They are able to better understand the work a volcano observatory does, as well as the types of data used by volcanologists around the world. Projects like this are an important resource in geoscience education and can also be adapted by scientists and volcano observatories to be used as a resource for education at other levels, including for public outreach.

Improving volcanological outreach in Italy: the experience of the new-born AIVWEB YouTube channel

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In modern days, Internet plays a fundamental role in information sharing (through video platforms, blogs, social media) and scientific outreach activity makes no exception. Unfortunately, the easy access to these powerful communication channels facilitates the out coming of superficial and sometimes incorrect information.

Communication in volcanology is extremely important on different levels. It has not only impact on science enthusiastic people, but it also has the function of conveying correct information to educate individuals to volcanic hazards (and resources). Needless to say, such outreach activities are essential in a country plentiful of active volcanoes like Italy.

In this framework, we present a new project aimed to divulgate volcanic processes and their various nature. The project, called AIVWEB, is based on teamwork between AIV (Italian Association of Volcanology) and a group of PhD students, postdocs and researchers from Roma Tre University. The main goal is to take advantage of the expertise of Italian volcanological community (AIV members and not) to create specific webinars to encourage people getting into volcanological topics and increasing the awareness of their living area. To enlarge as much as possible the outreaching of this activity we created a YouTube channel where all uploaded videos are easily and freely accessible to anyone.

As a starting point, we selected a famous Italian submarine volcano, i.e. the Marsili seamount, to tackle misinformation regarding the devastating impact of its future eruption. We found that this wrong risk perception is generated by the poor or misleading online information conveyed through exaggerated and/or sensational titles, which have the sole purpose of attracting views and/or comments.

Learning about Eruption Type in Mt. Usu with "the Volcano Lottery"

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We devised a game called "the Volcano Lottery" for children. We carried out this game at the event held around Mt. Usu and some Geoparks. Children were interested about past eruption of Mt. Usu. And they could learn four types of the past eruption in Mt. Usu with "the Volcano Lottery".

In Japanese festival, there is "the string lottery" that is one of the games held at street stall. This is a raffle where the prizes are attached to strings which are then bundled together so that we don't know what prize they will win when they pull the string. We can choose only one string one time. So, it is the pleasant game. We considered in "the Volcano Lottery" from this game.

There are five bicycle pumps connected to four volcano models and one prize. We choose one pump and pump up. The tube connecting pumps and volcano models gets twisted up and we can't clear those relations. When we pump up, one volcano model erupts (or nothing erupts). In front of four volcano models, there are some caption explaining about each eruption type. A game master comments after eruption about them. We can experience four types of past Mt. Usu eruption by this game. Plinian eruption, phreatic explosion, Lava flow and forming Lava dome. When we choose the pump that can't erupt, we can get the card of the blessing of the volcano.

These eruption models show only the superficial phenomenon of the real eruption, so we can't learn the mechanism. However, by this game, you can learn that there were various eruption types in Mt. Usu.

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S03.11 - Holocene records of volcanic activity and its effects on ecosystems and human societies

Analysis of volcanic landscapes and their relation with socioeconomic activities

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Volcanism directly affects landforms, and indirectly provides an age for both the land surface over which the erupted material lies. Geomorphological phenomena have significant repercussions on the environment, triggering changes in landscape that might have a severe socio-economic impact. Thus, a quantitative classification of volcanic landforms, which uses morphology, ground observations and remote sensing data can provide an understanding of the relation of human activities with volcanic effects in an area. The present investigation proposes a methodology to correlate different data that comes from geomorphologic to socioeconomic, integrated with an indicator analysis. The indicator analysis is performed in a GIS database that can be operated in different scales, regional and local. In the database there are three types of data that are used: (a) raw data, from maps remote sensing and field observations. (b) Analytical data, produced by analyzing the previous categories and (c) thematic data, created by interpreting the various types of data. In the present study three sub-indices are used. The first index refer to the geomorphological characteristics that include landforms, topography, lithology and hydrology. Natural forcing indicators related to geological structural stability, vegetation cover, soil erosivity, past hazardous events, form the second subindex. Finally, in the third indicator, the socio-economic is included, which contain settlements, cultural heritage sites, transport networks and infrastructure, land use and economic activities. As case study the Aeolian Islands and Ustica Isl. are considered. The areas under investigation present different characteristics in their geomorphological but also to their societal evolution. Data were further analysed in a ternary diagram that indicated the relative influence of each of the three sub-indices in each area. From the diagram it can be seen that the location of human activities are strongly affected by past and recent volcanic activity.

Relationships between human settlements and volcanic landscapes at Etna and Lipari archaeological sites from the Neolithic to the Iron ages

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Studying the relationships between human settlements and volcanic activity is important in order to reconstruct both the eruptive and anthropic history and to provide information about settlement systems features. The aim of this work is to study the patterns of Neolithic, Cooper and Bronze Age settlements, based on known archeological sites at Etna and Lipari, and to generate hypotheses about the relations among settlement patterns and volcanic landscape. In this work the spatial relation of Neolithic, Copper and Bronze age settlements with the geological, hydrological and geomorphological characteristics of the two areas is presented. At Etna, during the Neolithic, populations generally settled on land more suitable for agriculture, located along the volcano slopes and river valleys. In this area, the oldest site (VI-V millennium BC), was built on a lava flow dated 330 ka, whereas most of the Neolithic settlements are located on lava flows dated 40-15 ka characterized by variable cover of soil. Conversely, Copper and Bronze Age settlements were often located on lava flows dated 15-3.9 ka. The oldest evidence of anthropic activity in the Aeolian Islands, dated back to the V-VI millennium BC at Lipari, is closely linked mainly to the exploitation of the Pomiciazzo obsidian flow dated about 10 ka. During the Middle-Late Neolithic the demographic development of Lipari Island was linked to the trade of this rock that was exported throughout the Mediterranean basin. The analysis of the natural landscape features and the development of human activities indicates that on Etna is dominant the agricultural and pastoral exploitation of the soils located in the lower and middle slopes. Conversely, at Lipari human settlement is mainly related to the location of the obsidian outcrops and following to the morphological features that allowed the trade and the defense of the key settlements.

Political, social and economic dynamics in the shadow of Vesuvius. The case of Nola (I-V century A.D.)

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«The pyramid of Vesuvius divides the Campania plain into two parts that are connected by the wide valley of Nola». With these words Julius Beloch in his *Campanien*, published in Breslau in 1890, follows virtually «…et *vicina Vesevo ora iugo*» from Virgil *Georgics* and clearly defines the centrality of the Nolan territory in what in the II century A.D. Polybius calls "the country around the crater". It is a territory attacked numerous times by the eruptions of the volcanic complex Monte Somma-Vesuvio, sometimes with devastating effects, but which derives from the activity of the volcano the fertility of its land. The birth and the emergence of the urban community, with the alternation of moments of growth and crisis are closely linked to the activity of Vesuvius, because the eruptions of the volcano do not only model the territory from an environmental point of view, but also from a political point of view. The effects of the eruptions affect the development of the political community of Nola both when the catastrophe hits the city and its *ager*, and when it hits other urban centers, since it produces a reorganization of the relations between the centers of power within the region. This is the case after the eruption that destroyed Pompeii in 79 AD. And after the eruption so called of Pollena in 472 A.D.

S03.11 Talk

Volcanoclastic mass flows in the Campanian Plain and surrounding valleys related to historic and prehistoric Vesuvius eruptions: geological and archeological data

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Explosive volcanic eruptions generate both pyroclastic-fallout and - current deposits, which mantle areas of hundreds of km^2 even at considerable distances from the eruptive vents. These deposits can be remobilized soon after their deposition or even a long time after the eruptive event, leading to the emplacement of variable kinds of volcanoclastic mass flow deposits. These latter can have a significant impact on the population and human structures, also inducing dramatic changes in the territory.

The investigations carried out in at least 300 sites, included the analyses of drill cores, outcrops, archaeological excavations and stratigraphic trenches, located both in the plains around the Vesuvius and in the Apennine valleys. These studies allowed to define the sequences of primary eruptive events and the following episodes of reworking.

Particular attention was paid to the definition of the timing of the phenomena according to the main Plinian and sub-Plinian eruptions of Somma-Vesuvius (Avellino, 3,900 years BP; Pompeii, AD 79; Pollena, AD 472; and 1631). The presence, among the deposits, of paleosols, erosional or anthropized surfaces and anthropic pre-existences, together with the sedimentological and lithological characteristics of the deposits allowed to define their typology, distribution and impact on the land.

Data processing allowed to reconstruct the relationships between primary and secondary events, their recurrence in the past, and the sedimentation rates in various periods.

The Campanian Plain and the Apennine slopes were affected in the past 4,000 years by the deposition of the products of numerous eruptive events of variable intensity, both from the Somma-Vesuvius and the Campi Flegrei volcanoes. The reworking of these deposits generated a significant impact on the surrounding territories, even in very distal areas that were not directly affected by the eruptions. The eruptive events of greatest impact, from this point of view, were the eruptions of Avellino and Pollena.

S03.11 Poster

Volcanoes, people and vegetation in the Northern Andes during the Late Holocene

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The northern Andes of South America is a highly complex region in terms of its tectonic realm, geology, biodiversity, and climate. In a relatively small area comprising southwestern Colombia and northern Ecuador, more than 20 active strato-volcanoes, ranging from basaltic-andesitic to rhyolitic, have modified the landscape during the last 6000 years, imposing great pressure on natural ecosystems and on the inhabitants that have occupied the area for millennia. We establish the chronological relationships between volcanism, climate, people, and natural ecosystems for the last 6000 years, by comparing a high- resolution pollen and charcoal record, with available C^{14} dates from archaeological sites, and C^{14} dates from volcano-borne charcoal and paleosols buried under tephra all over the region. Our data suggest that frequent volcanic activity co-occurs with a lack of cultural remains in the archaeological record of the region during the intervals between 5000-3000 cal BP, and between 500 cal BP-present. Most of the radiocarbon dates in archaeological sites are recorded between 2700-500 cal BP but the spatial distribution of the sites is not homogeneous. Human settlements in the coastal Pacific lowlands occurred first, and only at *ca.* 1500 cal BP human occupation of Andean mountain settings was frequently recorded. The archaeological record signing the occupation of the high Andean region strikingly coincides with charcoal maxima and relatively dry conditions inferred from pollen records. Cultural changes after European contact are reflected as a decrease in archaeological sites, increased number of volcanic eruptions documented in historical records, the recovery of secondary forested areas, and overall wetter conditions.

The eruption history of Meru volcano, Tanzania, and the spatio-temporal links between volcanic geology and fluoride contamination

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The majority of active African volcanoes remains poorly documented in terms of eruptive history and their interactions with society. Meru is an active stratovolcano in the eastern branch of the East African Rift system, near the city of Arusha, with its last eruption in AD1910. Reconnaissance studies suggest that the volcanic geology of Meru is dominated by debris avalanche deposits as well as major pyroclastic formations indicative of Plinian-style eruptions. The stratigraphy, petrology, spatial extent, chronology and the impacts might be caused by these pyroclastic deposits have however not been systematically documented. Surface and ground water around Meru (especially in leeward side where rainfall is low) are heavily contaminated by fluoride sourced from the volcanic rocks, leading to dental and skeletal fluorosis among the local population .

We present the first evaluation of the most recent eruptive history of Meru, based on detailed field stratigraphic logging and mapping of pyroclastic deposits. The western side of Meru is characterized by pyroclastic fall and pyroclastic density current (PDC) deposits; with evidence of >4m-thick pumice fall deposits separated by thick ash tuffs and in some places palaeosols. The largest eruption deposited multiple meters of Pyroclastic density current alternating with fall deposits which can be traced up to 25km from the volcano. Although they result from major Plinian-style eruptions, these deposits are not found on the eastern side of volcano where the landscape has been reshaped by the most recent debris avalanche. The different geological formations (pyroclastic vs debris avalanche deposits) have a first-order control on the spatial distribution of fluoride contamination, posing a persistent health risk to local communities.
This work therefore, contributes to our understanding of both the potential future volcanic hazards at Meru but also the long-term hydrological and societal impacts of young volcanic deposits in an active continental rift setting.

Eruption of the Joya de Yuriria maar volcano (Guanajuato, central Mexico): Stratigraphy, tectonic configuration and reconstruction of paleoenvironmental conditions

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The Joya de Yuriria maar, also known as Yuririapúndaro (*Blood Lake* in Purépecha, the language of the Tarascan people in central Mexico) probably derives its name from the red color produced by occasional algal blooms in its shallow crater lake. It is situated at the southern margin of the intermontane Yuriria lake basin and is one of the 22 phreatomagmatic vents within the ~40,000 km^2 wide Plio-Quaternary Michoacán-Guanajuato Volcanic Field. Its crater is elongated in a NW-SE direction with a diameter of ~0.9 km and a height of ~60 m above the crater lake. It erupted through the northern distal lavas of the Pliocene/Early Quaternary (?) El Capulín and Santiago shield volcanoes. The andesitic lavas (SiO_2= 57.4-60 wt.%) of the Santiago shield are exposed as steep cliffs at the inner walls of the crater and are overlain by a decameter-thick sequence of phreatomagmatic surge and fallout deposits ($Md\varphi$=0.35 to -6.05, $\sigma\varphi$=1.10 to 3.28) with scarce juvenile clasts (<20 vol.%). The date of the eruption has not yet been determined radiometrically but its morphology points toward a Late Pleistocene (~30 to 60 ka) age. The characteristics of its deposits all indicate formation by explosive interaction of an ascending basaltic andesitic (SiO_2= 54.4 wt.%) dyke with water in shallow aquifers represented by the fractured lava flows of the shields. The monotonous nature of the phreatomagmatic sequence indicates a continuous supply of external water fueling explosive activity during the entire eruption. Today, the climate is relatively dry (679 mm annual precipitation with a high evaporation rate), but conditions were probably more humid with a higher regional groundwater table at the time of the eruption. Determination of the age of the maar together with studies of nearby lake deposits should allow to further reconstruct the paleo- environmental evolution of central Mexico during the Quaternary.

Impacts of Huaynaputina volcano eruption in southern Perù

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The historical largest eruption in Latin America occurred at Huaynaputina volcano between 19 February and early March 1600. This event caused the death of approximately 1,500 people, buried more than ten villages located within 20 km around the vent and disrupted the early Colonial economy in Peru, northern Chile and western Bolivia. With the aim to understand the variety of impacts of such a large-scale volcanic eruption (VEI6), peruvian researchers together with international Institutions initiated the “Huayruro” project (funded by CienciaActiva - Fondecyt) in 2015. This project is being carried out by a multidisciplinary group encompassing geologists, geophysisists, climate experts, archaeologists and educators at different stages of the project development:

- During the “Huayruro” project, 12 of the 30 buried villages were successfully located. In particular, the researchers made a precise map of the hidden walls of the Calicanto and Chimpapampa exceptional sites, with the combination of drone remote sensing (visible and thermal infrared) and geophysical imagery (EM31, magnetic method and ground penetrating radar). This work is now used for the archeological excavation and the building of the future site museum;
- Tephrostratigraphy and dendrochronology studies were performed to quantify the volume of the emitted ash in the affected area, the height of the eruptive column and the effect of this event on the local and global climate;
- Educional work was realized in schools and several meetings were organized to raise public awareness on volcanic hazard, in collaboration with the local and regional authorities. Finally, the “Huayruro” project is definitely aimed to serve as a reference study for other volcanoes in Peru, but also worldwide.

S03.11 Poster

Coastal hazards in volcanic landscapes.
Examples of socio-ecosystem dynamics and resilience in ancient Lipari, Sicily- Italy

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This work presents the results of recent archaeological investigation in Lipari, a volcanic island of Sicily-Italy, and focuses on socio-ecosystem dynamics related to volcanic landscapes.

Lipari is the largest island of the Aeolian Archipelago, a group of seven volcanic islands located in the lower Tyrrhenian Sea. Lipari has been inhabited since the Neolithic up to the present day. Archaeological evidence indicates that volcanic activity played a major role in the life of its inhabitants, as well as in shaping the maritime landscape.

In this contribution, archaeological evidence of eruptions as well as land subsidence is presented. Focus is given to the Sottomonastero site: a submerged structure dated to the Roman period. The evidence is now located at -12 below sea level due to volcanic-origin subsidence and sea level rise. A relative sea level rise of 12.3±0.7 m with a subsidence rate at 5.79±0.01 mm y-1 has been inferred for the last 2100±100 years BP.

The submerged evidence of an anomalous construction located above the roman period structure has been preliminary interpreted as a coastal flooding barrier, and might indicate resilience to land sinking. It has been argued that land sinking was perceived by the inhabitants of Lipari as coastal flooding. Therefore, it was necessary to create a barrier in order to avoid water from the ocean to invade the waterfront. This evidence suggests that the inhabitants of ancient Lipari worked cooperatively in order to cope with the challenges of living in a changing coastal landscape.

As land subsidence in Lipari is still active at rates up to 11.5 mmy-1 during the last two decades, and sea level rise at 2mm/yr during the last century is attested. This picture predicts that by 2100 the sea is expected to flood up to 17.500 m^2 of the coast of Lipari.

The ~AD 1250 El Metate shield volcano (Michoacán): Mexico's most voluminous effusive Holocene eruption and its significance for archaeology and hazards

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The Michoacán–Guanajuato Volcanic Field is the largest subduction-related monogenetic volcanic field in the world and includes more than 1000 scoria cones and a few hundred medium-sized domes and shields. Although medium-sized domes and shields are less abundant, hazards associated with the renewal of this type of activity should not be neglected. Here, we focus on El Metate volcano, the morphologically youngest shield of the field. This volcano has a minimum volume of ~9.2 km^3 DRE, and its viscous lava flows were emplaced during a single eruption over a period of ~30 years covering an area of 103 km^2. El Metate is thus best labeled as a monogenetic andesite shield, as also evidenced by our paleomagnetic data. This eruption had a significant impact on the environment, which included modification of the hydrological network and forest fires. Hence, nearby human populations probably had to migrate. New C^{14} dates for the eruption yield a young age (AD 1250); just before the initial rise of the Tarascan Empire (AD 1350–1521) in this region. By volume, this is certainly the largest eruption during the Holocene in the Trans-Mexican Volcanic Belt, and it is the largest andesitic effusive eruption known worldwide for this period. Such a large volume erupted in a relatively short time bears important implications for evaluating future hazards in the Michoacán–Guanajuato Volcanic Field. Equally interesting is the fact that some of El Metate's lavas became one of the prime sources of raw material for the manufacture of grinding stones (metates and molcajetes) in Michoacán. This artisanal tradition is still alive in the Purépecha town of Turícuaro and probably goes back to pre-Hispanic times. Hence we show how collaboration between geologists and archaeologists can lead to better understanding of the relationship between human society and their volcanic environment.

The climatic and societal impacts of distant volcanism on late Stone Age foragers in Arctic Norway at around 3600 BP

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Using multiple archaeological, chronological and environmental proxies, this paper makes the case for a possible distant volcanic forcing of human demography in late Stone Age Arctic Norway, and the response mechanisms responsible for bringing about the termination of the so-called Gressbakken complex, a marine-oriented cultural complex of considerable complexity with large sites and elaborate material culture. We show that very likely volcanically induced, long-lasting climate deterioration around 3600 cal BP coincided with a population decline as reflected in the frequency of radiocarbon dated archaeological material as well as a major change in material culture and settlement pattern. Together these proxies suggest a return to less complex forms of social and economic organisation. We review the relevant tephrochronology and the demographic and ecological mechanisms potentially responsible for this event, and discuss the material culture and settlement pattern characteristic for this period in an effort to disentangle the relation between culture historical changes and demographic fluctuations in the area. Significantly, the changes recorded in Arctic Norway reference both changes in the biophysical environment but most likely also changes in the cultural and political geography of Europe at the time. The results indicate that the Gressbakken collapse was of a social/organizational character rather than a demographic collapse, resulting in settlement abandonment, relocation and a shift toward inland exploitation requiring increased mobility. Our study supports the notion that increased social complexity actually increases vulnerability in the face of rapid biophysical and social network changes.

S03.11 Talk

Small monogenetic eruption causes large environmental impact: The case of the ~cal 29,000 BP Alberca de los Espinos tuff cone and the Zacapu lake (Michoacán, México)

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Alberca de los Espinos is a 110-m-high tuff cone with a 740-m-wide crater that erupted ~cal 29,000 BP at the former outlet of a large but shallow lake occupying the tectonic Zacapu basin in the west-central part (Michoacán) of the Trans-Mexican Volcanic Belt. As a result of this phreato-magmatic eruption, the outlet became blocked and the table of the lake rose by several meters before spilling over a topographic low near the present town of Villa Jiménez and, hence, reconnecting the lake with the Lerma river to the north. As a consequence of the eruption the lake surface increased by ~30%, from ~205 to 310 km^2, expanding a life-habitat hosting numerous aquatic plant and animal communities, that later became attractive as a source of food and other commodities to early nomadic humans peopling central Mexico. Much later, during the Holocene, the perennial occurrence of water and fertile soils near the lake's shore promoted the development of agriculture in this area, as evidenced by numerous pre-Hispanic archaeological sites discovered nearby. Our study shows that palaeo-environmental studies of lacustrine sequences need to consider not only climatic factors, but also tectonic and volcanic activity as potential variables controlling the level of lakes in central Mexico. Furthermore, the present case is a good example for how even small eruptions can have long-lasting effects upon the ecosystem contributing to the atractiveness of entire regions and the fostering of human dwelling hubs.

S03.11 Poster

Statistical Analysis of Volcanic Disaster Database

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The direct and indirect economic damage of the volcanic ash has been brought to Korea by the volcanic eruption in March and April of 2010 from Mt. Eyjafjallajökull in Iceland. Along with this situation, the concern about the potential damage caused by the volcanic eruption of Mt. Baekdu, which had a large-scale explosion record of VEI 7 in the mid-10th century, has increased. However, it is difficult to accurately predict the time and size until the volcano actually erupts and it is a very uncertain risk due to the characteristics of the ash that causes social and economic damages of large scale once it explodes. In addition, it is difficult to collect information and data because there are not enough organizations to provide professional information on damages caused by volcanic ash. The purpose of this study is to collect data on human injury, facility damage, and industrial damage caused by volcanic eruptions occurring worldwide, and to utilize it as a basis for analysis of volcanic disasters.

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Historic Record of Ash Cloud Movement from Mt. Baegdu Volcano on October 21, 1654

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The volcanic history of the volcanic ash cloud movement recorded in the annals of the Choson dynasty in 1654, presumably due to explosive eruptions from Mt. Baekdu volcano, Korea. On October 21, 1654, volcanic ash and volcanic gas erupted from Mt. Baekdu could be interpreted as wind-remobilized volcanic ash cloud, which was transported to low altitude by winds of north and northeast winds and descended to the south of the peninsula along with volcanic ash clouds. The affected area appeared northward in the southern boundary of Hamgyeongdo, North Korea, which is estimated to have moved the volcanic ash from Mt. Baekdu to the south of the Korean peninsula. Clouds of volcanic ash have passed through Jeokseong and Jangdan area, Gyeonggido (near Seoul) about 500 km away from Mt. Baekdu. This is interpreted as a result of the formation of a volcanic ash cloud along the ground in a curved shape due to the influence of the strong prevailing wind, which was formed by Plinian-type eruption at Mt. Baekdu. This is reproduced by numerical simulations on the similar weather pattern model.

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S03.13 - Geothermal Energy Exploration and Evaluation in Volcanic Environments

Magnetotelluric study for searching Teide volcano magma chambers, Tenerife, Canary Islands

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The Teide volcano (3717 m.a.s.l) is the central structure of the island of Tenerife (Canary Islands, Spain) and together with the Pico Viejo as well as the Las Cañadas caldera form the most important complex of the island known as the Las Canadas-Teide-Pico Viejo Complex. The regional 3D electrical resistivity model of the island (Piña-Varas et al., 2014, 2015 and 2018 and García-Yeguas et al., 2017) has reveal the internal structure of the island being a low resistivity structure associated to the clay cap the most distinctive feature of the model. In this work we present the results obtained from the acquisition of new magnetotelluric stations to detect the presence or not of possible local small shallow phonolite chambers (less than 1 km depth). Thus, previous to the new data acquisition a sensitivity study (Piña- Varas et al., 2016) was carried on to study the distribution of the new magnetotelluric soundings in order to detect the presence or not of low resistivity anomalies that can be associated to those chambers. Joint interpretation of the obtained magnetotelluric results together with other geophysical and geological information is summarised in a hypothetical model, allowing us to better understand the internal structure of the island.

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Environmental and health impact of geothermal power plants, Amiata Volcano, Italia

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At Amiata Volcano geothermal energy impacts the environment in a number of ways:

- The total amount of subsidence since 1992 is only a few decimeters, but it must have been much larger since the beginning of exploitation. Gravel deposition have reduce fertility of soil, erosion of foundations have collapsed two bridges.
- Induced and triggered seismicity pose a relevant risks to poorly constructed houses. The 1-April-2000 induced earthquake has generated much damage in old villages.
- Reduction of the geothermal reservoir pressure which has been induced by geothermal field exploitation has lowered the Amiata Volcano water table by 200-300 meters. In turn:
  1. springs have drastically reduced their flowrate;
  2. geothermal gases enter and pollute freshwater aquifers;
  3. soil gas emissions have increased.
- Emissions from the geothermal power plants at Amiata are significant (Bravi and Basosi, 2014):
  1. for an equal amount of energy production, CO_2 emissions are about 1.5 times those of gas-fired combined-cycle power plants, while the acidification potential is comparable to that of coal-fired power plants;
  2. Ammonia atmospheric emissions, have consistent health costs (calculated in the order of 10-100 M$ per year).
  3. Mercury emitted at Amiata is 42% of the mercury emitted from all Italian industries (an equal amount is emitted from the geothermal power plants of Larderello).
  4. Emissions of Uranium, Tallium, Thorium, etc. although present are unaccounted for.
- An epidemiological study shows a direct correlation between higher environmental concentrations of geothermal pollutants and an increased number of illnesses and deaths. Also, samples of urines and hairs of people living within a few kilometers, particularly downwind, from the geothermal plants have metal concentrations that are well above reference ideal values.

If the environmental and heath costs are taken into account, Deep Borehole Heat Exchangers (DBHE) are probably the only technology that can be proven to be economically and environmentally friendly.

S03.13 Talk

The seismic sequence of 30th May - 9th June 2016 in the geothermal site of Torre Alfina (central Italy) and related variations in soil gas emissions

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In the framework of a medium-enthalpy geothermal exploitation project, seismicity and soil gas emissions have been monitored in the area of Castel Giorgio-Torre Alfina since 2014. A dedicated local seismic network deepened the knowledge of the natural local seismicity in terms of source mechanisms, high-quality event localization and magnitude estimation. From November 2014 to May 2016, 846 seismic events were recorded, with a magnitude range of M_d 0.1-2.8 and hypocentres 4-8 km depth. On 30th May 2016 a M_w 4.3 earthquake occurred near Castel Giorgio, followed by almost 1700 aftershocks; the moment tensor solution depicts a WNW-ESE oriented normal fault. An overview of the epicentral distributions since 2014, highlights that the active tectonic structures are NE-SW and WNW-ESE orientated. The diffuse soil CO_2 flux is monitored since 2013 in six target areas located around the future production and reinjection wells, in order to assess the level of background natural degassing. In all target areas the maximum value of soil CO_2 flux has been recorded during the 2016 seismic sequence. However, the values of $\delta^{13}C$ of the emitted CO_2 indicated a shallow biological origin of the gas. At Torre Alfina, the Solfanare natural gas emission, with a CO_2 dominated gas, has same composition of the gas hosted in the geothermal reservoir. Here, high values of diffuse soil CO_2 flux were recorded. During the 2016 seismic sequence, the Solfanare gas was continuously analysed by an automatic gas- chromatographic station. Results show that apart from small perturbations, no significant compositional variations were recorded. The significant contribution of CLVD and isotropic components suggest a possible opening of fluid cracks below the geothermal reservoir hosted in fractured Mesozoic limestones. The seismo-tectonic scenario indicates that the Solfanare fault was not activated. Kinematics and orientation of the activated faults suggest a relationship with the Bolsena caldera collapse.

Rule of thumbs for ambient noise tomography at a local scale

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In recent years the development of techniques of seismic tomography using ambient seismic noise opened new possibilities in the field of scientific and industrial exploration of the Earth's crust. Not requiring active sources it provides a cheap and convenient technique which can be applied nearly everywhere, at arbitrary spatial scales. The major drawback of this technique is the need for long field surveys, with acquisition times usually spanning from a few weeks to a few months, depending on the specific case.

This technique essentially consists in retrieving empirical Green's functions (GFs) between pairs of stations by cross-correlating the background noise signals. Those cross-correlations can be used for different applications as the determination of surface waves dispersion curves to perform ambient noise tomography. Depending on the considered frequencies and the distances between the stations, the achievement of reliable GFs depends on the length and the quality of the considered signals. In practice a long recording is split into smaller windows, on which cross-correlations are computed. The resulting functions are then stacked, after removing noisy windows where transient signals may disrupt the retrieval of GFs.

One of the main problems in achieving empirical GFs of good quality is determining the optimal length of the recordings. This is a relevant problem when designing an ambient noise tomography experiment, which has of course economic implications.

In this work we propose empirical rules which, depending of the inter-station distance and the considered frequency, allows estimating "a priori" a minimum data acquisition time. Furthermore we compare different criteria to check the quality of the retrieved GFs during an ongoing experiment.

Monitoring volcanic and geothermal fields using seismic noise: the case study of the Las Tres Vírgenes geothermal field (Mexico)

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Volcanoes are known to be dynamic systems where physical properties change over the time because of the magma ascending into the main and secondary conduits. Geothermal systems under exploitation are often compared to volcanoes because re-injection of fluids in depth through wells may create small perturbations of the field that could induce seismicity.

In the last decade the analysis of large records of seismic noise allowed to retrieve useful information about the non-stationary condition of the physical properties of volcanoes with the aim to develop efficient forecasting eruption models. Also the first attempts to detect seismic velocity variations during injections also showed that the seismic noise monitoring might be use to observe and describe such variations over the time.

In this work we show how the seismic noise correlation technique can be applied to monitor changes on seismic velocities into a geothermal field operating in a volcanic region, and which part of the observable is originated by the power plant activities and which one related to the natural activity of the area. Here, we show also how the velocity changes observed can be used for exploration propose.

Groundwater survey at Ischia island after the August 2017 earthquake

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Fractured geothermal reservoirs assessment continues to challenge geoscientists due to their complexity and unpredictable nature (Maffucci et al., 2015). Fault architecture play a major role in fluid flow circulation, especially where high temperature are present because of intense water-rock interactions. Ischia has an intense surface thermal activity (springs, fumaroles) that reveal the presence of a hot hydrothermal system at shallow depth. In fact, geothermal gradients of 150-220°C/km^{-1} have been measured in the wells of the south-western sector of the island. The complex aquifer system indicate that fractured lava layers could represent the main hydrothermal source. Based on the hypothesis that changes or movements along faults may influence the fluid flow, we survey the thermal waters in and out the epicenter area of the M4.0 earthquake that occurred in 2017.
13 thermal waters and 2 cold-water were collected during December 2017. Thermal water data show a wide range of electrical conductivity (2.3-16.6 mS/cm), pH (6.9 - 9.1) and temperature (29ºC-70ºC) values. Comparing the concentrations with some historical data is not possible indicate a clear trend. Some point has less temperature and less salinity (nº6) and other indicate a temperature increasing with no salinity loss. Eh in situ measure are positive in all samples except for samples nº5 (-60mV) and nº6 (-86mV). The system appears feed by surficial waters as indicated by Eh (19-140mV) and nitrates (7-76 ppm) values.

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S03.13 Talk

Evaluation of the low-enthalpy geothermal potential in volcanic terrains: a case study from the Island of Salina (Aeolian Islands, Italy)

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Geothermal energy in Sicily could play a key role among renewable resources. Indeed, numerous active volcanic zones (Etna, Aeolian Islands, Pantelleria) or areas with high hydrothermalism (Paternò, Sciacca, Mazara del Vallo, Termini Imerese) make the region very suitable for the exploitation of medium-high enthalpy geothermal resources. Although there are anomalous geothermal gradients with rather high temperatures at shallow depths, there is also a huge low-enthalpy geothermal potential in the shallow subsurface that is not always economically used. The Aeolian Arc is one of the most interesting geo(hydro)thermal site of Southern Italy, which could offer exploitation of geothermal resources from low to medium-high enthalpy. Here, we present a case study from Salina, focusing the attention particularly on the area of Santa Marina Salina. Exploration of the subsurface with assessment of lithological and petrographic/petrophysic characteristics of rocks (e.g. type, structure and texture variability, thermal conductivity, etc.) has been performed. Results provide indications about the maximum possible low-enthalpy geothermal energy potential, which is useful for planning technical solutions characterized by high efficiency. The detailed field survey allowed us to get information on lithological/lithostratigraphic features and hydrogeological conditions of the area, with extension of the thematic cartography to the shallow subsurface (0-150 m of depth). These data have been used to derive the distribution of thermal conductivity of the subsurface at various depths. Application of a theoretical model has led to the definition of the most favorable areas for exploitation of low-temperature resources through vertical closed loop systems by using geothermal probes installed at depths lower than 100 m. Our data become crucial for the correct sizing of low- enthalpy geothermal installations.

S03.13 Poster

Soil gas physico-chemistry for geothermal exploration application on the volcanic oceanic island of Gran Canaria, Spain

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Geochemical prospecting of soil gases and volatiles in the soil matrix itself can provide information on which areas are permeable as well as potential gas upflow zones. Gran Canaria is one of the central islands of the Canary Archipelago, located off the West African continental margin. We report herein the results of an intensive soil gas physical-chemical study in the younger northeast portion of Gran Canaria, carried out during June-November 2017, to investigate the possible existence of permeable portions of deep-seated actively degassing geothermal reservoirs. Several physico-chemical parameters of the soil gas matrix were studied, with particular attention to soil CO_2, He and H_2, due to their unique characteristics as geochemical tracers. Around 3000 sampling sites were selected covering ~603 km^2 in the central and north-east sections of Gran Canaria, where Holocene volcanism has taken place. The accumulation chamber method was used to perform soil CO_2 efflux; soil gases were sampled at ≈40 cm depth using a metallic probe with 60 cc hypodermic syringes and stored in 10 cc glass vials for later laboratory analysis. Diffuse CO_2 output released from the study area was estimated at 3,509 ± 57 t d^{-1}, which represents the highest normalized emission rate of the Canaries, excluding Teide volcano. Soil He concentration ranged from 5.2 up to 76.9 ppm, with an average of 6.0 ppm. Soil H_2 concentrations ranged from typical atmospheric values to 31.2 ppm, with an average of 0.8 ppm. Soil CO_2 concentration and isotopic composition data show total CO_2 comprised variable mixtures of atmospheric and biogenic CO_2, with small inputs from deep-seated (volcano-hydrothermal) sources. The results given here can help to identify the existence of permeable portions of deep-seated actively degassing geothermal reservoirs, particularly where the application and interpretation of geophysical data is difficult.

S03.13 Talk

Overview of a new geothermal resource assessment for the State of Hawaii

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Electricity prices in the State of Hawaii are the highest in the USA and about double the national average, in part due to the fact that roughly 80% of Hawaii's energy is from imported petroleum. The Hawaiian Islands are volcanic in origin, yet the extent of the State of Hawaii's geothermal resource is largely uncharacterized. A statewide geothermal resource assessment published in 1985 found a potential resource on all islands. Since then, little additional exploration was conducted, until the US Department of Energy-funded Hawaii Play Fairway project, which started in 2014 and is ongoing. Phase 1 of this project identified, compiled and ranked existing geologic, groundwater, and geophysical datasets relevant to subsurface heat, fluid and permeability. A statistical methodology to integrate these data into a resource probability map was developed, and provided a new statewide resource assessment. Phase 2 of the project involved collection of new groundwater and geophysical data in 10 locations across the state, with an intensive focus on Lanai, Maui, and central Hawaii Island, as well as modeling of topographically induced stress to better characterize permeability. Phase 2 data were incorporated into an updated resource probability map. Here I will present an overview of Phases 1 and 2 of the Hawaii Play Fairway project, and comment on Phase 3.

The Salinelle of Paternò mud volcanos: first results on water and soil compositions and continuous temperature monitoring aimed at a correlation with Mt. Etna activity

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The salinelle of Paterno mud volcanos are a well know phenomena developing at the border of the Mt. Etna (Sicily – Italy), the largest European volcano. They outcrop in 3 sites near in an area of a few kilometres at the interface between the sedimentary sequences and the volcanic lava flows. Usually the water temperature from the volcanos is cold but it is known that sometimes it can reach up to about 50°C, usually in correlation with the activity of the Etna. The aim of the study is to characterize the emission of this areas.

The programme is to collect samples of water and soil in different time steps to quantify chemical, mineralogic and physical variations. Moreover, 3 temperature sensors were set-up and they are measuring in continuous the temperature changes in pooling waters.

In particular, in the field will be done: thermographic measurements using infrared camera, temperature and thermal conductivity of both soils and water/mud, temperature profiles in proximity of wells close to the mud sources area, together with pH, Eh, Oxigen, electrolytic conductivity, alkalinity, VOC, CO_2.

On the sampled materials - in the lab - will be performed: solid/liquid ratio, density and porosity determinations for the solid part, grain size analysis, thermal conductivity, mineralogical composition (SEM-EDS with XRF aimed at EDS, ICP), major elements and isotope composition (dO/dH and C) in water.

These results will be compared with the Etna eruptive activity, with the purpose of finding evidences suitable as early warning of new magma up-rise from depth and accumulation into the volcano. Discussion about geothermal potential of the area will be treated.

A multidisciplinary strategy to investigate hydrothermal systems on Mt. Etna volcano (Italy)

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Mt. Etna is characterized by three zones (south flank, upper north-northeast flank and west flank) with a higher density of eruptive fissures than other parts of the volcano. These areas are assimilated to volcanic rift zones. Similar to classic rift zones, those of Mt. Etna may host hydrothermal systems. In the north-northeast rift zone (NNERZ), visible steam emission occurs in a stable way from the ground, sometimes along fractures and/or old eruptive fissures, at altitude between about 2400 m and 2600 asl. Along the south rift zone (SRZ) active hydrothermal systems occur only above 2600 m asl and mostly close to the summit craters. No such evidence occurs in the west rift zone (WRZ). We applied a multidisciplinary strategy, integrating data from different geochemical and geophysical prospecting methods (soil heat flux, soil CO_2 flux, self-potential and geomagnetism), to define the mechanism of gas/fluids transport from depth to the surface in the evident hydrothermal systems of the NNERZ, and to possibly detect new hydrothermal systems across the SRZ in places where they have no field evidence. We carried out two parallel profiles of measurements across the NNERZ, showing a clear active convective system centered on the 2002 eruptive fissure. We also carried out measurements across the SRZ at an altitude between 1800 and 2000 m asl and the results showed evidence of an active large, double convective system with fluids that rise along faults/fractures located at the sides of the hydrothermal system and then flow back down, after condensation, along its central part. This system is relatively shallow and testifies a large transfer of mass and energy along the SRZ.

S03.13 Poster

Communication and geoethics in Italy since 2012 about geothermal Energy on cities on volcanoes

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The paper is a scientific study – using the Communication Science tools - to analyse the "messages" appeared on the media, coming from various sources, on argument: geothermal energy on cities on volcanoes in Italy. The work was performed from 2012 to 2018, in Italy, in a critical period where at least 1000 articles/video, etc… were published. The articles published in newspapers and on blogs are analyzed in details, highlighting the positive and negative aspects of those who dedicate themselves to scientific communication, journalists, bloggers. Is considered in detail how the written texts and the scientific communication, that provides those who are involved in responding to the requests of the populations, NGOs, stakeholders, policymakers, for a better geo-ethics reliability of the geothermal technologies. The most important fairs of citizens are analyzed and some solutions are discussed. This can, indeed, be done homogeneously and consistently through press releases, videos, letters to newspapers and group of interviews. It is absolutely necessary to establish a priori how to handle possible errors, unfortunately always possible, to present correct and appropriate reviews, as soon as possible, always explaining in a transparent way the reasons for errors. Credibility is something irreversible if lost.

S03.13 Talk

Geochemical potential in South-east Sicily assessed from a review of hydrochemical data

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The south-eastern sector of Sicily, namely the Hyblean plateau, is important because it is densely populated (almost one million people live there, distributed among thirty-five municipalities), it is site of two of the largest industrials poles of southern Italy and because of the many economic activities locally carried out, mostly related to agriculture (grapes, lemons, oranges, almonds, tomatoes, cheese, etc.). We studied this area in order to evaluate its geothermal potential through the analysis of a large dataset of chemical parameters in local groundwaters (data from 143 water sampling sites). We recognized and thence selected the most promising sites from their main geochemical characteristics. From their calculated equilibrium temperature (between 50 and 90 °C), using different geothermometers, we applied Principal Component Analysis (PCA) to this restricted dataset. In this way, we were able to discriminate between different sources of solutes, both natural and anthropogenic. Mapping of the factor scores obtained from PCA allowed us to distinguish the areas with the highest geothermal potential. This study opens new perspectives on the possible use of geothermal energy in east Sicily both for heating and, potentially, also for the production of electrical power using binary systems.

S03.13 Poster

The seismogenic potential of withdrawal- reinjection cycles: numerical modelling and implication on induced seismicity

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Induced seismicity can be associated to the activity of fluid withdrawal and injection from/into the shallow crust (fracking, wastewater disposal into the deep crust, EGS technology, fluid extraction in oil fields and geothermal power plants). Long-term injection of large volumes of fluids is normally associated with induced seismicity, but the effect of withdrawal-reinjection in the same reservoir is largely unknown. However, it is common experience worldwide that small geothermal plants with withdrawal and re-injection of fluids in the same reservoir are not associated to any significant seismicity. This paper aims at understanding how to discriminate the seismogenic potential of withdrawal-reinjection with respect to injection only. With this aim, we analysed the induced pressure changes, the perturbed volumes of rocks and the potential for induced seismicity due to the above activities. A set of simulations of injection/reinjection cycles into the same reservoirs, by using the numerical code TOUGH2®, is applied to simple models of geothermal reservoirs, with varying permeability and lateral confinement. For each permeability model, we then compare the time growth of perturbed volumes obtained with withdrawal-reinjection cycles to those obtained during simple injection, using the same flow rates. Our results clearly show that, for all models, withdrawal-reinjection is by far less critical than simple injection, because the perturbed volumes are remarkably smaller and remain constant over the simulated time, so minimizing the likelihood of interference with seismogenic faults. Our results have significant implications for geothermal projects, and in the assessment of the potential risk related to fluid stimulation and induced seismicity.

S03.13 Talk

The thermal spring of St. Venera al Pozzo (Catania, Sicily, southern Italy): historical evidence of a long-standing interplay between man and the volcano

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We describe the site of St. Venera al Pozzo, placed along the eastern flank of Mt. Etna volcano in eastern Sicily (southern Italy), through a multidisciplinary approach based on history, archaeology, geology, geochemistry, geophysics and seismotectonics. The site refers to an ancient Roman *statio* mainly composed both of a thermal bath complex and of a Roman factory, located in a territory very rich of natural water springs, some of which show signs of slight thermalism. The presence of numerous water springs in the Greek period has favored the birth of a settlement where the cult of the associated deities was of great importance. The study area is affected by well-developed tectonic faults, and indeed some archeological ruins are crossed by remarkable fractures, suggesting the occurrence of a capable fault zone across the area. Archaeological evidence of faulting on ancient remains always improves our knowledge on the seismicity and seismotectonics of regions, for which information about the historical seismicity as well as about the evidence of tectonic features is often scarce or uncertain. From an historical point of view, this area was continuously inhabited since 3000 BC due to the presence of copious sulphurous thermal springs, which are normally associated with tectonically active areas. A geochemical monitoring of the gas emissions from these springs was started in early 2018. Anomalous changes in the composition of gases emitted with water (mostly regarding CH_4, H_2S and CO_2 contents) were observed, suggesting that the fault that damaged the archaeological site at least once in the past could be still active and that the local hydrothermal system could be affected by changes in the heat/gas flux coming from the magmatic system of Mt. Etna.

Applications of outdoor unattended micro-gaschromatography and their potential in geochemical monitoring of volcanoes

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Unattended gas-chromatography monitoring stations (U-ChroM) equipped with micro- gaschromatograph, computer, sampling systems, router) have been developed to allow complete remote control of the microGC and the automatic transmission of data. Furthermore, some specific parts have been adapted in order to allow a full automatic collection of gas samples from fumaroles, plumes, soil and also of dissolved gases in cold and thermal waters in well. The instruments also permits in-situ gas analyses on samples either collected in vials or directly through a line stuck in fumaroles or in the soil. This technique allows to obtain very quickly, in nearly real-time, soil gas concentration maps. We have already tested these devises during the unrest crises of Santorini (Greece), Turrialba (Costa Rica), Solforata (Campi Flegrei, Italy), as well as at the quiescent La Fossa volcano (Vulcano Island, Italy). We present some of these soil gas concentration maps as well as the results of continuous time series of collected data on fumaroles at Vulcano and on soil gas and gas dissolved in thermal water at the geothermal field of Torre Alfina (central Italy), discussing their geochemical and hazard implications.

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S03.14 - From old cauldrons to young quaternary calderas context, processes, and economic potentials for geothermal energy and ore resources

The Tulancingo multi-collapse graben caldera and the intra-caldera Acoculco lava dome complex, central-eastern México: A potential site for geothermal energy

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Acoculco (Puebla) is a potential site for geothermal energy and has been studied since the 1980s by Comisión Federal de Electricidad Mexican agency. Previous studies indicate that Acoculco is an elliptical-shaped caldera, 18 by 15 km in diameter, nested within the 32 km Tulancingo caldera (López-Hernández et al., 2009). Recent studies in Acoculco by other groups confirm its character of caldera. Our stratigraphic and structural work in progress suggest an alternative explanation for this complex; there is a Tulancingo caldera, but it is graben type, as defined in Aguirre-Díaz (2008), linked to regional fault systems in the area, and Acoculco is not a caldera but a lava-domes complex formed in the central part of the Tulancingo caldera. This interpretation agrees with geophysical studies and with the information from two deep wells (2000 m) in Acoculco. Tulancingo caldera started activity at about 2.7 Ma and finished it at about 0.8 Ma, with several caldera collapses associated to pumice fallouts and ignimbrite-forming eruptions, with emplacement of lava domes in between and at the end. The youngest rocks are scoria cones and related mafic lavas as young as Pleistocene, which are aligned to the fault trends. Geothermal heat in the zone may be related to this mafic volcanism and the local fault system of the graben caldera with no need of a subcaldera magma body for the heat source. Another hypothesis is that there is a subcaldera magma body which heat was preserved until Present by continuous inputs of mafic magma that fed the scoria cones. Both hypothesis would explain the heat anomaly just beneath the Acoculco dome complex, where there is fumarole activity, and the anomaly at the Chignahuapan fault at the SE border of the graben caldera, with intense hot springs.

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Induced and trigered events in geothermal fields following large earthquakes. The example of the Los Humeros caldera, Mexico

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The local seismicity in geothermal fields is generally associated with perturbations of the pore pressure because of the fluid circulation imposed to run the power plants. On the other hand the geothermal regions are also susceptible to earthquake triggering as a result of transient stress variations caused by surface waves originated by strong regional earthquakes, as documented by several studies. To investigate possible changes in the seismicity rate in geothermal fields during and after the occurrence of regional strong earthquakes, we have analyzed the seismic records of 3 strong earthquakes that have been recorded in the Los Humeros geothermal field, Mexico; the first one, of magnitude 8.2, occurred on September 7, 2017, 500 km southeast of the geothermal field and associated with the interplate slipping of the Cocos subduction zone. The second one occurred after 12 days, on September 19, 2017 had magnitude 7.1 and located 180 kilometers southwest of the geothermal field and considered as an intraplate earthquake. The third event occurred on February 16, 2018 whose magnitude resulted of 7.2 and located 400 kilometers south of the caldera, and associated with the pacific subduction zone too. From these observations an intense local seismic activity has been identified in the geothermal field, from which it has been possible to determine useful information on the active faults of the field and to obtain patterns about the behavior of such induced seismicity.

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Reactivation of the Los Humeros volcanic complex (Mexico), implications for the geothermal field and hazards

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Los Humeros Volcanic Complex (LHVC) is one of the largest caldera systems within the Trans-Mexican Volcanic Belt. It is related to two main caldera collapse events (Los Humeros and Los Potreros calderas) and several explosive and effusive eruptions. Recent studies on its volcanologic evolution based on new geochronologic data (zircon U/Th and $^{40}Ar/^{39}Ar$: Carrasco-Núñez et al., 2018) support a much younger evolution than previously proposed (from 460 ky: Ferriz and Mahood, 1984; to 164±4.2 ky: Carrasco-Núñez et al., 2018) for the initial caldera formation (Los Humeros), which is associated with the emplacement of the large 115 km^3 (DRE) Xaltipan Ignimbrite. Recurrent injections of new magmas have occurred in pulses during post-caldera volcanism, and have greatly increased during the Holocene. This recent volcanism has produced contemporaneous explosive eruptions of both rhyodacitic and basaltic-andesite magmas at 7,300 yr B.P. (Cuicuiltic Member), followed by an intense period of mostly monogenetic activity erupting lavas and pyroclastic material of diverse composition including trachytic, trachyandesitic, basaltic-andesitic and basaltic lava flows, pumice and scoria fall deposits. This volcanism is distributed in all sectors of the caldera, except in the western rim, and is much younger towards the southern caldera ring- fracture system, where the recurrent injection of new magmas during the Holocene seem to seal these conduits as geothermal fluid´s paths. Prehistoric lavas form a well-defined extracaldera lava field derived from about a dozen of vents that erupted multiple lavas of different composition in two main periods (3,800 yr B.P. and 2,800 yr B.P.), as suggested by C^{14} dating and paleomagnetic data. This activity reflects recurrent injection of magma with important implications of hazard to the future. At the same time this rejuvenation of the magmatic system reveals more favourable thermal conditions for greater geothermal potential.

Structure of the Los Humeros geothermal field, Mexico, using seismic noise tomography

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One of the major high enthalpy geothermal fields in México (T > 350 °C) is installed into the caldera of Los Humeros, which has been intensively studied in the last decades to develop the actual power plant. Nowadays the power plant consists of almost about 45 wells (between producers and injectors), where only 21 are exploited allowing a net electric power of about 40 MW.
However, until now the deeper part of the calderic systems is unknown as well as the heat source feeding the shallow geothermal reservoir making difficult to understand the inefficiency of some wells and to plan new extension of the power plant. In this work we present the results of a noise cross correlation tomography performed using 45 seismic stations installed in the framework of the Mexican-European project GEMEX. Data processing of the first months of data allowed for the reconstruction of Green's functions for most of the stations pairs, and thanks to NDCP, a newly code developed to fairly estimate group velocity dispersion curves, we were able to build tomograms of the Los Humeros caldera for periods ranging from 1 to 7s. The tomograms with larger period are expected to image the heat sources feeding the geothermal reservoir allowing a better plan for the future activities of this important geothermal field.

This work is performed in the framework of the Mexican European consortium GeMex (Cooperation in Geothermal energy research Europe-Mexico, PT5.2 N: 267084 funded by CONACyT-SENER: S0019, 2015-04).

New passive seismology network deployed in Los Humeros caldera (Mexico): first results

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Recent research in super-hot geothermal systems, where deep geothermal fluids exceed temperatures of 350°C, has been conducted in several areas in the world. Most of these systems are poorly characterized. We therefore propose the usage of passive seismic approach, which has demonstrated its usefulness in currently exploited geothermal areas.

The geothermal system at Los Humeros (Mexico) is currently exploited. The northern part of the area, however, is much hotter (>380°C) than the wells used for production today. The development of this part of the reservoir presents a challenge, both because of the high temperature and because of the water chemistry. In addition, the area has only been poorly characterized by geophysical and geological surveys. Therefore our understanding required for the development and exploitation of this super-hot resource is limited.

In order to address those challenges, we deployed in august 2017, within the framework of a collaboration between the EU Horizon 2020 GEMEX project and Mexico, a new network of 45 seismic stations in the caldera of Los Humeros caldera, Mexico. The network has been designed in order to allow us to apply several imaging and monitoring techniques, such as travel time tomography, ambient noise techniques, etc. Our objectives are multifold. For example, we will use natural and induced earthquakes to image the structure of the caldera with a focus on the exploited areas. Where no earthquake occur, we also use ambient noise techniques for imaging at least the S-wave velocity structure. We present first results of the campaign and will discuss the next steps of the study.

S03.14 Poster

Assessment of geothermal potential in the Aeolian Islands, Italy using continuous seismic noise records

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Volcanic fields are subject to several seismic phenomena due to its particular tectonic set and, at the same time, these host hydrothermal systems of great interest for geothermal exploitation. In recent studies, changes in the physical properties of geothermal systems (pore pressure, fluid circulation, etc.) were observed as small temporal variations of seismic velocities. These changes are measured using seismic noise cross-correlation functions (CCF) and the Moving Window Cross Spectrum (MWCS) analysis between pairs of stations. The analysis of such a temporal velocity variation (dv/v) makes it possible the detection of areas with geothermal potential as zones where large dv/v are observed. In order to assess the potential of this method we analyzed long time series of seismic data recorded at stations installed by the Italian Instituto Nazionale di Geofisica e Vulcanologia on the Aeolian Islands, Italy, where large hydrothermal systems have been documented and studied since long time (Boyce *et al*, 2007; Revil *et al*, 2011; Finizola *et al*, 2002). To obtain the dv/v curves, we calculated one-day cross-correlograms between pair of stations for long time series. Signal processing included instrument response correction, 1-bit normalization, spectral whitening, CCFs from 1-hour chunks, stacking of a day (current CCFs), stacking of a longer period of time (reference CCF) and the MWCS analysis using the MSnoise software. Mapping the dv/v variations along all station pair trajectories is giving us an idea where the zones with geothermal potential are allowing the validation of the method for geothermal assessment.

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S03.14 Poster

Petrogenesis of the magmatic heat source of the Los Humeros caldera geothermal field

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The Los Humeros Volcanic Complex (LHVC) is located in the northeastern Trans-Mexican Volcanic Belt (TMVB) and it is one of the three most important geothermal fields in Mexico with, in 2017, an installed 65MW of electric power produced from 20 wells (Carrasco-Nuñez et al., 2017). The LHVC is a large active resurgent caldera on a basement constituted by Mesozoic limestones and Miocene-to-Pliocene andesitic lavas. The LHVC magmatic history starts at ca 700 ka, characterized by explosive and effusive events with erupted products spanning from basalt to rhyolite. The LHVC is characterized by two major-caldera forming eruptions that produced Xaltipan (164 ka)and Zaragoza (70 ka) ignimbrites and generated Los Humeros and nested Los Potreros calderas respectively. Recently Carrasco-Nuñez et al. (2017) reviewed all existing geochronology and geochemistry data that were integrated in the new detailed geological map of LHVC.

In this study we present a comprehensive study of the whole rock geochemistry of rock samples from the full rock stratigraphy. Magma types belong to a subalkaline to alkaline serie with medium-K to shoshonitic signature. Trace and rare-earth elements behaviors suggests a supra-subduction zone magmatism. Trends of major elements together with Sr- Eu contents suggest a main control of plagioclase on evolution of melts.

Aim of our work is extend the present knowledge with an implemented dataset (mineral compositions, whole rock and Sr-Nd isotope geochemistry). These data define the source of the LHVC magmas, the acting FC-AFC processes responsible for the wide compositional range of erupted products and the thermobarometric conditions of the LHVC magma- storage system.

Defining the initial development strategy for the Borinquen geothermal field (Cañas Dulces caldera, Costa Rica)

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The uncertainty regarding the dimensions and exact location of the geothermal resources associated with caldera systems, along with the cost of drilling process of geothermal wells, are usually two factors that hinder the wider use of high enthalpy geothermal energy to generate electricity. In this contribution we show how we defined the exploration strategy, from the characterisation and quantification of the energy potential, of the Borinquen geothermal field in Costa Rica. This geothermal resource is located in the Cañas Dulces caldera, which is home to the Rincón de la Vieja-Santa María active volcanic complex and forms part of the northwestern sector of the inner magmatic arc of Costa Rica, together with other calderas and the active volcanoes of Miravalles, Tenorio, and Orosí-Cacao. In order to design the initial development strategy, we combined available and new topographic, geological, geophysical and thermal gradient data, together with a conceptual model of the hydrothermal system. As a result, we obtained a suitability model that allowed us to identify the most appropriate locations for drilling pads, zoning the high enthalpy geothermal resource, and to identify the areas to be used as production and reinjection poles of geothermal fluids, as well as to estimate the electrical energy that could be produced by the geothermal reservoir.

The Jubones Fm: an Oligocene VEI 7 caldera-forming eruption

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The Jubones Fm. (26 - 23 Ma - Pratt et al. 1997) crops out in the Giròn - Santa Isabel basin, in the southern sector of Ecuador between 3° and 4° S of Western Ecuadorian Cordillera and it covers ca. 2700 km^2. The Jubones Fm. stratigraphically represents one of the last eruptive events of the Saraguro Fm.

The Jubones Fm consists of 4 high aspect-ratio ignimbrites (named B1, B2, B3 and B4) with maximum thickness of about 500 meters and a maximum run out of 30 km from the inferred source. The main lithofacies were characterized to locate the volcanic source and reconstruct the paleotopographic environments. The caldera is located in the sector of El Tablon and San Sebastian de Yulue, as evidenced by the presence of massive lithic breccia and in accord with main flow direction indicators. The four ignimbrite units generally present a basal dark-toned crystal-poor vitrophyre where mm-size fiamme are visible. In contrast, the main body of the ignimbrite is very crystal rich with a high quartz content (≈20 vol.%). Small amounts of hornblende and biotite permit to distinguish the four units. The texture of the Jubones Fm. is characterized by a parataxitic fiamme that permit to reconstruct the main flow directions. Fumarole pipes and blister structures were recognized within different ignimbrite level. Unit B1 volume was determined using 4 different interpolation methodologies (Spline, Natural neighbor, krigging and IDW) using GIS methods with the thickness values. The calculated total volume of the B1 unit is 101.9 ± 0.2 km^3. Taking in account that this value is a minimum volume value, the eruption was a 7 VEI (volcanic explosivity index). This work permitted to determine and classify a caldera- forming eruption that hit the southern sector of Ecuador during the Oligocene and to estimate the volume of its product.

S03.14 Poster

Evidence For A Miocene Caldera-Forming Eruption at Pucarà (Azuay, southern Ecuador)

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The volcanic sequence in the Pucará-Santa Isabel sector (southern sector of Ecuador) is composed by the Saraguro Fm. (26-21 Ma) followed by the St. Isabel Fm. (18 – 7.6 Ma) and the Tarqui Fm. (6.3 Ma). Series of thin welded ignimbrites mainly compose these volcanic sequences. They show large lithofacies variability (boulder to lapilli-size lithics, crystal rich and fiamme-rich ignimbrites) that reflects different PDC run-out and principally different sources. The geomorphology and the tectonic environment show a complex volcanic system that was influenced by the Calacali – Pallatanga Fault (NE -SW trend) and locally by the Jubones (W-E trend) and Giròn (NE-SW trend) faults.

A major eruptive cycle started with the St. Isabel Fm. that stay above the lacustrine sediments of the Jacapa Fm. SW of Pucarà is present a partly dismantled elliptical depression, on the edge of which brecciated ignimbrite deposits are locally exposed. These ignimbrites are characterized by a coarse-grained ash matrix with m-sized boulders and heterogeneity of the nature of the lithic fragments. These lithofacies are interpreted as products of a large eruption whose source caldera, in accord with cinematic indicators and lateral facies variations, is sited in the North of Pucará city. Stratigraphic and geomorphologic constraints allow us to associate the eruption of the St Isabel ignimbrite with collapse of the ~13 X 7-km-wide Pucará caldera.
The aim of future work is to obtain a detailed characterization of the geometry and evolution of the Pucarà caldera, and to document the lithofacies of the ignimbrite in order to assess the mining potential of this miocene caldera.

S03.14 Talk

Link between gulf-inherited regional structures and hydrothermal circulation inside La Reforma Pleistocene caldera complex, Baja California Sur, Mexico

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La Reforma is a 10 km wide nested caldera complex located 20 km NW of Santa Rosalía, Baja California Sur, Mexico. Pleistocene volcanism moved from La Reforma (1.38 Ma) to Sierra Aguajito (1.17 Ma, Schmitt et al. 2006) and to Las Tres Vírgenes (Middle Pleistocene- Holocene) complex, currently hosting the fourth largest producing geothermal field in Mexico (Gutiérrez-Negrín 2015). Detailed field mapping and structural analysis performed across Las Tres Vírgenes region during 2015-17 (CEMIE project) allowed to reconstruct the caldera main phases of evolution, the Quaternary interplay between regional and volcano- tectonic features and related geothermal potential. Four caldera-forming ignimbrites and several ring fault systems characterize La Reforma syn-caldera phase and at least two separate resurgence pulses (syn- and post-caldera) have been recognised. The structural character of the study area is complicated, as regional features combine with volcano- tectonic structures. Faults, fractures, veins, dykes and intrusions mapped at the scale of 1:25,000 were sorted according to their regional or volcano-tectonic nature. Major regional lineaments consist in NW-SE trending dextral strike-slip structures inherited from the Gulf of California spreading phase (Miocene) and reactivated in a transtensive regime following stress rotation induced by the San Andreas Fault recent dynamics. These, together with NE- SW conjugate fault systems and N-S normal faults, are responsible for the fractal repetition of the pull-apart geometry at several scales (macro-, meso-) throughout Las Tres Vírgenes region. Volcano-tectonic structures, mainly including ring faults and resurgence-related ENE-WSW striking reverse faults and folds, overlay this network of regional active features. This study reveals the strict link existing between regional gulf-inherited features and magmatism, hydrothermal circulation, as well as their active role, together with resurgence, in exhuming Cretaceous basement cropping out in and around La Reforma caldera. Pervasive hydrothermal circulation along regional features delineates "warm spots", of primary importance for production optimization and future exploration.

The Santa Cruz Central Caldera Field: concealed Jurassic calderas of the Chon Aike volcanism in southern Patagonia, Argentina

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The Argentine Patagonian region is characterized by a predominantly acidic Jurassic volcanism that stretches from the Andean to the extrandean region, where it forms an extensive volcanic field referred to as the Chon Aike Province, part of a larger silicic LIP and related to the Gondwana breakup. The effusion of the acidic volcanites is linked either to calderas or to large fractures or, most likely, to the combination of both. In the Deseado Massif, southern Patagonia, this volcanism is known to bear gold and silver epithermal deposits which has traditionally constituted an additional interest for its study. Among the main caldera structures so far identified in the Deseado Massif are e.g., in the extra-Andean zone, the La Josefina, Cerro 1º de Abril, El Dorado-Monserrat and Cerro Torta Calderas, and in the Andean region, the La Peligrosa Caldera.

Based on the premise of the existence of additional, unexposed and, hence, still unidentified, calderas in the Deseado Massif, so as to justify the huge volume of Chon Aike ignimbrites, we have scrutized the aeromagnetic data available for this region, with a view to detect new caldera structures. As a result, we have firstly identified two large calderas concealed under thin Cenozoic sedimentary deposits in the Río Seco area, and secondly we have newly identified three additional calderas and a number of associated lava domes in the Los Manantiales area. All of these five structures, with dimensions of –14 to 30km– taken together define a caldera field herein referred to as the Santa Cruz Central Caldera Field, extending roughly in an E-W direction for at least 150 km, and occuring in the context of a structural corridor of the same orientation. The discovery of this Caldera Field may well open a new frontier in the exploration for Au-Ag mineralization in the Deseado Massif.

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S03.16 - Volcanoes in the cities non institutional communication in volcanic areas

Teaching Children to Prepare for Natural Disasters in Hawaii

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CSAV is best known for its International Training Course in Volcano Hazards Monitoring, in which scientists from developing nations learn how HVO & CVO study volcanoes; participants share their methods, as well. But CSAV also strives to educate the general public in Hawaii about natural disasters, since Hawaii has everything: earthquakes, volcanoes, tsunamis, and hurricanes. We know from comparisons of Armero in Colombia, and Rabaul in Papua New Guinea, that an educated public survives. Back in 1995, thanks to a grant from FEMA, CSAV began a series of public outreach programs: public seminars, teacher training classes, working with communities, and visits to schools around the Big Island. Teacher Training programs were brilliant. Schoolteachers loved getting the "inside scoop" on natural hazards, and the program created a "ripple effect," in that, you teach the teachers once, and they teach their classes, for years to come. But by far, the school visits turned out to be the most successful, because children are the most receptive audience—and, they go home after school and tell Mom & Dad what they learned. We found that folks could understand the impact of natural disasters better, if they could relate it to something familiar, something local, so we developed a series of videos, now on YouTube, showing how to prepare for natural disasters. For educational programs like this, it's important to understand the roles that different organizations play, and to speak with one voice. In Hawaii, we have a saying. "If you plan for one year, plant kalo. If you plan for ten years, plant koa. If you plan for a hundred years, teach the children."

The European Volcanological Association (L.A.V.E.): a French-speaking non-profit organization dedicated to general public communications, activities and meeting of volcanology enthusiasts

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Funded in 1986, the European Volcanological Association (L.A.V.E.) is a dynamic association and use predominantly the French language. Currently the association counts nearly 600 members with a passion for volcanoes, coming from all socio-professional groups.

The aims of the association are simple:

Allow people interested in volcanology to meet each other
Carry out communication activities on volcanology dedicated to the general public
Contribute to the development of research in the volcanology field

L.A.V.E. is managed by a board elected every year and divided in delegations. The activities of delegations are centered on **field trips** and/or **presentation of journey's movies/photos and conferences.** Beside this, L.A.V.E. pays particular attention in **providing high quality media from collaborative work** of the members:

The L.A.V.E. journal (190 issues - 40/44 pages) published every 3 months, all in color and offering in-depth articles on recent volcanic activity, travel accounts, scientific articles, photographs and more.
Two **books** titled ***Chasseurs de Volcans***, containing photographs from the association's members. A DVD is provided inside the second edition with footages from the members.
One **DVD:** ***Les Eruptions de L.A.V.E.,*** one hour of videos from 19 volcanoes.
The L.A.V.E. exhibition made of thirty panels and a volcano model, intended for schools and general public.
The L.A.V.E. website with two live webcams on Stromboli and Etna, and containing more than 1800 photographs and 56 volcano-sheets.
A partnership with Vulcania, the "European Park of Volcanism" located in the Chaîne des Puys (France). L.A.V.E. furnish the park with member's pictures and movies illustrating volcanic phenomena.

Moreover, each year, **L.A.V.E. offers a 1000€ grant** in order to support a student research project dedicated to volcanology.

In the future, L.A.V.E. will develop a brand new website and a YouTube channel to keep up with current communication means and also consider a partnership with other foreign organizations to have a more European perspective.

S03.16 Talk

The Vesuvio Guides' role: the importance to communicate the volcano every day

Mara Fogliamanzillo, Imma Sbrescia, Luigi Maisto

Guide Vulcanologiche Vulcano Vesuvio, Italy

Vesuvio is considered one of the most famous and visited volcano in the world.

In the last years, the visitors of the Vesuvio's crater (Presidio Permanente Vulcano Vesuvio area) have been, on average, between 450.000 and 600.000 per year. They are mainly organized groups, single hikers, cruise passengers, international school, university groups that come to visit the volcano to admire its beauty but also for scientific purposes or to practice trekking. The volcanological guides, that works every day on Vesuvio, adapt their own communication regarding the volcano according to the different types of visitors, in order to make it effective.

The profession of Vesuvio Guide has changed a lot since the time of the improvised Ciceroni. The volcanological guides, in charge at Presidio Permanente Vulcano Vesuvio, are winners of a special contest that certified their technical skills and knowledge, physical fitness, knowledge of two foreign languages. they undertake a training that, according to the law (L. 6/89) needs to be updated each three years with a special practical technical training course. Moreover, in the last years, Vesuvio Guide have concluded agreements with the Institute of Osservatorio Vesuviano that provides them professional updates in exchange for cooperation in surveillance monitoring operations.

The daily comunication of Vesuvio Guide on the volcano, performs many task then: stimulating interest, awareness, wonder, curiosity; increasing public awareness the volcano's risk and how to live with it; spreading knowledge of the local environment and how to protect it; monitoring the condition and the practicability of the volcano's paths and safeguarding visitors' safety.

Vesuvio guides: a long history of comunication

Mara Fogliamanzillo, Imma Sbrescia, Luigi Maisto

Guide Vulcanologiche Vulcano Vesuvio, Italy

Vesuvio is certainly one of the most important volcanoes in the world, known mostly for the catastrophic eruption of 79 A.D., which overwhelmed the cities of Pompeii, Hercolaneum, Stabiae and Oplontis. It is also one of the most visited volcanoes in the world because of the easy access, the mild climate and it's no far from the sea and the city of Naples.

For centuries people have reached the top of Vesuvio on foot, on horseback, on the back of a mule, by sedan chair, by funicular or by chair lift. There are thousands of written documents, engravings and gouaches, which reports guides presences and their activity. The oldest document that refers about Vesuvio guides is dated back to 1632, soon after the terrible explosive eruption in december 1631, which caused devastation and death. This eruption drawn the attention of scientists and voyagers for all over the world about Vesuvio, making the neapolitan volcano a must of the european "Grand Tour". From this moment on, it starts the profession "Cicerone del Vesuvio".

The first document that rules this profession, has been issue in 1855, talking about them as Vesuvio Guides of Naples Kingdom. When the Italian Kingdom was founded, Vesuvio Guides became the first Italian Guides. In 1991 they established the first "Collegio Regionale Guide Alpine" in Italy. In 1995 Vesuvio became National Park and nowdays it's Unesco world Heritage Site, and has became one of the most visited natural touristic places in the world.

Currently Vesuvio Guides work every day along the path that leads to "Gran Cono Vesuviano", accompanying, assisting and communicating the volcano to the great amount of tourists.

La Cité du Volcan, Museum of volcanology

Florence Fontaine, Patrice Huet

La Cité du Volcan / SPL Réunion des Musées Régionaux, France

La Cité du Volcan is a museum of volcanology, working in close collaboration with the scientific institutions of La Reunion Island, which study its geology and volcanism. The two main institutions are, the Volcanological Observatory of Piton de la Fournaise (OVPF/IPGP) and the Geosciences Laboratory of the University of La Reunion (LGSR). Recently, we contributed to the dissemination of new knowledge from two projects of these two institutions. The RHUM-RUM project, study of the hotspot of La Reunion Island and the SLIDE VOLC project, study of the major destabilization of flanks of the volcano. The studies and their results, of these two institutions (OVPF/IPGP and LGSR), are valued in La Cité du Volcan through various actions, such as: temporary exhibitions, editions of books and documentary productions, workshop, lectures for the general public, guided tours by our scientific mediators (in the museum and in the field). Updates to the contents of the permanent exhibition are also made as soon as possible, when the results of the studies are validated.

The evolution of technologies and the power of computer hardware (processor and graphics card), has allowed us recently to realize a simulation software volcanic eruptions in 3D hyper realistic and real-time, to allow our audience to better understand, all the characteristics of a volcanic eruption at Piton de la Fournaise. The development of a Virtual Reality interface with this simulator, allowed us to go even further in the immersion of the public, which is at the heart of the speech, for a better understanding.

In the coming years, the integration of Augmented Reality will allow us to take a step further in the diffusion of this knowledge, to reach a maximum of public.

S03.16 Talk

NGO' scientific outreach and communication

Henry Gaudru

Sociéte Volcanologique Européenne, Switzerland

The popularization allows a diffusion of science to a wider audience; it also plays a role in the prevention of natural hazards. Therefore, a good public information requires a good popular science. Deadly volcanic disasters are still too often felt as a deficiency of the scientists to predict a volcanic eruption. This misunderstanding is often related with a lack of appropriate cultural and scientific tools. Eruptions are complex phenomena and there are both epistemic and aleatory uncertainties involved, which can be large, making precise prediction of a certain event in time and space a difficult objective; that is, volcanoes can be intrinsically unpredictable. Scientific outreach and communication for a wide audience needs include a range of approaches and activities to be effective (popular scientific books, conferences, in-school presentation, exhibition, multimedia, field trips... These tools needs directly reach the public as a whole and especially the populations around volcanoes. For various reasons, the institutional communication cannot use regurlarly all these means. Consequently, it is very the important that media, ONG, or associations to disseminate complementary information about volcanoes and their risks. In this way, SVE created in 1992, an education department in the aim to develop a special program for general people, in addition with the scientific work carried out in collaboration with the United Nations.

S03.16 Poster

Volcanes Sin Fronteras: the vision to share knowledge to non scientific public

Gino González, Carolina Salas-Moya, Iván Meza, Roberto Santamaría, Yemerith Alpízar, Carlos Ramírez, Óscar Zúñiga, Michael Durán, Auxiliadora Delgado, Paulina Chacón, Eduardo Redondo, Eduardo Robert

Volcanes Sin Fronteras

Many borders around the world are located very close to volcanoes or on top of them. Therefore, there is a problem in how different countries manages a possible volcanic event, specially if the countries have political problems, so people can be affected.

Another problem is that volcano monitoring usually depends on the budget and ackowledge of the scientist. Also, the information and collaboration with others countries or institutions is very poor.

One of the main problems is between scientists and local people. The first ones have realiability, competence and integrity. However, the way scientists sometimes send the message to the final user is not clear and it could create confusion because the information is contradictory. Moreover, the message is shared to the population in general no matter the distance they live from the volcano. They focused in populated areas, but the risk changes according to the distance, and the most vulnerable people live close to the volcano. In Central America 60% of the population live on top of the volcanoes, and is our responsability to share our research with the communities. It is necessary to ensure continuity to the projects by bringing people closer to the volcanoes with a clear message, education and telling the comunity the benefits of the volcanoes.

VSF is a NGO that pretends to attack these problems with different projects. It is a transdisciplinary team that works on making science and transmitting the knowledge to the non scientitis public by local participation. As a result, the population can understand the geological enviroment where they live and the hazards associate with their communities. Furthermore, it is a way to make resilience and to reduce the vulnerability.

What makes a good volcano? Narrative driven behaviour change

Dave Lynch, Peter Eyres, Christophe de Bezenac

Cultural Institute, University of Leeds, UK

A good volcano has the potential to inspire changes in behaviour. Volcanoes are culturally disseminated through multimodal narratives. Over hundreds of generations, they have impacted on people's lives, traditions and movements across the globe, giving birth to gods, myths and rituals evidenced in some of the oldest human records. Volcanoes now also catalyse international, cross-disciplinary teams to understand the diverse physical and socio-cultural impacts of such landscapes.

Through a series of historical examples and artistic research, we explore how global and personal volcanic perceptions can influence behaviour change and drive science communication, collaboration and awareness. Building on these reflections, we propose methodologies for devising novel narratives and mass media communication strategies with an aim to drive social behaviour change. Second, we showcase a VR research experiment/film to capture the multi-disciplinary perspectives and languages used to deconstruct volcanic landscapes. Can these perspectives be utilised to develop novel collaborative strategies?

The VR experiment is born out of initial interviews exploring the languages used to deconstruct perceptions of volcanic landscapes through the arts and sciences. It forms early research for an immersive experience about how multiple disciplines create a visual coherence through their observations. These reflections have been formulated from a series of interviews and observations conducted by an artist/filmmaker during and after the UNRESP (https://unresp.wordpress.com/) expedition to the Masaya Volcano in Nicaragua during December 2017. It draws from conversations with specialists in volcanology, anthropology, history, computer science, medicine, the visual arts and interactions with local communities and national agencies.

S03.16 Talk

Vulcanalia:
an old name for a new way of communicating volcanoes to the people of Tenerife

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A basic understanding by the population of eruptive processes and their consequences is fundamental for an adequate mitigation of volcanic risk, specially at regions with low eruptive rate. This knowledge can be acquired through both formal and informal science education, for example by science festivals and similar performances. The effectiveness of such festivals in attracting new audiences increases when they are inserted into playful or cultural events in unusual places for scientific activity. Key elements that contribute to their success are the lack of ceremony of the context and the direct involvement of scientists. These principles inspire Vulcanalia, a scientific outreach activity named after the festival of ancient Rome. Vulcanalia is one of the complementary activities to the Canary Islands International Environmental Film Festival (FICMEC), the first of its kind in Spain. The current venue is Garachico, located on a coastal lava delta and almost completely destroyed by an eruption in AD 1706. Vulcanalia is coordinated by the Telesforo Bravo-Juan Coello Foundation and performed mostly by volunteers. It consists of open film-screening sessions, combined with dialogues with volcanologists. In the two editions held to date (2016 and 2017) have been programmed 4 dialogues and 8 films (2 fiction and 6 documentaries from 8 different countries) of eruptions of very different parts of the world. These films have been selected to reflect the volcanic phenomenon from various perspectives and to include environmental, social and cultural aspects. The success of the audience has been remarkable, with 1170 people attended the two editions. Workshops, field trips, lectures and debates are also held in the mornings, open to the public but especially dedicated to students (to date: 100 students from 8 centres from all the Canary Islands). Next edition, in May 2018, will have a formal tool to assess the impact of the activity.

S03.16 Talk

Volcanes de Canarias Association, a successful citizen response in a volcanic active area, Canary Islands, Spain

Víctor Melo[1], José Manuel Marrero[2], Ángeles Llinares[2], Marcos López Armas[1], Ramón Ortiz[3], Alicia García[3]

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Citizens of a volcanic zone have the capacity to commit to helping their communities to improve their knowledge of the volcanic phenomenon. Non-institutional communication through Internet is a very useful tool to raise awareness in society before, during and after a volcanic emergency. A wise use of social networks and Internet permits the disclosure of multiple activities, allowing citizens to reach a more efficient way than institutional communication. The society usually gives greater credibility to the information generated from an unofficial collective. This information is successful among citizens when it is rigorous, clear and useful.

Since 2004, a group of volunteer citizens of the *"Volcanes de Canarias"* Association has become a reference for the communication of the monitoring of the volcanic activity in Spain and part of the Spanish-speaking world. The experience of this Association demonstrates that non-institutional communication is an effective tool to prepare society to face volcanic phenomena and other natural risks. In order to guarantee the success of non- institutional communication, it is necessary to accomplish a previous training and education of both members of the Association and people following the information. This global approach allows the elaboration of rigorous and understandable reports. However, the most important key factor will be the extensive and great collaboration with scientists. Quality information products about volcanic phenomena, far from alarming, will be well valued by the citizenship. People are really interested in being correctly informed about volcanic activity and they even participate in excursions and activities to learn more about the place where they live. These associations could be a very useful link between the authorities and the population in situations of volcanic emergencies.

S03.16 Talk

A school trip around Vesuvius and Phlegraean Fields: volcanoes as resource and risk over the centuries

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This work illustrates the approach used for the preparation of the educational trip "Volcanoes in Campania - resource and risk for the territory".
The four-day trip was attended by students of a technical Institute in the Province of Turin and included excursions and guided tours in the Vesuvian and in the Phlegraean area to observe the territory in its uniqueness and complexity.

The trip was aimed to highlight the interactions between man and environment, cause-effect relationships, involving various disciplines such as geography, geology, botany, history, archeology, art, economy, technique, etc ..

The metropolitan area of Naples, dominated by the presence of Vesuvius and Phlegraean Fields, so close but so different by volcanological evolution, is perfect to face up these issues in the school in a comprehensive and incisive way, that shows the evolution and the characteristics of the territory in its abiotic, biotic and anthropic components.

Excursions were held at Vesuvius, Herculaneum ruins, Virtual Archeological Museum, Galleria Borbonica, Pozzuoli with Rione Terra and Serapeo, Monte Nuovo, Baia Sommersa, and Piscina Mirabilis.

Using conceptual frameworks, videos, documents, diagrams and photographs, the following issues were highlighted:

- The volcanoes and the landscape are compared: the Vesuvius and the Phlegraean Fields, with different volcanological evolution, produced rocks and landscapes with different characteristics which differently influenced ancient settlements.
- The volcano as a resource: the volcanic rocks have been used as building materials, the large underground quarries in the tuff have been used for various purposes over the centuries, the volcanic soils favored the strong development of a prestigious agriculture, etc.
- Volcanic risk: reading historical documents with the description of the eruption of 79 AD of Vesuvius and eruption of 1538 of Monte Nuovo, the concepts of vulnerability and risk, warning signs, monitoring and prevention have been introduced to the students.

S03.16 Poster

A Study of the Toya-Usu Volcano Meister System 10 years

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Mt.Usu, in south west Hokkaido is one of the most active volcano in Japan. The most recent activity of Mount Usu is 2000 eruption. And, Mt. Usu has been erupting every 20-30 years, so education for disaster mitigation is top priority for sustainable local community. Because to know well about volcano is important to mitigate disaster. And we need good communication between researchers, local people and town officers.

So, Toya-Usu Volcano Meister system began since 2008 in this area. 48 Meister have been authorized until now. They are the organization who develop sustainable human resources for learning and sharing. And this system is training course and certification system for local people. Furthermore, they are local leader for disaster mitigation when the volcano erupts, or geoguides when the volcano is calm.

By the way, ten years passed since this system began. Most Meister play an active part as a local disaster prevention leader in various scenes. In reference to this system, the Volcano Meister system began in Nagano from this spring. In addition, similar system that inhabitants became a disaster prevention leader has started in Costa Rica.

On the other hand, there are some troubles of volcano Meister oneself. “What we can do at the time of the next eruption?”. “I cannot give a specialized advice, because we are not scientists”.”Are the contents of our guide right?”. “We do not have even knowledge about a geological feature and the volcano”. “We have to learn more”.

Ten years passed, the Volcano Meister have begun to feel the need that they must grow up more.

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S03.18 - Leveraging the Power and Speed of Social Media to Expand Volcano Communication

Someone is wrong on the internet!
Managing social media during the 2018 Kilauea crisis response

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For better or worse, social media (Twitter, Facebook, etc.) is rapidly replacing traditional media (television, radio, print) as the primary source of news for many people. The eruptive phase of Kīlauea Volcano (Big Island, Hawaiʻi) which began on May 3, 2018 introduced a new level of social media interest for the USGS Volcanoes Facebook and Twitter channels. As the social media team began posting updates from the Hawaiian Volcano Observatory (HVO) website, we encountered a staggering level of engagement and questions about each new form of activity. In particular, residents of the Leilani Estates subdivision (where the fissure eruption began), and surrounding areas, were relying on social media for updates and clarification. In this work, we present lessons learned on how to best report facts and science, and the opportunities for the USGS social media team to reinforce HVO messaging, relieve pressure on HVO scientists and outreach staff, head off and refute poor reporting and misinformation, encourage factual scientific discussions about volcanic activity, and to maintain the USGS as the authoritative source of scientific information about the eruption.

The newspaper view of the Stromboli 2002-2003 eruption and evacuation: a content analysis to understand framing of risk communication

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Stromboli's 2002-2003 eruption was one of the most important effusive events of the last two centuries and was associated with a major explosive event (on 5 April 2003) that damaged buildings in the village of Ginostra. On 30 December 2002, two days after the beginning of the eruption, a landslide that entered the sea caused a tsunami that struck Stromboli's coastal areas. The events of 30 December led to "voluntary evacuation" by Stromboli's inhabitants. As part of the ANR-funded RiskAdapt research project, we analyzed the content of five newspapers, two national newspapers (Il Corriere della Sera and La Repubblica) and three regional newspapers (La Gazzetta del Sud, La Sicilia and Il Giornale di Sicilia), published during the period covering the evacuation (28/12/02–18/01/03) with the aim of assessing what type of hazard information was given and how it was framed. News regarding the eruption covered a total area of 11.9 cm2 for the national newspapers against
116.3 cm2 for the regionals. For both newspaper categories, most of this area was occupied by interviews with the public, followed by interviews with experts and, finally, politicians. Out of a total of 7837 words analyzed, the most popular was "tsunami" (384 cases) with the word volcano being repeated 315 times (the 4th most popular word). Lava (97), eruption (92), and explosion (51) were the 20th, 21th, and 43th most popular words. Negative words, such as "apocalypse" and "hell", which appeared 32 times, were much more frequent than positive words, which were rare and not present in all newspapers. Thus, reporting focused on the tsunami threat with little link back to the eruption and other hazards. This contrasted with imagery (that took of 41 % of the reporting space) that comprised relaxing pictures of a tranquil island surrounded by a calm blue sea.

Hashtag Hazard: Alaska Volcano Observatory uses social media accounts to convey volcano information

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The Alaska Volcano Observatory (AVO) has maintained a website since 1996. During the 2009 eruption of Mount Redoubt, many AVO stakeholders indicated they wanted to receive volcano updates via Twitter. At that time, most AVO employees were not able to use Twitter from their work resources, so AVO's Twitter account began on a cell phone. Nearly 10 years later AVO's Twitter and Facebook profiles are an essential part of how AVO communicates volcano hazard information to emergency managers, Alaska residents, and volcanophiles all over the world. AVO also has an Instagram account, but Instagram's format is more challenging for typically text-based volcano information.

Lessons we've learned over the past nine years include: during a high-profile eruptive event, the public wants as many updates as we can provide, but during slower times repetitive posts of "no change" are undesirable. Therefore, AVO posts color code changes and formal information statements, but does not auto-post the daily status updates, instead opting for hand-crafted volcano and preparedness messages.

Because AVO does not have dedicated outreach employees, our social media accounts carefully balance demands on staff time with the effort required to keep the accounts fresh and authoritative for Alaska volcano information. Although this effort is not insignificant, we find that our social media accounts yield benefits to AVO, including: providing authoritative information that can quickly tamp down misinformation; extending volcano awareness to groups that may not visit our website; and receiving unrest and eruption observations and images from citizens. Additionally, when we intensively work at distributing timely information via social media channels, email inquiries to the website drop. This indicates that small bits of effort into social media can be an efficient use of staff time, because we can answer many people all at once, instead of replying to individual emails.

Use and impact of social media in disseminating alert level changes and information for the Kick 'Em Jenny submarine volcano

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The University of the West Indies Seismic Research Centre, Trinidad and Tobago, W.I

The UWI Seismic Research Centre is the agency responsible for monitoring earthquakes and volcanoes for the English speaking Eastern Caribbean. Due to the region's geographic setting, social media platforms were championed as early as 2009 as a tool for rapidly communicating accurate and reliable information regarding these hazards to the general population. As time has progressed, these platforms have become the primary source of breaking news for most persons worldwide. This trend has not gone unnoticed in the region and we present a case study on the use and impact of social media in volcanic risk communication. Kick-'em-Jenny (KeJ) submarine volcano is the only known active submarine volcano in the region. It has had three periods of elevated seismic activity with two of these accompanied by clear eruption signals during the period 2015-2018. Social media played a key role in the dissemination of information and facilitating two-way communication with the public during each episode. We review our experience with the use of this media including the various products used, information shared and the subsequent impact on the Centre and region's populace and diaspora of this media. We share recommendations made following each episode. Finally, the challenges, uncertainties and limitations –regionally and globally are discussed and possible solutions outlined.

S03.18 Talk

#AgungErupts:
How Twitter and 24-hour media are changing the roles of volcanologists

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Scientists responding to the 2017 Agung activity in Bali, Indonesia, received an overwhelming number of inquiries about the status of the volcano and public safety from people at risk, the local and international news media, and interested public. Social media was one tool used to address this need effectively. Hazard maps and volcano updates, along with information on safety, monitoring and eruption activity were shared by authoritative sources using Twitter, Facebook, WhatsApp, Instagram, Line, official websites, and the MAGMA Indonesia smartphone App. Key information was sometimes mistranslated using Google Translate and shared widely around the globe. Social media provides the opportunity to see rumors developing in real time and to address them.

During the Agung response, several issues became apparent to scientists observing and engaging in online discourse. These issues are:

1. Managing rumor and social media demands were exceeding the local and even regional public information resources of the home volcano observatory.
2. A growing number of geoscientists, who are located in countries not affected by the event, are using social media to address rumors and misinformation. Volcanology needs a coordinated approach ensuring messaging and information from responding observatories are supported and amplified through social media.
3. Social media geoscientists are increasingly being asked questions that, depending upon how they are answered, can help or harm the responding local volcano observatory.
4. We propose that a social media international agreement and framework for geoscientists be explored to address these issues. The development of a framework and network of scientists could ensure a more coordinated and aligned response, both in real life and online. This network could benefit scientists by alleviating workload and by supporting people desperately seeking information about volcanic crises.

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S03.19 - Mitigating economic and insurance losses from volcanic unrest and eruption

Foundations for parametric insurance covering volcanic unrest and eruptions

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Losses from natural disasters have been mitigated through insurance for hundreds of years. Traditionally, this had been through indemnification against actual losses incurred by the insured, but in the last 20 years, a new form of risk transfer for weather risk and other natural disasters has emerged. Beginning as derivative contracts for hedging against warm or cold (for the energy industry) and wet or dry (for agriculture) weather, the concept of using a measured parameter of the weather – or other natural peril – as the basis for a financial contract has expanded and now includes a broad range of instruments known as index-based or parametric insurance. Such instruments have been applied around the world for almost all forms of weather hazard, and for earthquake hazards, and have gained particular traction in the development context from the sovereign government level through to microinsurance. We report on progress in a multi-institution collaborative project, commissioned by the World Bank, to explore the suitability and possible design of parametric insurance instruments for volcanic unrest and eruptions for five Asia-Pacific nations: Indonesia, Papua New Guinea, the Philippines, Tonga, and Vanuatu. All five of these countries are either using or have explored the use of parametric insurance as a tool for managing natural disaster risk for tropical cyclones and/or earthquakes, and all face significant risk through negative economic impacts due to volcanic unrest and eruption.

S03.19 Talk

Potential economic losses from a super eruption

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Globally, the biggest single event catastrophe insurance losses ever have been about USD 80-100 billion, with economic losses 2-3 times that depending on insurance penetration. It is reasonable to envisage economic or insured losses twice as large from modelled perils such as earthquakes, typhoons/hurricanes, severe thunderstorms and floods.

While hundreds of volcanic eruptions occur each year, potential economic and insurance losses are rarely modelled and losses from VEI 8 eruptions, which have a global average recurrence interval of about 17,000 years, are almost never considered.

Here we examine some of the potential economic losses in terms of human deaths, damage to buildings, and agriculture, from a repeat of a ‘middle-sized’ VEI 8 Aira eruption in Kyushu, Japan. We use ‘expert’ High and Low estimates of potential losses related to the occurrence of pyroclastic density currents, and distance from the Aira caldera as a proxy for tephra thickness. The immediate potential economic losses within Japan from this scenario would reach at least several hundred USD billion.

We also consider briefly the potential economic losses within Japan that we have so far ignored, some of the potential ‘knock-on’ consequences for the global economy, and some very limited mitigation options.

Understanding the impacts of future volcanic unrest for Campi Flegrei caldera

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Long-term volcanic unrest has the potential to disrupt both the livelihoods of the population and the local economy. At Campi Flegrei caldera, volcanic unrest during 1969-1972 and 1982-1984 caused significant building damage and led to the evacuation of over 40,000 residents. In both cases, unrest was focussed on Pozzuoli, near the centre of the caldera.

Three unrest scenarios have been developed highlighting the potential impact of future unrest on businesses, buildings and livelihoods. The results are presented as impact maps of the same unrest event occurring in three different locations. Pozzuoli was chosen to examine how a similar unrest episode would impact the area today. Baia because seismicity occurred here in the 1970s and Agnano has been highlighted by some studies to be the most probable location for a future eruption.

The scenarios show that evacuations associated with future unrest may involve the displacement of 30,000 – 140,000 residents and damage to as many as 3,000 buildings. Up to 200 km of roads, 40 km of railway track and 24 km of high-voltage electricity network are exposed in the scenarios. The Agnano scenario is associated with the greatest impact and involves the potential evacuation of 140,000 people and damage of 3,000 buildings. Agnano also lies between Naples and the rest of Campi Flegrei, so that damage to infrastructure, such as road networks and electricity lines here, will likely trigger a cascade of obstacles to managing evacuations during an emergency. Thousands of businesses, including large multi-national companies, could also be impacted within Agnano. The results highlight the importance of considering scenarios in which renewed unrest is not necessarily focussed again beneath Pozzuoli. With further input and vulnerability data, these results would help communicate the possibility of damage from future unrest to a wide variety of audiences.

Community approach in volcanic crisis management: From scientific to people

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On December 31, 2015, the Chilean National Volcanic Monitoring Network (RNVV) declares yellow alert level in Nevados de Chillán volcano. From this moment for more than two years, outreach activities and workshops with first responders, exposed community, and provincial authorities were carried out. After two years of yellow alert and three months of lava dome growth, on April 5, 2018, RNVV raises the alert to orange level for the volcanic complex, increasing the attention of the community, the media and authorities. Following this decision, professionals of Chilean Geological Service (SERNAGEOMIN) move to the exposed area. The aims was: (1) Providing clear information to community about current situation of volcano, the eruptive cycle chronology and hazard scenarios, (2) Technical assistance to the authorities and civil protection agencies, and (3) Geological survey focused on hazard microzonification and meeting points selection for local emergency plans. Within these activities, the correct use of social media for scientific and technical information was reinforced, at the same time, these tools allow community become human sensors in order to report different situations of the eruptive process (send images of eruptive pulses, report perceptible earthquakes, ash fall, etc.), complementing the volcanic monitoring, and generating a virtuous circle of information.

In addition, it has been detected that the community trust in direct scientific communication rather than through interlocutors or reports, the same happens with the authorities, who have greater confidence in their decisions when are taken with the direct advice from the experts. We propose this way of approaching a volcanic crisis. At first alert, professionals move to the area focus on: (1) Train on topics of volcanology, (2) Authorities assistances and (3) Microzonification of Hazard. We conclude the importance of understanding the role of the scientist and the technical organisms, that have to know how civil protection and emergency systems of each country works.

S03.19 Poster

National Biennials of Children and Young People Who Reside in Volcanic Risk Areas, a Strategy of the Colombian Geological Service (CGS) to Improve Social Understanding and Risk Management of Volcanic Disasters in the Country

Diego Mauricio Gómez-Martinez, Gloria Patricia Cortes-Jimenez, Adriana Agudelo Restrepo, Cristian Mauricio Lopez Velez, Marta Lucia Calvache

Servico Geológico Colombiano, Colombia

The volcanoes that supply natural resources and dominate landscapes are home to populations that have developed economic, cultural and social activities under the volcanos' influence, generating high dependency. There is also doubtless the destructive power that volcanic phenomena can bring; Throughout history, tragic events related to volcanoes have been generated.

In this context, since 2011 the CGS has pioneered an event of a national nature, with regularity and continuity, centered on children and young people residing in regions surrounding active volcanoes. Through different modalities (posters, conferences, experiments, stories of experiences, artistic expressions) the children share experiences and interact with peers from other areas, addressing the social, geoscience and cultural impacts of volcanoes. Goals include:

* Generate a space for children and young people residing in active volcanic regions, where they can establish discussions, leading to regional or national initiatives.
* Establish a scientific-cultural event focus as permanent and representative of the local cultures, in which the leaders are children and young people residing in volcanic risk areas.
* Consolidate in our country, the "national biennial of children and young people living in volcanic risk areas", based on experiences in the influence zones of the main active volcanoes.
* Motivate that generation to understand Earth Science research.

Between 2011 and 2018, under the coordination of the CGS, four national biennials have been held with headquarters in the cities of San Juan de Pasto, Sebastian de Mariquita and Popayán. Each one of these events bring together approximately 200 children and young people from the Departments of Caldas, Tolima, Quindío, Cauca, Huila and Nariño and from the regions of influence of Nevado del Ruíz, Cerro Machín, Nevado del Huila, Chiles, Cumbal, Doña Juana and Galeras volcanoes.

S03.19 Talk

Working in the grey – Uncertainty, teamwork and communication amongst New Zealand's calderas

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Is it going to blow or not? A simple question with no simple answer. One of the biggest challenges to managing caldera unrest is giving certainty where there is none. In today's data rich environment public expectations are high. Our community expect and answer in black in white but we are often working in the grey.

The Bay of Plenty and Waikato Caldera Advisory Group was established The Bay of Plenty and Waikato Caldera Advisory Group (CAG) was established in 2010 and comprises members of emergency management, scientific organisations and local authorities. The Groups' mission is to identify the risks and potential consequences of caldera unrest in the Taupō Volcanic Zone and coordinate multi-agency planning for management and mitigation of the effects on communities at risk.

The CAG quickly realised that one of the biggest risks we have to manage is how our communities respond to situations where the impacts are uncertain. It became clear that managing the threat of an eruption becomes almost as important as managing the eruption itself. Emergency managers and scientists walk the tightrope preparing our communities to take action when it is needed while giving reassurance and support during when the outcomes are uncertain. This presentation discusses the issues and opportunities we have found in the first 5 years of working as an advisory group team, and ideas and challenges for the future.

Warnings and Alerts during Volcanic Emergencies: Scientific Practice Informed by Community Experience (WAVE: SPICE)

Christopher Kilburn[1], Sabina Michnowicz[1], Claudio Correale[2], Eleonora Puntillo[2], Sara Garofalo[3], Francesca Barone[3], Laura Longo[4], Gabriella Gribaudi[4], Anna Maria Zaccaria[4], Gala Avvisati[5], Enrica Marotta[5], Rosella Nave[5], Matt Bannister[6], Joe Barlow[6]

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Intervals of several generations between eruptions are a key obstacle to improving resilience against volcanic activity, because they are long enough for the collective memory of previous events to have faded among exposed communities and scientific advisors. A classic example is the Campi Flegrei caldera outside Naples in southern Italy. After four centuries of repose, the volcano has been through two major, non-eruptive emergencies in 1969-72 and 1982-84 and is continuing a pattern of unrest consistent with a progressive approach to eruption. Each of the emergencies triggered evacuations of tens of thousands of people from the coastal town of Pozzuoli, near the centre of the caldera. Although no eruption occurred, persistent low-level seismicity damaged buildings throughout the town during the second emergency.

Our recent interviews in Pozzuoli show that expectations of a future response to unrest remain coloured by memories and stories of the previous emergencies. Recurring themes are that decisions on whether to evacuate are conditioned by political considerations; that the threat from volcanic activity is secondary to the danger from local seismicity; and that popular reports of scientific studies about Campi Flegrei, if not the studies themselves, exaggerate the threat of an eruption. All three themes feed distrust and uncertainty in scientific understanding of the volcano's behaviour. They have also emerged in spite of repeated institutional campaigns to raise public awareness of volcanic activity. New initiatives based around community theatre are being co-designed by local community associations Lux-in-Fabula and Le ali di Dedalo in Campi Flegrei, the UK's Royal Academy of Dramatic Art, social scientists and historians at the University of Naples, and volcano scientists from the INGV-Vesuvius Observatory and UCL Hazard Centre. The key goal is to complement existing top-down institutional methods for encouraging public trust before the next emergency.

S03.19 Poster

New Zealand's large new multi-agency multi-disciplinary programme 'ECLIPSE' Eruption or Catastrophe: Learning to Implement Preparedness for future Supervolcano Eruptions

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New Zealand hosts the world's most frequently active caldera supervolcano system: the central Taupo Volcanic Zone (TVZ). TVZ hosted the world's youngest supereruption at Taupo, beneath which currently there is several hundred cubic kilometres of partially molten rock. Every few decades central TVZ volcanoes become restive and every few hundred years erupt. Deciding if unrest will lead to eruption, estimating the timing and impacts of future eruptions, and isolating the probability of another supereruption remains a challenge here and globally. The media-born term 'supervolcano' has created global hype, leading some to assume that any caldera volcano eruption will lead to catastrophe. To prepare for the impacts of supervolcano eruptions and to reach a sophisticated level of resilience, there is the need to demystify these extreme geohazards. We discuss the issues and opportunities being explored by a large multi-disciplinary research programme that brings together volcano-related scientists, volcano monitors through the GeoNet project, emergency managers through the national Caldera Advisory Group, and researchers within Maori tribes across the supervolcano system. The programme includes research into the volcanoes' present physical and magmatic states, modelling eruption dynamics and impacts for future events, and the switches between dormancy, unrest and eruption to focus monitoring strategies. This knowledge will produce decision-support tools via co-production with our end users. Together we will develop implement all-agency community-focused mitigation strategies for future eruptions based on our hazard and impact models, and through citizen science initiatives. This New Zealand study will be joined by the European research program on Italy's supervolcano Campi Flegrei. This sister-volcano approach will combine global expertise and develop national and international capabilities to address the challenges of extreme volcanic geohazards.

S03.19 Talk

A Look Inside Taal Caldera: Challenges in Community-focused preparedness

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Two communities, Banyaga and Bilibinwang, in the town of Agoncillo, both located within the walls of Taal Caldera were selected as pilot sites for collaboration on community volcano preparedness. The focus is on understanding the views and practices of these communities living within Taal Caldera, whose last two major destructive eruptions occurred in 1911 and 1965. Results from interviews and group discussions with residents suggest that most current residents may have heard and are aware of the 1965 event, but the lack of actual experience and the long interval of major eruptions have contributed to the villagers' complacency when it comes to volcano preparedness. This work shares the experiences and challenges for this kind of collaboration. As we experienced, there is need to establish relationship with the villagers and slowly gain their trust, so that they are convinced, will prioritize, and will use their knowledge (about Taal Caldera) and translate these to action (planning for preparedness). Some challenges include finding ourselves needing to introduce the disaster risk reduction and management law and its relevant features due to unfamiliarity of most of the participating villagers. Second, in the process of introducing the volcano science part, we focused on individual stories shared (or lack of it) about volcano eruption experiences and existing background knowledge. We built on these to (re)introduce the types of eruptions from Taal Caldera, and relate these to what they have heard as stories from older people. We had to focus on ensuring villagers understand hazards maps, risk maps and evacuation maps and volcano alert level scheme. A huge portion of the process is introducing the community mapping exercises specially identifying and mapping of risk elements.

S03.19 Poster

Prototype training program of the human resource development for volcanic disaster management officers in JAPAN

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There are many kinds of training program for natural disaster prevention officers in Japan. However, when it comes to volcanic disaster prevention, only few trainging program exist due to the low frequent disaster. In this research, we performed three types of training programs for volcanic disaster prevention officers in Yamanashi prefecture-side's volcanic disaster prevention council of Mt. Fuji, and questionnaire survey were conducted in each training program. As a result, we could build up a few types of training programs of volcanic disaster prevention, using the past case, especially Japanese Cabinet Office's program named a Training Program for Disaster Prevention Specialists.

Improving volcano risk communication at the Long Valley Caldera and Mono-Inyo Craters volcanic system, California, USA

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Exposure to escalating volcanic unrest can lead to crises with or without an eruption, as demonstrated by the post-1978 response to caldera unrest in Long Valley California, USA. Consequently, volcanic events, including both unrest and eruptions, are said to be physical phenomena, while volcanic crises are social. Volcanic eruptions, unlike some other geologic hazards, are often preceded by months to years of precursors, which offer additional opportunities to reduce volcanic risk, so long as community stakeholders are engaged in the risk management process. The Long Valley Volcanic Region (LVVR) has experienced volcanic unrest since 1978, at which time a M5.6 earthquake ended 20 years of seismic quiet. Seismicity continued, followed by significant ground deformation and doming of the caldera floor. Extensive research in volcano science of the LVVR provides an understanding of volcano-seismic hazards, but comparatively fewer resources have been dedicated to understanding human processes in response to volcanic hazards. Misconceptions and uncertainty in the LVVR about both volcanic hazards and communication of risk across the breadth of stakeholders can amplify economic consequences volcanic unrest escalates. In order to understand community attitudes about volcanic hazards compared to seismic and wildfire hazards in the region, we conducted mail-based, sample survey research (N=178) of 1,200 households (February 28, 2018-May 18, 2018). This study utilizes aspects of the Protective Action Decision Model to understand how varying degrees of exposure to hazards (e.g., tephra fall) affect stakeholder perceptions, confidence in warning and evacuation messages, volcano preparedness, and preferences for hazard information sources.

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