ISSN 2039-6651
anno 2022 numero 70

MISCELLANEA INGV

Abstract Volume

5ª Conferenza A. Rittmann

Catania, 29 Settembre | 1 Ottobre 2022

ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

70

REGISTRAZIONE AL TRIBUNALE DI ROMA N.174 | 2014, 23 LUGLIO

Rappresentante legale: Carlo DOGLIONI
Sede: Via di Vigna Murata, 605 | Roma

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Acceped 26 August 2022 | *Accettato 26 agosto 2022*
How to cite | *Come citare* AA. VV., (2022). Abstract Volume 5° Conferenza A. RITTMANN, Catania 29 September - 1st October 2022, O. Cocina, C. Tranne, A. Vona, M. Viccaro (Eds). Misc. INGV, 70: 1-340, https://doi.org/10.13127/misc/70

Cover In the foreground the crater "La Fossa di Vulcano". On the left, in the background, the snow-capped summit of Etna volcano. The photo (courtesy of Stefano Branca) was taken on 8 April 2022 during an overflight with the support of the Coast Guard of Catania | *In copertina In primo piano il cratere La Fossa di Vulcano. A sinistra, sullo sfondo, la cima innevata dell'Etna. (Foto di Stefano Branca, ripresa l'8 aprile 2022 durante un sorvolo con il supporto del 2° nucleo aereo Guardia Costiera di Catania).*

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Conveners:
Gilda Risica, Arianna Beatrice Malaguti, Gino González, Federico Lucchi

The activity of Italian volcanoes represented in ancient maps and frescoes from Middle Age to Renaissance

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We examined ancient maps in manuscripts and in print or frescoes to look for the representation of the state of activity of Italian volcanoes between the Middle Ages and the Renaissance. The first evidence is found in a manuscript of an Arab geographer of the XII century, and in manuscripts of the fifteenth century. The printed maps of the 1500s are influenced by the production of Giacomo Gastaldi who, in our opinion, makes a peculiar error by reporting an activity, probably untrue at Filicudi. This error characterizes many subsequent maps and is finally corrected with the production of maps by authors of the Reign of Naples.
The maps reproduced after Gastaldi and the eruption of Vesuvius in 1631 are a reference mark that can be used to date some remakes and corrections of the maps of the Vatican Gallery.
We aim to show that the detailed knowledge of the record of activity of Italian volcanoes may help to better trace the origin of some maps and define also the age of restoration of the frescoes of the Vatican Museum.

S01 - Oral Presentation

Timescale of emplacement and rheomorphism of the Green Tuff ignimbrite (Pantelleria, Italy): a multidisciplinary approach

Alex Scarani[1], Carmela Federica Faranda[2], Alessandro Vona[1], Guido Giordano[1], Claudia Romano[1], Fabio Speranza[3], Silvio Giuseppe Rotolo[4]

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We present a multidisciplinary study based on geospeedometry, paleomagnetic, and numerical modeling techniques to gain information on the timescales of emplacement, syn- and post-depositional ductile deformations of the highly welded and rheomorphic Green Tuff ignimbrite (GT; Pantelleria, Italy).

Differential Scanning Calorimetry (DSC) measurements allow determining the glass fictive temperature (T_f; i.e., the parameter to account for the cooling dependence of glass structure and properties). Using the T_f-based geospeedometry procedures, we infer the cooling rate (q_c) experienced by the glassy phases in different lithofacies within the GT formation. We collected and analyzed glasses, or the glassiest phases within the deposit, along with a virtual vertical profile (i.e., basal pumice layer, basal vitrophyre, main welded ignimbrite body fiammae-rich, folded rheomorphic layers, and upper vitrophyre). The estimated q_c span several orders of magnitude. Glass shards from the pumice fall deposit record a fast-cooling rate of ~10 K/s, whereas the extensive welded and rheomorphic ignimbrite body returns variably slow q_c values ranging from ~10^{-2} K/s to ~10^{-6} K/s, depending on the stratigraphic position and ignimbrite lithofacies, with fastest q_c related to the vitrophyres and lower q_c to the main ignimbrite body.

We use paleomagnetic analyses to infer the emplacement temperature (T_e) of the GT. Measurements carried out on 75 lithics and 55 matrix samples return the predominant presence of magnetite as a ferromagnetic mineral and a T_e > 600°C.

Finally, DSC and Paleomagnetic analyses allowed to constrain a conductive cooling model (using the Heat3D software). We describe the temperature-time (T–t) evolution of the GT deposit from T_e to below the glass transition. The analysis of the cooling paths allowed us to quantify the timescales to reach specific rheologically critical temperature thresholds. We considered T_c the Curie temperature of magnetite, T_g the temperature at which viscosity (η) is 10^{12} Pa s, and T_f. The inferred T–t–η intervals correspond to different deformation regimes, including pyroclasts welding and rheomorphism (form macro- to micro-scale deformation), down to the complete flow cessation at the glass transition. Outcomes suggest that welding of the upper and basal vitrophyres occurs within a few hours after emplacement. Conversely, the central part can remain at a high temperature (in the viscous regime) for at least one month, promoting welding and rheomorphism.

On this basis, we propose a rheologically-constrained model to describe the syn- and post-emplacement deformations of the GT ignimbrite, founded on the key role of volatiles in widening the viscous window and locally controlling the rheological behavior of the GT deposit.

S01 - Oral Presentation

The crucial role of the Cyclopean Islands (Acitrezza, Catania) to deepen the early stage of Mt. Etna volcanism

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The small archipelago of the Cyclopean Islands is located a few kilometres north of Catania and consists in two main islands (Lachea and S. Maria) and a few smaller stacks. It's a place of incomparable beauty and geological interests that has deserved to be protected with the institution of the Natural Reserve “Isola Lachea e Faraglioni dei Ciclopi” and of the Sicilian Geosite “Vulcaniti dell'Arcipelago dei Ciclopi ed Acitrezza”.

The two largest islands (Lachea and Faraglione Grande) are made up of columnar basalts, with prismas of different size and orientation that have previously been interpreted as the remnants of a wider subvolcanic sill, which intruded into the Pleistocene marly claystone of the old sea bottom (Argille marnose azzure; Wezel, 1967). Most of the sill is currently located at the sea level due to the regional uplift of East Sicily, but widely extends also underwaterater (Chiocci et al., 2011).

According to the ‘Geological map of Etna volcano' (Branca et al., 2011), the Cyclopean Islands and other discontinuous outcrops in the Acitrezza-Acicastello-Ficarazzi area (Corsaro and Cristofolini, 1997) belong to the Basal Tholeiitic phase (~600-320 ka), the oldest of Etna stratigraphic succession.

Although the Cyclopean Islands have been fairly well-studied in the past, a few intriguing scientific issues are still open. Indeed, the dating of the Cyclopean rocks has not been carried out until now. Furthermore, the composition of Cyclopean rocks is not tholeiitic, but mostly transitional towards terms of Na-alkaline serie (Corsaro and Cristofolini, 1997), probably more akin to the products of the subsequent Timpe phase (220-110 ka).

Therefore, to better constrain the stratigraphic position and role of Cyclopean Islands in the evolution of the old Etna magmatism, we have: i) carried out a geological survey of Lachea Island and its surroundings; ii) collected 25 samples of the most significant outcrops; iii) dated with $^{40}Ar/^{39}Ar$ selected samples of Lachea Island; iv) analysed major and trace elements of bulk rock and the mineral chemistry of selected samples belonging to the Timpe phase too.

We present the results of the work about to end, which has allowed to refine the position of the Cyclopean Islands into the stratigraphic succession of Etna and to deepen the transition from tholeiitic to alkaline magmatism at Etna, in a period of the volcano's history that is scarcely studied if compared to the present activity.

Paleomagnetic dating of prehistoric flank eruptions from the SE lower slopes of Etna volcano

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The volcanic hazard assessment is of fundamental importance for the densely inhabited lower slopes of an active basaltic volcano such as Mount Etna (Sicily, Italy). Indeed, the Etna volcano, despite its eruptive activity mainly concentrated at the summit craters, was also characterized in the past by large and less frequent eccentric eruptions. The chronological framework of the 2750-year-long historical period of the Etna activity is fairly well known. Conversely, the timing of the prehistoric flank eruptions is still poorly constrained, being supported by only stratigraphic evidence and a few Ra and paleomagnetic ages. Here, we report on the paleomagnetic dating of fifteen Holocene flank eruptions characterized by scoria cones and major lava flows distributed over the SE Etna lower slopes. They were produced by the S eruptive rift, the most historically active among the three main rifts of Etna. We paleomagnetically investigated 44 sites (440 oriented cores) and compared flow-mean paleomagnetic directions to the SCHA.DIF.4k geomagnetic regional model (for one eruption) and the SHA.DIF.14k global model (for the other eruptions). Our results show that many possible time windows can be obtained for a single eruption. In four cases, the paleomagnetic ages do not shorten significantly the input time window, either extending up to ~12 ka BC (Camporotondo Etneo and Blandano eruptions) or spanning the 6 ka BC - AD 750 (Dagala) and the 1520 - 122 BC (Mt. Gorna) intervals. For the other eruptions, input time spans are significantly reduced by paleomagnetic dating. In particular, the lava flows stack of Pisano, Passopomo, Mangano, Mt. Arcimis, and Cancellieri yield progressively younger ages from around 6 - 5.5 ka BC (Pisano) to ~400 - 150 yr BC (Cancellieri). Moreover, Mt. Trigona, Tremestieri Etneo and Mascalucia eruptions appear having occurred in a narrow time interval (between 3.4 ka BC and 2 ka BC). Furthermore, the dating of the Mt. San Leo lava flow confirms its old emplacement age: 8.7 - 5.4 ka BC. Finally, several paleomagnetic ages from 3.5 ka BC to 1.6 ka BC have been obtained for Mt. Serra eruption, whereas the underlying Trecastagni flow yields a narrow 3666 - 3545 yr BC time window. The new data yield a significant improvement of Holocene eruptive activity chronology, thus providing a better evaluation of the flank eruptions hazard at Etna volcano.

S01 - Oral Presentation

The chronicle of a small crater collapse at Stromboli: volcanological relevance of the 19 May 2021 ash cloud deposit

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

During the beginning of May 2021 a small scoria cone built up on the Stromboli crater terrace, after the progressive increase in the frequency and intensity of the Strombolian activity, also characterized by episodes of intense and continuous spattering. On 19 May 2021 the gravitational instability of the emplaced deposits caused the collapse of a portion of the Stromboli crater rim, which occurred without any explosion quake and infrasonic signals, hence was not associated with any major or paroxysmal explosion. The collapse produced a small pyroclastic density current (with a volume of about 10^4 m^3) that spread along the Sciara del Fuoco, the northwest flank of the volcano, and propagated over the sea for about 1 km offshore, producing a tsunami wave of about 20 cm entering the sea. The collapse of the crater terrace rim also opened a breach of the uppermost part of the conduit, and the overflow of magma produced a lava flow within the Sciara del Fuoco that rapidly reached the shoreline, producing hydromagmatic explosions while entering the sea, and remained active for a few days.
A thick grey ash cloud, generated by the combination of the ash elutriated from the pyroclastic density current and the convective plume of steam and ash produced during the littoral explosive activity, rose and swelled above the Sciara del Fuoco and rapidly propagated eastward over the village of Stromboli; eyewitnesses revealed that the northern and eastern parts of the island were completely shrouded in the cloud, while the southern and western parts were free from falling ash. The ash cloud deposit emplaced as a thin (1 mm) and continuous layer of fine pinkish ash and was sampled few hours later the emplacement, prior to any significant reworking or re-sedimentation. We focus on this ash cloud deposit providing a comprehensive characterization that includes dispersal, sedimentological, textural and geochemical features. The results are useful for the comprehension of generation (fragmentation), transport and deposition (settling) processes of these kind of deposits, which are frequently identified within the tephrostratigraphic record, but also observed during previous eruptions (e.g., December 2002 at Stromboli).

S01 - Oral Presentation

Resumption of the sustained column during the post-Plinian phase of the 79 AD Vesuvius eruption

Giulia Chiominto, Claudio Scarpati, Annamaria Perrotta, Lorenzo Fedele, Ileana Santangelo

Università di Napoli Federico II, Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Italy

Plinian eruptions are particularly dangerous eruptions that often have long-lasting consequences. They produce high eruptive columns that inject considerable volumes of pyroclastic fragments and volcanic gases into the stratosphere. Pyroclastic clasts fall back to the ground forming widespread tephra sheets in which different components are distinguished: juvenile clasts, lithic clasts and crystals. This 'classical' behaviour is well represented by the main sustained phase of the 79 AD Vesuvius eruption, which deposited a thick white to gray pumice lapilli fallout deposit. This phase was followed by a column collapse phase, which mainly emplaced several pyroclastic density currents (PDCs). While tephra deposits of Plinian eruptions are well-constrained in their sedimentological features and transport processes, little attention has been paid on the occasional fallout from post-Plinian activity. One outstanding reason for this is the impermanent nature of these fall deposits, which are generally small in volume and eroded by successive PDCs in proximal and medial sectors and swept away especially in their distal portions, due to the combined effect of rill and wind erosion, soil creep and other forms of mass wasting. Because of this, hazard assessment is inherently incomplete. Here, we present stratigraphic and volcanological evidences for the existence of five lithic-rich lapilli fallout layers interstratified with the pyroclastic density current deposits emplaced after the collapse of the 79 AD Plinian column. These late fall products are distributed south of the Vesuvius, at distances between 5 and 20 km from the vent (from Mt. Somma slopes to the Mt. Lattari). These lithic-rich horizons, named D, G1, G3, I and X2 from base to top, exhibit mantling structures, are massive and generally well sorted (sorting = 1.05-1.55). The Md Φ ranges from 8 mm (unit G1) to almost 0.5 mm (unit G3). Component analysis shows that layer D has 61 wt.% of lithics and 23 wt.% of juvenile clasts, while the upper layers have about 70-83 wt.% of lithics to less than 0.50 wt.% of juvenile material. The remaining part is made up of crystals and not separated fine ash. A number of outcrops were identified to reconstruct the distribution for the thicker units D and G1. We estimated the plume height by apply the method of Wilson and Walker [1987] to the lithics isopleth maps. We prefer to use lithic isopleths rather than pumice isopleths due to fragile behaviour of the pumice clasts, which could lead to a less reliable result. When more than one isopleth is used, Ht is the average value, and the error represents the difference between the maximum and minimum. These data highlight the oscillating behaviour of the 79 AD eruption plume during the post-Plinian fall phase. During the emplacement of layer D, the column rose about 17 km. A second sustained column, which rose to 19 km, occurred during the emplacement of layer G1. Both distributions show a SE trend even if the azimuth of the dispersal axis of layer G1 seems to be rotated by 10-20° relative to that of D. Erosion acting preferentially on the upper part of the succession prevented the isopleths of G3, I and X2 from being defined. The dispersion of the lithic-rich layers is similar to that of the basal lapilli Plinian deposit, including rotation of the dispersal axis. Our study suggests that the resumption of a sustained column was repeatedly established during the post-Plinian phase of the 79 AD Vesuvius eruption. The main difference with the basal pumice lapilli deposit is the strong enrichment in lithic clasts, possibly associated with a recurrent instability in the conduit-vent system.

S01 - Oral Presentation

Stratigraphy, lithofacies variations and transport and emplacement mechanisms of the most destructive PDC of the 79 AD Vesuvius eruption

Ileana Santangelo, Claudio Scarpati, Annamaria Perrotta, Lorenzo Fedele, Giulia Chiominto

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Plinian eruptions form a sequence of pyroclastic fallout deposits commonly overlain by ignimbrites. Partial column collapses often form intraplinian pyroclastic density currents (PDCs), and sustained column phases punctuate late, prevalent column collapse phases. In both cases, PDC deposits show longitudinal and lateral variations on a regional scale. Considerable facies variations have been identified in the Plinian 79 AD PDC deposits on a regional scale. A systematic survey allowed us to study in detail the distribution and lateral facies variations of the different PDC stratigraphic units to document factors governing PDC emplacement mechanism. Here we present a sedimentological analysis of lithofacies combined with grain-size and componentry data related to unit E, a post-Plinian deposit that exhibits the most destructive impact and show the most widespread distribution, being traceable on mountain slopes beyond 20 km from the vent. We used a stratigraphic approach to identify and correlate this stratigraphic unit sandwiched between a lithic-rich fallout layer at the base and an accretionary lapilli bearing deposit at the top. Unit E, extensively studied [Luongo et al., 2003; Gurioli et al., 1999, 2005; Cioni et al., 2020], which partially coincides with the EU4pf unit [Cioni et al., 2004], shows a remarkable lateral variation in thickness (0.5 to 4 m), texture and sedimentary structure both at regional and local scale. Several facies are observed at different distances and azimuth from the vent. In proximal locations, on the volcano slopes, the deposit is mainly coarse-grained, cross-stratified and laterally discontinuous, showing low-angle erosional truncations. It forms small to large bedforms up to 130 cm in wavelength and up to 15 cm in amplitude. Locally, massive and clast-supported lenses composed of very fine lithic fragments occur between the layers. In medial locations, up to 10 km away from the vent, the most common lithofacies is a thick, up to 3.95 m, massive, moderate to very poorly-sorted (Φ ranging between 2.1 and 3.5), matrix-supported deposit with well-rounded medium and coarse lapilli pumice clasts dispersed in the ashy matrix. At the same distances, a massive or faintly stratified, reverse-graded, coarse and lithic rich lithofacies also occurs. Over a wide sector N of Vesuvius, where the 79 AD sequence thickens, the deposit consists of thick, massive, very coarse-grained lithic breccias characterized by lithic and pumice blocks supported in a coarse sandy matrix composed of the same constituents. In distal areas, on the Lattari mountains, between 50 and 750 m asl, the deposit is a fine-grained (Md Φ ranging between -0.2 and 3.5), thin (from 3.5 to 15 cm), massive and very poorly-sorted, with diffuse pumice clasts set into the matrix. In some proximal to medial stratigraphic sections, the basal unit E passes upwards into a stratified deposit with plane-parallel to cross-bedding stratification forming progressive bedforms up to 25 m in wavelength and 105 cm in amplitude.

The unit E also shows lateral and vertical variations in abundance and type of components, with, e.g., an increase in the juvenile content (between 0.36 and 47.2 wt.%) and a decrease of the lithic content (between 87.0 and 28.7 wt.%) at gradually increasing distances from the vent. These pronounced down-current and vertical facies variations suggest an aggradational deposition of a single, sustained, non-uniform and unsteady PDC, spreading with a high erosive power and shear strength over a distance up to at least 20 km from the volcanic source, and characterized by a depositional system very sensitive even to smallest variations of the substrate. In particular, our systematic facies study suggest that the basal portion of the flow could have moved down-slope developing different depositional regimes, topographically confined, mainly coinciding with paleovalley-ridge topography and ranging from traction (on topographic ridges) to grain flow and fluid escape dominated (in paleovalleys). Down-current, across a relatively flat landscape, the PDC decelerated (depletive behavior), developing a concentrated bedload. On distal high-reliefs, direct fallout from the transport system could be the dominant depositional mechanism. Instead, the vertical lithofacies association of the unit E indicates temporal changes of the dominant physical flow process in the flow boundary zone, suggesting an increasing turbulence with time of the PDC, which spread as a strongly diluted current only within certain distances from the vent.

Deadly thermal impact of detached ash cloud surges in 79CE at Herculaneum: a new hazard scenario at Vesuvius Volcano

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Short-lived phenomena as ash cloud surges are some of the deadliest volcanic events, able to produce huge devastation and mortality on a wide area around volcanoes. The temperature of pyroclastic surges is a fundamental parameter in determining their lethal power. Reflectance analysis on charred wood fragments collected in ancient Herculaneum allowed the reconstruction of the thermal events that impacted buildings and people during the 79CE Vesuvius eruption. The first ash cloud surge that entered the town had temperatures exceeding 500°C, capable of causing instant death of people, while leaving only a few decimetres of ash on the ground. Following pyroclastic currents progressively covered the town at lower temperatures. Our study shows that the early ash cloud surge was a very rapid event, detached from high concentration currents.

Reflectance analysis of charcoal fragments demonstrates to be the only proxy capable of recording multiple, ephemeral extreme thermal events, allowing us to disentangle for the first time the real thermal impacts of the 79CE Vesuvius eruption and reconcile apparently discordant data on the temperature of the pyroclastic currents that hit Herculaneum, derived from forensic/anthropological and paleomagnetic studies, all of which are instead valid, but refer to diachronic events.

The lethal impact detected for ash cloud surges produced during ancient and recent volcanic eruptions suggests that such hazard deserves much more consideration at Vesuvius and elsewhere.

S01 - Oral Presentation

Stratigraphy and eruptive dynamics of the Neapolitan Yellow Tuff, Campi Flegrei, Italy

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The deposits of the Neapolitan Yellow Tuff (NYT, 15 cal ky BP) form the country rock over which the city of Naples, Italy and surrounding municipalities are built on, hosting about 3 million people. These rocks were generated from the last caldera forming eruption of Campi Flegrei, the most active caldera in Europe.
Ash from NYT eruption were recognized across central Italy, Ionian, Adriatic seas and reached Croatia, Slovenia, and Austria. The stratigraphy of the NYT was the argument of some papers in late 80´s and 90´s, which presented differences in composite stratigraphy and eruptive mechanisms. In particular, there is still not general consensus if the NYT was a single eruptive event or it represents two or more eruptions separated by short time. Also, the eruption source parameters are poorly constrained, along with absence of data on total grain size distribution and erupted volume.
Here, we present an updated stratigraphy of NYT strengthened by compositional, componentry and grain size data, focusing on the lower sequence. Review of data from distal tephrostratigraphy allowed the drawing of dispersal area of the different phases of the eruption and the calculation of their volumes.

S01 - Oral Presentation

The Campanian Ignimbrite of southern Italy: a fissure eruption or caldera-forming event?

Giuseppe De Natale[1], Cristopher R.J. Kilburn[2], Giuseppe Rolandi[3], Claudia Troise[1], Renato Somma[1], Alessandro Fedele[1], Gianfranco Di Vincenzo[4], Roberto Rolandi[5], Judith Woo[6,2]

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We present a new stratigraphy for the largest volcanic eruption in Europe since at least the Late Pleistocene. The eruption produced the Campanian Ignimbrite of southern Italy. It is conventionally believed to have triggered collapse of the large Campi Flegrei caldera, which, in turn, has been identified as a source for future ignimbrite volcanism. New borehole and radioisotopic data, implemented in the framework of the Campi Flegrei Deep Drilling Project, challenge this interpretation. They indicate that the Campanian Ignimbrite was erupted through fissures in the Campanian Plain, north of Campi Flegrei, and was not responsible for caldera collapse. The results are consistent with ignimbrite volcanism being controlled by a common magmatic system beneath the Campanian Plain. Understanding the dynamics of the whole plain is thus essential for evaluating the likelihood of similar future events.

A new morphology-based classification scheme for intermediate to silicic lava flows: application to the Central Andean Volcanic Zone

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The morphology of a lava flow records the eruptive dynamics that governed its emplacement, evolution, and the rheological properties of the erupting magma. Although the eruptive dynamics and morphological classification methodologies for mafic lava flows have been widely addressed, the characterization of the morphological features of intermediate to silicic lavas is still not exhaustive. In this study, we present a methodology for the morphological characterization of lava flows based on DEM-derived data and satellite images. We also propose a morphology based classification for lava flows with a broad spectrum of features in the andesitic-dacitic compositional range. We analyzed a dataset of 49 lava flows from the Central Andean Volcanic Zone and quantified the maximum wavelength of their surface ridges, here described as folds, and their relationship with thickness distribution, pre-surface slope, composition, and rheology. Furthermore, we introduced a Fourier analysis for quantifying the plain-view shape of the lava flows and a novel method based on an S-Transform spectral analysis of grayscale satellite images to assess the surface folding pattern. We propose a classification for intermediate (andesitic to dacitic) lava flows: Ridged lavas have highly arcuate ridges with convex surfaces, large thickness, and a rounded frontal lobe. Coulee lavas are flows with characteristics intermediate between lava flows and domes. They have relatively simple shapes, with lengths that do not significantly exceed their width, vents generally located in the central zone of the flow, and prominent ridges and crumble breccias. Leveed lavas, which include a wide range of flow lengths, have the simplest shapes, are highly channelized, and have a unique frontal toe of maximum thickness. Breakout lavas have the most complex plain-view shapes with lateral and frontal lobes, poorly developed levees, and fronts with increasing width and thickness. Finally, Transitional lavas are common between the different types and exhibit intermediate features, folding patterns, and shapes. We show that the maximum wavelength is not continuous along with the flow surface and spatially correlates with thickness distribution. In addition, the maximum wavelength is poorly correlated with the SiO_2 content and partially by lava viscosity, with a good correlation with the gravitational component of the shear stress applied to the flow. Results support that the pre-eruptive slope and viscosity on thickness, together with the effusion rate, govern the general dynamics of the flow, and therefore the lava morphology, impacting different features such as the length, width, branching, and general deformation dynamics of the flow. The recognition of the main features of the different lava types and their controlling factors represent a first step for interpreting lava flow morphology in terms of the characteristics of the eruption. Our methodology and results are potentially applicable for the analysis and interpretation of remote, terrestrial lava flows and extra-terrestrial case studies.

S01 - Oral Presentation

New insights on the intimate structure of natural volcanic aggregates through X-ray micro-tomography

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Volcanic ash aggregation is a primary natural process, responsible for the formation of large particles starting from single ash fragments in a volcanic eruption. As a result, it strongly affects ash sedimentation in the atmosphere, with fundamental consequences for ash dispersal forecast and, hence, hazard assessment. An accurate knowledge of the internal structure and of the physical properties of volcanic ash aggregates is therefore essential to understand the underlying physics of aggregation processes and to improve the capability of forecast models to provide an unbiased characterization of ash dispersal in the atmosphere.
Up to now, the accurate knowledge on the intimate structure of common ash aggregates is still far to be achieved. This is due to the typically low preservation potential of the fragile structures of ash aggregates after their impact on the ground and to the challenging conditions that characterize ash collection during ongoing volcanic fallout. As a result, also the strategies used so far for ash sampling are unable to preserve the airborne structures of the most fragile ash aggregates, making the characterization of the original morphology almost impossible.
In this study we provide the first highly detailed characterization of both the internal and external structure of several unbroken ash aggregates collected during November 2019 at Sakurajima Volcano (Japan). Aggregates were directly collected using special UV-resins and then analyzed with X-Ray, micro-Computed Tomography (XR-mCT). The samples analyzed cover the most common aggregates categories generally observed during explosive volcanic eruptions in variable meteorological conditions, e.g. Particle Clusters (PC) and Accretionary Pellets (AP).
The results achieved by this study include descriptive 3D models of the structure of the different aggregates types, and couple them with accurate quantifications of important physical parameters such as density, volume, porosity, surface irregularity and external shape. All the extracted quantities are crucial for a correct parametrization of the aggregation process inside numerical models aimed to the hazard assessment. Data also provide precious insights about the formation mechanisms of the different types of aggregates and about their life-cycle within volcanic plumes.
This study represents a unique example of an innovative sampling strategy combined with the state-of-the-art technique of non-invasive tomographic reconstruction. The study outcomes represent the first close look to the hidden structure of volcanic ash aggregation.

S01 - Oral Presentation

Deposit-derived block-and-ash flows: the hazard posed by perched temporary tephra accumulations on volcanoes; 2018 Fuego disaster, Guatemala

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The impact of hazardous pyroclastic density currents (PDCs) increases with runout distance, which is strongly affected by the mass flux. This paper shows that the mass flux of a PDC may derive not only from vent discharge during the eruption, but also from partly hot, temporary stores of pyroclastic material perched high on the volcano. The PDC that occurred at Fuego volcano (Guatemala) on June 3, 2018, was unforeseen and happened c.1.5 hours after the eruption climax. It overran the village of San Miguel Los Lotes causing an estimated 400+ fatalities. Analysis of the facies architecture of the deposit combined with footages shows that a pulsatory block-and-ash flow flowed down the Las Lajas valley and rapidly waxed, the runout briefly increasing to 12.2 km as it filled, and then spilled out of river channels, entered a second valley where it devastated the village and became increasingly erosive, prior to waning. Paleomagnetic analysis shows that the PDC contained only 6% very hot (>590°C) clasts, 39% moderately hot (~200–500°C) clasts, and 51% cool (200°C) clasts. This proves that the block-and-ash flow mostly derived from the collapse of loose and partly hot pyroclastic deposits, which were gradually accumulated high on the volcano during the last 2+ years, leaving a collapse scar. Progressive collapse of unstable deposits supplied the block-and-ash flow, causing a bulk-up process, waxing flow, channel overspill, and unexpected runout. The study demonstrates that deposit-derived pyroclastic currents pose a particular hazard that is easy to overlook and requires a new, different approach to assessment and monitoring.

S01 - Poster

Reconstruction of the subaerial Holocene volcanic activity through paleomagnetic and ^{14}C dating methods: El Hierro Island (Canary Islands)

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Volcanic hazard assessment relies on the accurate knowledge of the eruptive style and recurrence of volcanic eruptions that occurred in the past. At El Hierro (Canary Islands) historical and prehistorical records are still poorly defined, and although the island was the location of the second-to-last eruption (La Restinga, 2011 CE) of the Canarian archipelago, the recent subaerial volcanism is still poorly studied. Information about the chronology of Holocene volcanic activity as well as the stratigraphy of the deposits is scarce: a few eruptions are dated so far, whereas the others are classified as pre-or Holocene events on the base of the lava flow characteristics along the coast. Here, we report on the dating of eleven (Mña Chamuscada, Mña del Tesoro, Orchilla, Las Calcosas, Mña Negra, Lomo Negro, Below Lomo Negro, Cuchillo del Roque, Malpaso Member, and Mña del Guanche) Holocene subaerial eruptions, distributed along the three rift zones, combining paleomagnetic and ^{14}C dating methods. For nine eruptions, we also provide geochemical analyses. Results indicate that two eruptions, Mña Chamuscada and Mña del Tesoro, occurred more recently than previously considered, setting them within the last two thousand years. Conversely, new paleomagnetic and ^{14}C ages obtained for the Lomo Negro eruption are consistent with literature data and constrain this event in the XVI century CE. For Malpaso Member deposits, the two ^{14}C datings obtained by charcoals found below and above the trachytic layer set the eruption during the Holocene epoch, between ~7300 BCE and ~4700 BCE. Finally, for the other eruptions, in two cases (Orchilla and Las Calcosas) many possible time windows during the last 14 ka have been found, whereas a few possible ages have been obtained for the others. Overall, the resulting chronological reconstruction of the recent activity of El Hierro indicates that eruptions occurred unevenly along the three main rifts, with nine eruptions in the WNW rift, six in the NE rift, and four in the SSE rift. We document two periods characterized by a high eruptive frequency at least: an old one, between 8000 BCE and 1000 BCE, with eight eruptions, three of which were characterized by phonotephrite and trachyte, and a recent one, between 1000 BCE and the present day, with at least seven eruptions, mainly showing basanite compositions. The new data yield a significant improvement in Holocene eruption chronology and thus are instrumental for a correct evaluation of the volcanic hazard at El Hierro.

S01 - Poster

Age of the Valle del Bove formation and chronology of the post-collapse flank eruptions, Etna volcano (Italy)

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The Valle del Bove is a profound and wide scar on the east Etna flank witnessing the Holocene main volcano-tectonic event of the volcano, frequently invaded by lava flows during the last centuries. The Valle del Bove slope failure produced the Milo debris avalanche deposit on the lower east flank that is partially covered by the Mongibello lavas and pyroclastic succession. In this paper, we constrain for the first time the age of the Milo debris avalanche deposit and of the overlying lava flow succession exposed at three quarries recently caved at valley mouth through a multidisciplinary approach integrating stratigraphic and petrographic analyses, ^{14}C, and paleomagnetic dating. In particular, ^{14}C age determinations of the Milo debris avalanche deposit indicate that the initial stage of the catastrophic flank collapse of the Valle del Bove occurred at 7478-7134 BC during the Mesolithic age. Conversely, the main portion of the lava succession filling the valley floor emplaced after the sub-Plinian picritic eruption occurred at 2579-2278 BC (FS tephra layer) consistently with the increasing occurrence frequency of flank eruptions documented in the geological record of Etna during the past 4000 yrs. Paleomagnetic dating highlighted that in the study area the sub-Plinian eruption was followed by two quasi-contemporaneous flank eruptions during the Late Copper age (2600-2399 BC), whereas in historical time other two flank eruptions occurred during Greek-Roman and Medieval ages.

S01 - Poster

The contribution of drone images to reconstructing volcanic history: application to the island of Lipari

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The reconstruction of the eruptive history of island volcanic systems encounters considerable difficulties due to the impossibility of establishing the general architecture of the main tephra units, starting from the distal and mid-distal sequences dispersed in the downwind sectors. The need to conduct investigations directly on the proximal deposits usually produces a reasonably satisfactory reconstruction of recent events, while there is an increasing lack of clarity and uncertainty for progressively older events due to the scarcity of outcrops resulting from the burial of ancient deposits under recent deposits (pyroclastic and lava), and also due to the location and type of natural cuts that are often characterised by vertical and inaccessible walls (coastal cliffs and deep incisions).

This work presents the first results of a re-examination of the volcanic history of the eastern sector of the island of Lipari, mainly based on the contribution of images and drone footage of vertical outcrops not accessible by land. The framework now consolidated in the literature indicates that several rhyolitic eruptions (explosive and effusive) have occurred over the last 15,000 years, produced by vents aligned along regional fractures oriented in the NS direction. According to the same framework, the main events recognised to date (explosive and effusive) would be those of: i) Capo Rosso and Canneto Dentro (11000-15000 years), ii) Gabellotto-Vallone Fiume Bianco (8500 and 7200 years; iii) Monte Pilato (776 AD) and iv) Forgia Vecchia-Rocche Rosse-Lami (circa 1230-1300 AD).

The close analysis of laterally extended outcrops, exposed in vertical walls devoid of vegetation, located from the north to east of Monte S. Angelo and M. Chirica, not reached by paths, as well as the 3D observation of volcanic structures taken from different panoramic angles, reveal a greater complexity than the picture reconstructed from the analysis solely on the ground. In particular, evidence emerges of the presence of new elements that have not been identified to date, such as explosive volcanic units that had not previously been surveyed, paleosols and new lava bodies (flows and domes) that do not fit within the conceptual schemes adopted up to now. The sector of the island occupied by Monte Pilato, in particular, appears to mainly consist of a complex of domes and lava flows dating between the Gabellato eruption /Pomiciazzo lava flow and the Monte Pilato eruption, today partially buried and/or mantled by recent ashes and pumices produced by the same volcano (including those of Lami-Rocche Rosse). A new lava unit appears to be present along the southern sector of Monte Pilato between the M. Pilato eruptive event and the Lami eruption.

The main novelty of the work is of a methodological nature and consists in showing how the use of drones, especially in volcanoes of the insular type, allows acquiring highly informative images on which it is then possible to considerably broaden the stratigraphic and structural picture. This work also has the merit of orienting and guiding subsequent targeted field inspections, starting with the most significant and complete outcrops, in sectors that are highly inaccessible.

S01 - Poster

Growth, collapses, and evolution of the long-lived Ollagüe volcano, Central Andean Volcanic Zone

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Volcanic landscapes result from the interplay of alternate phases of construction and destruction. Destruction processes such as sector collapse profoundly influence the growth and evolution of large volcanoes. These modifications of the external morphology largely and suddenly modify the mass distribution above shallow magma reservoirs, leading to shifts in the style, rate, composition, or distribution of post-collapse eruptions. The Ollagüe volcano (21°18' S, 68°11' W) is an active composite edifice located along the Chile - Bolivia border in the Central Volcanic Zone of the Andes. It is a long-lived, 1,230 ka to present, and multiple-collapsed volcano, developed along an NW - striking extensional fault, belonging to the Pastos Grandes - Lipez - Coranzuli regional fault system. In this contribution, we present a new detailed field-based mapping, accompanied by a morphological and morphometric analysis based on DEM-derived surface parameters, petrographic and whole-rock major oxides and trace elements characterization of the different products. In addition, we redefine and propose a new evolutionary scheme based on the description of lithostratigraphic units. From a morphological and volcanological perspective, the volcano comprises the products of an old and eroded cone dominated by central activity on the northern and eastern flanks. The southern to northwestern portions of the volcanic edifice comprehend the youngest activity with growth-destructive cycles due to catastrophic flank collapses and a dynamic shift of the activity from a central to lateral mid-flank vents and vice versa. Based on field observations and satellite-DEM analysis, we identify deposits of at least three debris-avalanche events with their classical hummocky morphology. In addition, we recognized two debris-avalanche deposits in the western flank of the volcanic edifice and at least one blast deposit, challenging the proposed unique debris-avalanche nature of the deposit emplaced in the Salar de Carcote basin and thus, redefining the volcano evolution. The volcano predominantly comprises the effusive emission of andesitic to dacitic lava flows and domes, while basaltic-andesite products typically occur as mafic inclusion, defining a high K calcalkaline suite. The Ollagüe lavas are generally dominated by plagioclase, clinopyroxene, orthopyroxene, amphibole, and biotite. Spatially and petrographically, they are distributed in two main groups. The first comprises andesitic lavas from the old cone and some post-collapse lateral flows with a modal composition of two pyroxenes and amphibole with scarce biotite. Whereas the second group corresponds to the northwestern lavas, lateral parasitic domes, and youngest post-collapse domes, with their associated block and ash deposits, present an assemblage dominated by amphibole and biotite with only minor pyroxene. These two main domains indicate that the shift from central to lateral activity may be likely related to the effects of the edifice load and magma compositions as a response to the volcano multiple-collapse nature.

S01 - Poster

$^{40}Ar/^{39}Ar$ dating of the trachytic crystal mush of the Green Tuff ignimbrite, Pantelleria island

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The Green Tuff (GT) is the last of nine ignimbrite eruptions associated with the peralkaline volcanic complex of Pantelleria island (Sicily Channel, Italy).
Well known in the scientific literature for its petrological and eruptive peculiarities, the GT eruption withdrew a shallow chemically zoned magma reservoir, consisting of a deeper and a late-erupted trachytic crystal mush (P = 1-1.5 kbar, T = 925 C°, H_2O_{melt} = 1.5-2.5 wt. %) to a shallower pantelleritic magma batch (P = 0.5-1-2 kbar, T = 730 °C; H_2O_{melt} = 4.0-4.5 wt. %) [Romano et al., 2018, 2019].
In this work we focus on the trachytic top member, which is characterized by high porphyricity (> 35 vol.% Na,K-feldspar phenocrysts), high Ba concentrations and positive Eu anomalies both in the groundmass glass and in cpx-hosted H_2O-poor melt inclusions as well [Romano et al., 2018, 2019].
To better constrain the Green Tuff eruption and to stress the relationship between trachytic and pantelleritic members, we performed new $^{40}Ar/^{39}Ar$ age determinations on anorthoclases phenocrysts (mean composition: $Ab_{70}Or_{25}An_5$) [Romano et al., 2018].
Irradiation with fast neutrons along the flux monitor FCT (Fish Canyon Tuff) at the Oregon State TRIGA Reactor was followed by a long degassing at low temperature, a necessary step to discard any extraneous surface-bound ^{40}Ar. Single crystal laser ablation was followed by the isotopic ratios measurements of argon using a Helix SFT (2013) mass spectrometer housed at Institut des Sciences de la Terre d'Orléans (CNRS-ISTO). Despite accurate hand-picking selection, xenocrysts cannot be avoided, but their effect can be mitigated using the single grain fusion approach to provide a robust eruption age.
Pantelleritic members (basal fallout deposit and ignimbritic member) were previously dated at 45.7 ± 1.0 ka (2σ) [Scaillet et al., 2013]. Here, we obtained a statistically indistinguishable weighted mean age (WMA) of 43.9 ± 0.5 ka (1σ), with a mean square weighted deviation (MSWD) of 1.34. This age confirms previous dating and point to variable (lesser) xenocrysts contaminations relative to the other GT members. This is unexpected on the premise that more 40Ar should be stored in crystals accumulating at the bottom of the pantellerite magma chamber due to feldspar fractionation and accumulation in the magma mush.
Compared to the age of the pantelleritic members, our new data basically supports field evidence, confirming no stasis took place between the plinian/sub-plinian phase of the eruption (basal fallout deposit and ignimbrite) and the late extrusion of the trachytic ignimbrite top member representing the deeper portion of the Green Tuff reservoir.

Emplacement temperature estimation of the 2015 Calbuco pyroclastic density currents (PDCs) using charcoal reflectance (Ro%) method: preliminary results

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Calbuco is considered one of the most active stratovolcanoes of Chilean Andes during the last 100ky. Since postglacial times, almost twenty pyroclastic density currents (PDCs) and ten pumice fallout have been generated. The last eruption, which took place on 22-23 April 2015, consisted in two sub-Plinian pulses with eruptive columns heights up to 15 km above the crater level.
During the volcanic activity, tephra fall deposits (volume ~0.27 km^3) and a series of PDCs were generated, reaching a considerable distance of up to 6 km from the emission point. Along the N-NE flank of the volcano, in the Rio Blanco and Rio Tepu valleys, trees were charred and buried by PDCs.
In several case studies, PDCs have demonstrated their ability to maintain very high temperature for long distances when confined within paleo-valleys. The flow channelling and the consequent inhibition of the heat dispersion, strongly influence the flow dynamics and the PDCs capacity to reach farther distances respect to unconfined currents. Therefore, the evaluation of PDCs emplacement temperature and its variation from proximal to distal areas are extremely important regarding volcanic risk assessment in terms of civil protection.
Reflectance analysis of charred wood (Ro%) has been widely applied as a geothermometer in volcanic environment for the estimation of PDCs emplacement temperature. In this study, we performed Ro% on charred fragments collected from still standing trees along both Rio Blanco and Rio Tepu valleys, in order to give preliminary estimations of the transport thermal capacity of PDCs occurred during the 2015 Calbuco eruption.

S01 - Poster

Magnetic fabric and paleomagnetism of the Mount Calanna dyke swarm: a comprehensive study on swarm emplacement

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Dyke swarm emplacement has been a significant field of interest among volcanologists, structural geologists, geophysicists, and geochemists in recent times. Due to their passage from a deeper magma chamber through the crust to the surface or near-surface settings, dykes can provide valuable information on the source and how magma has interacted with crustal rocks. So, dykes are often called as the sensitive indicators of geological processes. Here we are using the techniques of Palaeomagnetic and Anisotropy of magnetic susceptibility (AMS) analysis to untangle the geological Evolution of Mount Calanna.
Mount Calanna dyke swarm of Mount Etna is one of the least studied dyke swarms in Italy. It includes ~ 200 dykes spread over the deeply altered and faulted volcanic rock within an area of 0.7 km^2. Topographically, this isolated hill is located at an altitude of 1325 m with respect to the mean sea level. We used 45 oriented hand samples from 11 dykes to conduct systematic AMS and palaeomagnetic analysis where special attention was given to choose samples from both the marginal and central parts of all the dykes.
Based on the structural data, we classified the sampled dykes into two classes: a) vertically emplaced, which concentrates on the flank; b) horizontally emplaced, mostly on the top part of Calanna. AMS failed to provide a uniform flow direction for the first group, whereas the second group provides a consistent flow direction along the S-E direction. Moreover, the magnetic foliation plane of most of the samples appears to be parallel to either sub-horizontal or sub-vertical joints. Using the AMS results we tried to interpret the flow fabrics of each sample and later grouped them into 1) sub horizontal fabrics 2) inclined fabrics and 3) subvertical fabrics. Besides, paleomagnetic techniques enabled us to unravel the nature of natural remanent magnetization (NRM) and the coevality of dyke injection. Interestingly we found 3 cluster of paleomagnetic directions, one of this associated to highly altered dykes, as confirmed by rock magnetic data.

S02 - MULTIDISCIPLINARY APPROACHES FOR VOLCANO-TECTONIC STUDIES

Conveners:
Stefano Vitale, Paolo Madonia, Mariarosaria Falanga, Roberto Isaia, Jacopo Natale

Earthquake cycles in Central America and the impact in the volcanic activity

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Large cities in Central America have been affected by earthquakes and volcanic eruptions throughout their history. Some volcanic eruptions took place a short time after the earthquakes, in other cases the number of eruptions per year in the region increased years after the earthquakes. However, the lack of observation cases and incomplete catalog hinders the possible relation between these two geophysical extreme phenomena.
From late 18th century the catalog of tectonic earthquakes with Mw>7 and eruptions with VEI≥2 in Central America has been well registered. In two centuries, we identify 8 earthquakes cycles divided in two "major" (~40 years) and "six" minor (~20 years) cycles based on time and seismic moment and interrupted by Mw: 7.6-8.1 earthquakes. We found that in six of these eight earthquake cycles, the eruption rates per year increased in a factor from 1.1 to 3 times, during the ten years that followed the beginning of the earthquake cycles, in relation to the ten years prior. However, to determine why some volcanoes erupted and why others did not after each earthquake cycle is not well understood. In our investigation, we found evidence that volcanoes with previous unrest and without large previous eruptions are more prone to erupt after each earthquake cycle.
These results can forecast the possible increment in volcanic eruptions in the region and identify which volcanoes will erupt in the next earthquake cycle and this could help to reduce the risk of disaster in a region.

Influence of tectonic inheritance on the distribution and characteristics of rift-related volcanism: examples from the Main Ethiopian Rift, East Africa

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During continental rifting, tectonics and volcanism closely interact, and tectonic structures may strongly influence the characteristics and distribution of volcanic features. In this context, the existence and reactivation of pre-existing structures, inherited from previous tectonic phases, may exert a strong, yet sometimes enigmatic, control. The Main Ethiopian Rift (East Africa) represents an ideal place to analyse this influence: it is indeed a magmatic rift where a complex pre-rift tectonic history created pre-existing discontinuities that influenced later extension-related processes, including faulting and volcanic activity.

Many examples from the Main Ethiopian Rift document that reactivation of inherited crustal/lithospheric fabrics played an important role in controlling the distribution and characteristics of volcanic activity at different scales. At a large (regional) scale, expression of this control is volcanic activity located well away from the rift in the plateaus surrounding it, i.e. the so-called off-axis volcanism. Depending on the orientation of the inherited crustal/lithospheric fabrics, this may result in alignment of volcanic centres sub-parallel (mostly in the Somalian plateau) or sub-orthogonal (mostly in the Ethiopian plateau) to the main rift trend. At a smaller (local) scale, pre-existing structures may control the overall orientation of Quaternary volcanic fields or the (complex) distribution of individual vents within them (e.g., in the Ririba rift, at the southernmost termination of the Main Ethiopian Rift). Inherited structures are also suggested to control the location of large peralkaline calderas at the rift axis (e.g., Fantale, Kone, Gedemsa and Corbetti), as well as their geometry (e.g., pre-existing faults reactivated during the collapse, giving rise to fault-controlled caldera rims).

S02 - Oral Presentation

Analysis of the aseismic deformation referred to the Ripe della Naca fault system (Mt. Etna): a volcano tectonic approach through geological and geophysical data

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The Ripe Della Naca Fault System striking ENE-WSW near the North-Eastern sector of Mt. Etna Volcano. This Area is affected by several active faults related to the NNW-SSE oriented extensional dynamics [De Guidi et al., 2012; Monaco et al., 2010]. During 1928, an historical eruptive event occurred in the studied area [Branca et al., 2017]. In particular, the propagation of the fracture-fissure system gave rise to the 1928 eruption mentioned above and was controlled by the tectonic lineaments of the Ripe Della Naca fault system. Thus, in this work we present a directly focused study on the Ripe Della Naca Fault System with the aim to provides its geometrics and kinematics features through a multidisciplinary approach, combining geological, morphological, seismic and geodetic data. We also provide the compute of the fault related stresses field in order to better understand the volcano-tectonic processes related to magma ascent and regional stresses interacting in this area. In particular, we provided: i) a schematic profile showing Ripe Della Naca geometry in depth and surface morphology; ii) the analysis and the compute of the fault related stresses field by using Coulomb and Griffth Criterions [Griffith, 1924] and also the TDE's (Triangular Dislocation Elements; [Meade, 2007]) method, at various depths (e.g., 1 km, 2 km 3 km); iii) the model of the Ripe Della Naca Fault plane by using Midland Valley's Move software (academic grant). The results obtained through the above mentioned workflow, allowed us to define a clear volcano-tectonic conceptual model, useful to study similar settings and scenarios.

S02 - Oral Presentation

Evidence of seismic-related liquefaction processes within the volcanic record of the Campi Flegrei caldera (Italy)

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We report the occurrence of several sand liquefaction structures, such as sand dikes, in the stratigraphic record of the Campi Flegrei volcano located both inside and outside the caldera. Five sites were analyzed within the caldera and two outside. The grain size analysis of the sand fillings indicates that these deposits are very fine-to-coarse sands generally poorly sorted. All granulometry curves fall within the field of the liquefiable loose sediments. Frequently, dikes are characterized by two fillings, a rim showing poorly sorted finer sands and a core with extremely poorly sorted coarser sediments. We suggest that seismic-related liquefaction processes triggered the injection of these sand dikes during unrest episodes in the last 15 kyr. The frequent occurrence of dikes formed by sands with two different grain sizes can be associated with the grain size segregation phenomenon during the liquefaction process. Segregation may occur both within the source layer and dike itself, with the finer sediments moving and forming an infiltration layer and being injected upward, followed by the coarser sediments. The sand dikes located outside the caldera, characterized by larger thicknesses and lengths, mark an important extensional episode probably associated with the caldera formation during the Neapolitan Yellow Tuff eruption at 15 ka. This caldera-formation event produced a radial extension outside the caldera and intense seismic activity that caused lateral spreading, sand liquefaction and upward migration of liquefied sands along fissures randomly oriented. Furthermore, liquefaction structures within the caldera are related to the seismic activity probably occurring during the Agnano-Monte Spina caldera formation and the volcano-tectonic ground deformation predating Epoch3b (4.3 ka) and Monte Nuovo (1538 CE) eruptions. This study highlights as these seismic-related liquefaction structures are common within the volcanic record of the Campi Flegrei, suggesting that the sand source can be both the widespread marine succession underlying the Epoch3 deposits in the caldera central sector and the primary ash layers extensively present in the volcanic record.

S02 - Oral Presentation

Volcano-tectonic, electrical and electromagnetic investigations at different resolutions highlight the structure of the most active sector of Campi Flegrei

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The Solfatara-Pisciarelli sector has been the site of small phreatic, phreatomagmatic and effusive eruptions, which emplaced domes and crypto-domes. One of the open scientific problems concerns the deeper feeding system of the Pisciarelli hydrothermal field, its relation to the Solfatara system, and the main structures governing the fluid rising.
The present study aims to define in detail the surface and buried volcano-tectonic structures and their interaction with hydrothermal fluids in the Solfatara-Pisciarelli area and to characterize the presently unknown feeding zones.
Through the geological-structural field surveys, we reconstructed the geological map of the area and implemented the fault and fracture orientation and kinematic dataset. On the other hand, geoelectric surveys were carried out along profiles of different lengths to characterize the structure in depth of the investigated sector and assess any changes as a function of electrical resistivity. Electrical resistivity tomographies (ERT), which reach a depth of investigation up to about 100 m, show strata with variations as a function of electrical resistivity and present sub-vertical discontinuities that can be interpreted mainly as normal faults. The results of the electrical tomography and the geo-volcanological and structural survey allowed the reconstruction of geological sections showing the main structures that characterize the Solfatara and Pisciarelli area.
A detailed 3D survey of the shallowest part of the Pisciarelli hydrothermal system (down to a depth of 20 m) was reconstructed using high-resolution electrical geophysical surveys. The results of the multiparameter survey, including high-resolution measurements of electrical resistivity, induced polarization, and self-potential, allowed us to derive a model of the shallow part of the fumarolic field that provides fundamental information about the processes governing fluid circulation and gas/vapor emission in the area. Results indicate that the major fault systems in the area control the circulation of fluids, promoting their accumulation in a deep reservoir (already identified by the deeper ERT investigations) and subsequently, in response to pressure changes, their upward migration into the shallower system.
An Audio-MagnetoTelluric (AMT) survey was carried out in the central sector of the Campi Flegrei caldera to obtain information on the deeper feeding system of the Pisciarelli fumarolic field and its relations with that of the Solfatara and the volcano-tectonic structures of the area. The survey involved 47 measurement sites whose inversion produced a 3D resistivity imaging, which identified the electrical pattern of the investigated structure down to a depth of 2.5 km below sea level, highlighting several electrical resistivity anomalies related to distinct processes and physical conditions in the system.
The model represents the first three-dimensional image of the first few kilometers of the central sector of the Phlegraean area. Results highlight the main volcano-tectonic structures already hypothesized by previous shallower electrical surveys by describing their development in depth.
The analysis of the 3D resistivity model, together with volcano-tectonic and more superficial

ERT investigations, identified the main structures playing a major role in the ongoing dynamics of the investigated area and provided crucial information for the formulation of scenarios related to possible impulsive events such as hydrothermal and phreatic explosions.

Fault systems in the offshore sector of the Campi Flegrei caldera (southern Italy): implications for nested caldera structure, resurgent dome, and volcano-tectonic evolution

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The Campi Flegrei caldera (southern Italy) has over one-third of its extension below the sea. Its volcanic history has been characterized by two major caldera-forming eruptions, namely the Campanian Ignimbrite (CI) and the Neapolitan Yellow Tuff (NYT), at 40 and 15 ka, respectively. We analyzed high-resolution seismic reflection profiles allowing us to characterize the faults in the offshore portion of the Campi Flegrei caldera. Two main fault systems have been recognized: those forming the caldera rims and those affecting the intra-caldera resurgent dome. The former system is 2-3 km wide and comprises three concentric fault zones (outer, medial, and inner ring fault zones) depicting a nested caldera geometry. Considering the relations between faults and seismic units, the latter corresponding to the marine and volcaniclastic successions filling the caldera, all ring faults were formed during the CI eruption and subsequently reactivated during the NYT eruption. In this last caldera-forming event, the inner and medial fault zones accommodated most of the collapse and were episodically reactivated during post-caldera periods. The second fault system occurs in the apical zone of the resurgent dome and comprises dominantly high-angle normal faults that are mainly related to the volcano-tectonic collapse following the Agnano-Monte Spina Plinian eruption (4.55 ka). Furthermore, the ring faults convey a significant amount of fluids toward the seafloor and, above all, have confined the distribution of post-NYT volcanic vents and the subsequent intracaldera deformation field. The marine seismic record studied here documents that the caldera evolution in the last 40 kyr results from the interplay among ring and dome fault activity, volcanoclastic sedimentation, ground deformation and sea-level changes. The detailed reconstruction of the offshore caldera structural architecture and the timing of the fault activity allowed us to provide a volcano-tectonic evolutionary model of the last 40 kyr.

S02 - Oral Presentation

Resolution and characterization of seismic swarms and clusters at Mt. Etna volcano (Sicily, Italy)

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Mt. Etna is among the most active volcanoes in the world and is considered one of the most interesting natural laboratories for the understanding of eruptive processes and the ascent of magma.
The seismicity on Etna is released both in the form of isolated shocks and in seismic swarms, which can frequently occur both in conjunction with eruptive activity (e.g. 2001, 2002-2003, 2008-2009, 2018 eruptions) and also during periods of background seismicity.
About 50% of Mt Etna earthquakes are shallow (focal depth 5 km b.s.l.) and mainly located in the eastern flank [Patanè et al.,2004]. The seismicity is present in a wide range of depth (up to 30 km); however most of it is concentrated within the first 7 km of depth.
In this study, we have analysed the earthquake catalogue recorded by the permanent seismic network of the Istituto Nazionale di Geofisica e Vulcanologia - Osservatorio Etneo - Sezione di Catania (INGV-OE) in the period 2000-2021, in order to define and identify the seismogenic areas of the volcano in which the energy is released mainly in the form of seismic swarms.
An automated identification of spatial clusters of seismicity is challenging, partly because of the voluminous nature of the seismic catalogue at Mt. Etna, counting more than 20,000 events over 20 years, but also due to the heterogeneous distribution of seismicity, with substantially uneven seismicity rates at different regions and depth ranges. The temporal evolution of the seismic network, instrumentation and data analysis procedures, over the last decades, has resulted in a varying time dependent completeness of the catalogue and accuracy of the hypocentral location. To overcome these challenges, we implemented an extended version of Seiscloud [Cesca, 2020], a density based clustering algorithm for seismicity. In our new approach, the catalogue is iteratively processed using progressively stronger seismicity density requirements to identify clusters. In the first iteration, low density requirements lead to the identification of few, large, heterogeneous clusters, which are further processed in the following iterations to progressively discover smaller-size and more compact subclusters. The analysis of the INGV-OE Mt. Etna catalogue, performed over different time intervals, leads to the identification of a large number of seismic clusters. They are located in the entire region surrounding the volcano and affect different depth intervals. Seismic clusters are identified, for example, along the Pernicana-Provenzana Fault, Valle del Bove region, M. Parmentelli and summit craters areas. After this identification, we investigate clustered seismicity separately, using both temporal clustering techniques and applying inter-event time statistics to discuss the temporal evolution of earthquake magnitude with the primary goal of assessing the presence and location of seismic swarms.

S02 - Poster

Dynamics of the main active faults bounding the mobile flank of Mt. Etna volcano, through very-long period comparisons of survey data

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As known, all the eastern side of Mt. Etna is affected by continuous seaward motion induced by a complex interaction of regional stress, gravity forces, magma pressurization and dike-induced rifting. In this context, the Pernicana and the Trecastagni-Tremestieri Fault systems identify the northern and southern boundaries of the main eastern unstable sector.
The dynamics of these faults has been analysed by a multi-disciplinary approach with terrestrial and satellite ground deformation data. Terrestrial data consist in levelling across both faults and extensometers record on the Trecastagni fault. Satellite data consist in GPS surveys, both on wide and local networks, and InSAR data.
The levelling network across the Trecastagni fault has been installed on 2009; last survey has been carried out in 2021, allowing a more than 10 years of vertical deformation time series to be investigated on this fault. The surveys show a mean vertical slip rate of about 10 mm/y and episodic acceleration on short segments of the fault, with displacements of almost 30 mm. The monitoring of the Trecastagni fault is also performed by two continuous wire extensometers and a system for periodic direct measurements across the fault in its central and north-central sectors. Each extensometer is equipped with a data-logger programmed for 48 data/day sampling, storing displacement and ground temperature. The two stations measure the relative displacements perpendicular to the fracture. Data recorded by extensometers highlight an opening trend of about 2-3 mm/year with some acceleration leading up to more than 2 mm in 15 days at the end of 2009.
Levelling lines were installed on Mt. Etna on eighties. Part of the levelling route crosses the Pernicana fault, at an altitude of 1500 m asl and another segment intersects the fault at 700 m asl (Rocca Campana). Measures on this network provide a high detail on the vertical kinematics allowing strong constraints in modelling the sources of slip episodes. In 2021, a long part of the route on the NE flank of the volcano has been surveyed, from the upper NE flank crossing the 1928 eruptive fissure, towards South around the Ripe della Naca faults and down to NE. This part of the route is connected to the reference point in Linguaglossa village, outside the volcano edifice. Thus, this survey allowed the vertical deformation to be referred to the stable reference point of the entire levelling route. This means that we are able to measure not only the relative motion of the two sides of the Pernicana fault but also the absolute vertical displacement of all points, related to global and very-long-term volcano dynamics, over a 40 years period, to be compared to the more continuous but covering shorter time intervals data coming from other ground- and space-based techniques.

S02 - Poster

Mt. Etna volcano (Sicily, Italy): is the 2021 deep seismicity recorded on the eastern flank it represents an anomaly?

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Mount Etna is an open conduit volcano characterized mainly by effusive activity interspersed with explosive and/or paroxysmal activities. Two geodynamic domains affect eastern Sicily: the first (in the northern sector) is represented by the Apennine –Maghrebian thrust belt; the second affects the southern sector and is represented by the Iblean Foreland, which is the northern part of the Pelagian block. Etna is located between these two important geodynamic systems. It is also crossed by other regional fault systems such as: the NE-SW Giardini-Messina alignment and the WSW -ESE Mt. Kumeta - Alcantara System (MKAS). A last important structure is the Malta escapement with NNW-SSE orientation. It is a structure that have a continuation towards the Ionian Sea.
Instrumental and historical seismic analyses show that 80% of the earthquakes of Mount Etna involve the eastern side with depths of less than 5 km [Azzaro et al., 2011]. In this sector of the volcano, surface extensional seismicity originates from the NNW-SSE seismogenic orientation of the structures. However, the strongest earthquakes on the contrary occur on the western slope, with focal mechanisms mainly oriented NNW-SSE and SW-NE [De Guidi et al., 2014]. The analyses of focal mechanisms and the stress tensor computation indicate an orientation predominantly NNW-SSE orientation of the P-axis and maximum compressive stress in the lower crust (depth>10 km.) under the western sector of the volcano. This is consistent with the regional trend of central and western Sicily, relating to the Africa-Europe convergence. In this domain, compressive overcomes the ESE-WNW extensional regime, leading to faulting along the eastern flank of the volcanic edifice, largely in the shallow crust.
The eastern flank of the volcano is characterized by important structures, mainly normal faults (the so called 'Timpe') with NNW-SSE orientation, which represents the northern extension of the Hyblean-Maltese escarpment. Furthermore, in this sector several earthquakes of high magnitude and intensity have occured [Azzaro et al., 2011].
Another important regional trend, with a NE-SW trend, is characterized by the Messina-Fiumefreddo alignment that is detectable on the northeastern side of the volcano. We focused on the seismicity recorded by the permanent seismic network of Istituto Nazionale di Geofisica e Vulcanologia - Osservatorio Etneo (INGV-OE) in an area located between the villages of S. Alfio, Milo, S. Venerina and Macchia di Giarre on the eastern flank of volcano, in the period between January 2021 and May 2021. We have analysed seismic swarms that occurred in an anomalous depth range (up to 20 km) for this sector of the volcano. It is worth noting that no seismic activity has ever been recorded in this sector of the volcano. This seismicity could represent an anomaly in the seismic picture of the last twenty years or be explained in the context of regional geodynamics.

S02 - Poster

Historical photogrammetry-derived models to investigate the architecture of the Fremrinamar rift, Northern Iceland

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We present a study focused on studying the architecture of an entire rift, named Fremrinamar, which is one of the seven volcanic systems that characterized the Northern Volcanic Zone of Iceland; the latter accommodates the plate spreading in Northern Iceland.
The Fremrinamar rift has a length of 130 km and a width between 8 to 19 km. Considering its dimension, it has been necessary to design a methodology to identify and characterize all the structures remotely.
We reconstructed a Digital Surface Model (DSM) and an Orthomosaic by photogrammetry processing applied to different set of historical aerial photos of the area, freely available through the National Land Survey of Iceland. Their resolution is of 0.52 and 2.07 m/pixel, respectively.
Starting from these products, we mapped the Fremrinamar rift at a scale of 1:2.500, identifying 3674 normal fault scarps, 1717 extension fractures and 218 eruptive fissures. The overall strike of the structures shows values between N-S to NNE-SSW, with minor values between NE-SW and E-W, and a maximum length up to 7000 m represented by the normal faults. For both normal faults and extension fractures, the highest length values are associated with a N-S strike, while such pattern is not clearly recognizable for the eruptive fissures.
More in detail, The Fremrinamar rift is characterized by the presence of NNE-striking grabens, often associated with eruptive fissures at their center. As an example, the Sveinar Graben is the most representative graben that characterized the south-eastern portion of the Fremrinamar Volcanic System. This graben has mainly developed during the eruption that generates the Sveinar Lava, 6000 to 8000 years ago [Tentler and Mazzoli, 2005]. The width of the graben ranges from 0.5 to 0.8 km and extends for 20 km [Trippanera et al., 2015]. The analysis of the photogrammetry-derived models shows an asymmetric graben, associated with an eruptive fissure at its center. Northward there is a change in direction of both faults and eruptive fissures from N-S to NNE-SSW. The northern portion of the Fremrinamar Volcanic System is differently characterized by a paucity of eruptive fissures, graben structures are associated only with extension fractures. North of the Nupar hyaloclastic Shield, the eastern portion of the fissure swarm abruptly changes its strike toward NNW-SSE.
This methodology has proven to be a useful tool for the investigation of a wide area, returning promising results, consistent with field observations.

S02 - Poster

S03 - TEPHROCHRONOLOGY: A POWERFUL TOOL FOR UNRAVELLING THE PAST

Conveners:
Lorenzo Monaco, Alessio di Roberto, Ivan Sunyé Puchol, Giuseppe Re, Federica Totaro

A tool for the evaluation of the completeness of the volcanic records in the Mediterranean area

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Tephrostratigraphy and chronostratigraphy allow paleoclimatic and sedimentary events to be accurately dated in an absolute and relative way, thereby enabling their correlation with related eruptions, which can be used to determine the chronology of the deposits. In order for a model to be elaborated relating to the dispersal of tephra from a volcano during an explosive eruption, it is important to consider the typical variables associated with eruptions, such as magnitude and the wind pattern during the eruption. One of the most critical points for tephrostratigraphic reconstruction is the analysis of space-time completeness of the stratigraphic record in a certain place. To solve this problem, we developed a tool that matches grain size of tephra and wind statistics. The wind statistics in the Mediterranean area was obtained from the online database Climate Data Store-Copernicus, for the 1990-2020 period. Joining the wind statistics with terminal velocity of volcanic particles of different size, allowed us to draw maps of the probability to find tephra deposit from a given volcanic source and with a given size in the stratigraphic record of any location in the investigated area. These analyzes quantify, for each volcanic district, the probability that eruptions of different magnitudes can be recorded in the stratigraphic successions of the Mediterranean area. The input parameters of the tool are: i) eruptive column height (proxy of eruption intensity); wind statistics (direction and intensity) randomly sampled over 30 years; and, iii) settling velocity of a selected grain size [Costa et al., 2016; 2017]. In particular, the parameterizations provided by Costa et al. (2016) made possible identifying the minimum center of mass sampling distance associated with a given particle size class. The volcanoes considered in our study are Phlegraean Fields, Somma-Vesuvius, Aeolian Islands, and Mount Etna, while the heights of eruptive columns are discretized as 5-10-20-30 km. The comparison of probabilistic maps with tephrostratigraphy of known marine and terrestrial cores will allow the statistical quantification of the completeness of the recovered tephrostratigraphy. On the other hand, the probability maps will guide for location of sampling sites for a certain tephra deposit. The probability maps might also support the study of the completeness of the overall eruption catalogues through time, allowing to study the cyclical and non-stationary behaviors of eruption frequency of different volcanic sources, correlating these behaviors with possible external forcing from geodynamics or climate change.

Tephrochronological study of the lacustrine succession of the Castiglione maar (Central Italy) and evaluation of the possible impact on the climate of the explosive eruptions of the peri-Tyrrhenic volcanoes

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The AMUSED project, funded by the Istituto Nazionale di Geofisica e Vulcanologia, represents an integrated, multidisciplinary study of the climate change indicators in the Mediterranean region in the last 280 ka. The project aims at deriving the chronology of changes, driving mechanisms, and possible consequences on the paleoenvironment. It relies on high-sensitive, high-resolution, and well-dated multi-proxy data recorded in lacustrine sediments sampled in the Castiglione maar (Central Italy), in marine sediment cores from the Tyrrhenian Sea, and in speleothems from the central Apennines. Within the project, the study of tephra records is coupled with the high-resolution climatic records to investigate the potential relationship between specific volcanic eruptions and past climate variations, at a local and regional scale. We present the advancement of the tephrochronological study carried out on two parallel, 120 m-long lacustrine sediments cores sampled in the Castiglione maar. Valle di Castiglione maar is an eccentric explosive centre, located on the northern flank of the Colli Albani volcanic complex, ca. 20 km E of Rome. Its volcanic activity, of hydromagmatic origin, occurred about 373±8 ka [Marra et al. 2003]. Previous low-resolution and chronologically poorly constrained investigations, indicate that the Castiglione maar hosts a long and continuous lacustrine sediment succession, spanning at least the last ~250 kyr [Narcisi et al., 1992], furthermore the site is located in a pivotal position with respect to main volcanic centers of central Italy characterized by an intense explosive activity during the Quaternary. Volcanic activity in this area was dominated by explosive eruptions with a broad spectrum of intensity and magnitude, and fed by magmas differing in composition. Eruptions comprise mild explosive Hawaiian to Strombolian, sometimes hydromagmatic events from monogenetic eruptive centres (es. scoria cones, tuff cones and tuff rings), to large Plinian eruptions characterised by sustained columns, caldera collapses and volumetrically relevant pyroclastic flow. In the time window approximately covered by the sedimentary sequence of Castiglione maar, the volcanic complexes of Monti Vulsini, Monti Sabatini, Vico, Colli Albani and Roccamonfina were repeatedly active with very large, energetic eruptions capable of spreading relevant deposits in the drilling site area.
45 macroscopic tephra layers were recognized in the continental sequence, and characterized for texture, mineral assemblage, major and minor elements glass compositions and trace elements. Preliminary results indicate that tephra in the continental sequences derive mostly from explosive eruptions of the Roman Province volcanoes such as Mt. Vulsini, Vico, Mt. Sabatini, Monti Albani and Ischia occurred in the last c. 360 ka. Results are crucial to build sequence age models and consequently chronology of climate changes and to test possible feedback effects between large volcanic eruptions and climatic signals.

S03 - Oral Presentation

Tephrochronology of marine sequences in a cold seep area of the SE Tyrrhenian Sea (Paola Basin) as a tool to reconstruct main episodes of methane release

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Here we present preliminary correlations of tephra deposits recognized in several sediment cores to constrain the chronology of methane release. These cores were collected during two oceanographic campaigns (MVP11 and MB14) at depths between 520 and 750 m in a cold seep area of the southeastern Tyrrhenian margin (Paola Basin), which is characterized by mounded structures aligned along an anticline (Paola Ridge) and covered by pockmarks [Rovere et al., 2014; Rovere et al., 2022].
The sediment cores contain methane-derived authigenic carbonates that precipitated due to Anaerobic Oxidation of Methane in the Sulfate Reduction Zone with associated chemoautotrophic symbiontic shelly mega fauna [Rovere et al., 2015; Franchi et al., 2017]. The down-core trend of abundance and isotopic characteristics of clam beds, benthic and planktonic foraminifera show that these seep sites have remained geochemically optimal habitats over a period of more than 40,000 years. Episodes of enhanced methane flux are also recorded and these have been dated using radiocarbon on macro fauna shells and foraminifera. The tephra in the investigated sequences occur as both primary and secondary deposits and they have been recognized and correlated between the cores through visual characteristics, magnetic susceptibility, and X-Ray Fluorescence log profiles using diagnostic elements and element ratios. Electron microprobe and LA-ICP-MS analyses have been carried out on single glasses from selected samples of selected primary tephra in order to characterize their composition in terms of both major- and trace- element content. These results allow to relate the studied deposits to eruptions from southern Italy volcanoes and to establish proximal-distal and distal-distal correlations, thus implementing previous tephra studies of the region. This multi-proxy stratigraphic approach to the studied marine sequences provides a first chronostratigraphic framework for a complex area and constrains the timing of the main episodes of enhanced methane release.

The tephra layers in the Crotone sequence: a microanalytical study

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The Crotone series includes three main sections, i.e. Santa Lucia, Vrica and Semaforo. The series extends from 2.47 to 1.21 Ma, including 30 complete glacial/interglacial climatic cycles, corresponding to Marine Isotope Stages (MIS) 97 to 37. It is internationally known for containing, at the base of the Vrica sequence, what was previously considered the Global Stratotype Section and Point of the base of the Pleistocene. However, following the successive decision to lower the Pliocene-Pleistocene boundary down to 2.588 Ma, the Point marks the base of the Calabrian stage, and the whole sequence is included in the Pleistocene. The succession consists of open marine deposits (fossiliferous, silty marl claystone) with interbedded sapropel layers. At least three volcanic ash layers are also interbedded within the section. For the lowermost tephra ash (a1) an age of 2.31 ±0.34 Ma has been inferred [Suc et al., 2010 and references therein], while the uppermost layer (a4) outcrops above the Gelasian-Calabrian border and is therefore younger than 1.806 Ma.

Despite the several works on the Crotone series, the geochemical characterization of the tephra layers is not well constrained and only mineral compositions are currently available. In this work we have carried out a petrographic and microanalytical study on the glass and mineral phases of three ash samples: VR_S1, the lowermost ash layer outcropping along the Semaforo section, and VR_A3 and VR_A4, corresponding to the two uppermost levels in the Vrica section.

All the samples are almost exclusively composed of volcaniclastic fragments. Samples VR_S1 and VR_A3 are very similar, mainly composed of glass shards with elongated or cuspidate shapes and rare pumices. Mineral phases are mainly represented by plagioclase, amphibole, ortho-pyroxene and rare clinopyroxene and olivine. The average grain size of the glass shards ranges from a few tens to several hundreds of micrometers. In sample VR_A4 the size of the shards is smaller (usually less than 50 micrometers) and highly vesiculated pumices are more abundant. Some lithic fragments, represented by lavas with microcrystalline texture, also occur. Among the mineral phases plagioclase is the most abundant, followed by biotite and pyroxenes. Fe-Ti oxides and apatites are rare.

The chemical composition of the glass shards is rhyolitic, with the first two samples more silica-rich (SiO_2 ca 75 wt%) than VR_A4 (SiO_2 ca 70 wt%). All the samples show a High Potassium calc-Alkaline affinity, with VR_A4 glasses falling at the border with the shoshonite field. Microanalytical results indicate a strong similarity between VR_S1 and VR_A3 showing lower alumina, CaO, MgO, FeO and alkalies, and higher chlorine contents than VR_A4.

The source of these tephra layers has been identified in the southern Tyrrhenian Sea volcanism in the early Pleistocene [Suc et al., 2010]. However, the poor resolution of the early Pleistocene tephrostratigraphic record and the proximal products of the eruptive sources makes it very difficult to confirm this hypothesis. As for the level VR_A4, an attempt has been made to compare its composition with the lowermost tephra levels of the Montalbano Jonico sequence, representing the upper part of the Calabrian stage. The comparison was made using the microanalytical data of Petrosino et al. [2015].

However, the glass of Vrica level shows a decisively higher alkalies content with respect to the calc-alkaline glass of V1 from Montalbano Jonico.
Though not decisive for attributing the tephra levels to a specific volcanic source, our data provide a useful database for future tephrostratigraphic studies.

Insights into the explosive eruption history of Campi Flegrei prior to the Campanian Ignimbrite eruption

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Accurate tephrostratigraphic reconstructions reveal the magnitude, frequency and dispersal of past eruptions and can also provide insight into how magmatic systems change over time. Proximal sequences, close to the source volcano, often only provide fragmentary insights into eruption histories due to burial and erosion. Consequently, difficulties arise in correlating distal records owing to these incomplete proximal records and geochemical data for many large eruptions. However, the generation of accurate eruption records requires the integration of both proximal and distal records with robust chrono-stratigraphic and geochemical information.

The Campanian Volcanic Province (CVP) comprises multiple active volcanoes, and includes the Campi Flegrei and Ischia calderas. These caldera volcanoes have produced some of the largest eruptions in the past 200 ka, such as the Monte Epomeo Green Tuff (MEGT; Ischia) at 56 ka and the Campanian Ignimbrite (CI; Campi Flegrei) at about 40 ka and these deposits form widespread isochrons across the Mediterranean region. These closely spaced volcanic centres produce predominantly trachytic glass compositions that are similar, and it can be somewhat challenging to correlate the deposits to specific volcanic sources. Both proximal and distal sequences have alluded to explosive activity in the lead-up to the caldera forming CI eruption, and this study aims to constrain the tempo and compositional changes of the system prior to the evacuation of such large volumes of magma.

Here we present a detailed tephrostratigraphy for Pre-CI eruption activity using the units preserved within a sequence at Acquamorta (also referred to as Monte di Procida within the literature). The Acquamorta outcrop is located on the west side of the CI caldera ring fault and is a wide exposure along a sea cliff. The stratigraphic section has previously been described noting the preservation of numerous pyroclastic units beneath the CI from multiple volcanic sources; Campi Flegrei, Procida and Ischia. Both the distinctive, and dated, MEGT and CI units can be recognised in the section and various units were logged and sampled between these two marker beds.

We have acquired new single grain EMPA and LA-ICP-MS glass data to characterise the units between 40 and 56 ka at Acquamorta. The detailed compositional data allow tephra from Campi Flegrei and Ischia to be identified and distinguished, analysis reveals three Ischia and six Campi Flegrei eruptions, highlighting the intense volcanic activity of these centres between the large caldera-forming eruptions. The three Ischia layers between the MEGT and the CI are indistinguishable both in major and trace element data and thus cannot be correlated with known eruptions. The similarities between these layers demonstrates the diligence that must be taken when correlating in the distal realm, but this also has direct implications for hazard assessment on Ischia which are currently hampered by our limited knowledge of the volcanoes eruptive history for this time interval/span. The compositional variations between the Campi Flegrei eruptions reveal temporal changes in the magmatic system prior to the CI eruption.

Ultimately, this study demonstrates the potential for Neapolitan proximal outcrops to preserve detailed information on past CVP volcanism. Such information is critical for the assessment of the volcanic hazards associated with potentially large-volume explosive eruptions and their frequency, in close proximity to the densely populated Neapolitan area.

There she blows! Unravelling the eruptive history at Aso caldera (Japan) using distal ash deposits

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Mount Aso (southwestern Japan) is one of the largest active volcanoes in the world, with a caldera that was formed and modified by a series of at least four catastrophic VEI 6 - 7 eruptions between ca. 270 to 86 ka. These caldera-forming events produced widespread ash deposits blanketing Japan and the surrounding seas, with the final Aso-4 event generating pyroclastic density currents that can be mapped over 160 km from source. Between these large magnitude events Aso is known to have remained very active, but the frequency, scale and dispersal of these eruptions are poorly constrained. This is unsurprising since the proximal exposures are limited and the numerous cataclysmic events have destroyed and buried older deposits. Here, we highlight the critical role that distal records play in evaluating the eruptive history and hazard potential of Aso caldera. We review all known distal occurrences of tephra deposits, integrating new data from lake and marine sedimentary records across the East Asian/Pacific region. This detailed tephrostratigraphic framework highlights inconsistencies in tephra correlations and suggests large magnitude events were more frequent and widely-dispersed than previously anticipated. To further supplement this record, we used high-resolution sedimentary cores to identify non-visible ash (cryptotephra) deposits erupted from Aso, which provide new insight into the timing and dispersal of both pre- and post- caldera-forming events. The precisely dated Lake Suigetsu sediment core (central Japan) provides the most comprehensive distal eruption record for Aso, despite being over 530 km NE from the vent. The Suigetsu record is utilised to date and geochemically fingerprint (using major, minor and trace element glass compositions) thirteen ash fall events from Aso that reached the now densely populated regions of central Honshu. The cryptotephra layers preserved at Suigetsu show that both Aso and Aira (150 km south of Aso) volcanoes in Kyushu were very active in the 5 ka leading up to the VEI 7 eruption of Aira at 30 ka (AT tephra), producing at least nine widespread explosive events. This work serves as a critical reminder that even in volcanic regions that are intensely studied, numerous large Quaternary explosive events remain poorly understood and many are undocumented. Unravelling the past eruptive history, repose intervals and magmatic characteristics is essential for calderas like Aso which pose a significant threat for populated regions.

S03 - Oral Presentation

Tephrochronology, modelling and dynamics of large-magnitude eruptions in the Campi Flegrei caldera

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The study of tephra layers from marine and terrestrial environments is a very powerful tool in volcanology for studying past eruptive events [Lowe, 2011]. Near-vent volcanic successions commonly provide fragmentary records of past eruptions, due to volcanic and sedimentary processes they experience [Albert et al., 2019]. Hence, correlations with medial and distal records help to reconstruct the eruptive history, recurrence times and dynamics of past explosive eruptions more accurately [Albert et al., 2019]. In this context, tephrochronology can be used to acquire a better knowledge of past explosive activity, through the correlation of proximal and distal deposits to volcanic source areas.
Campanian volcanoes have widespread distal records in the Mediterranean area (i.e. Pomici di Avellino eruption from Somma-Vesuvius volcano, Neapolitan Yellow Tuff eruption from Campi Flegrei volcano). In particular, the Campi Flegrei, a Holocene caldera west of Naples, is one of the most productive volcanoes, with a volcanic history including large-magnitude eruptions (i.e. Campanian Ignimbrite, 39 ka; Neapolitan Yellow Tuff, 15 ka).
A lot of research has been done on the large-magnitude eruptions and on the history of the last 15 ka [Di Vito et al., 1999; Smith et al., 2011]. However, the volcanic record of the eruptions occurred before Campanian Ignimbrite is largely incomplete. In fact, recent studies [Albert et al., 2019; Donato et al., 2016; Giaccio et al., 2012; Monaco et al., 2022] highlighted the presence of widespread ash layers in the distal tephrostratigraphic record, that have never been described before in the Campi Flegrei history, with up to hundreds of thousands of km^2 of ash covering, tens of km^3 dense rock equivalent of the magma erupted and VEI>6 [Albert et al., 2019]. This shows that there are still a lot of gaps in the eruptive history of the volcano and reduces drastically the recurrence intervals of large-magnitude events at Campi Flegrei caldera. Therefore, a full reconstruction of eruptive dynamics and modeling of these large-magnitude eruptions still lack.
In summary, the current research on the tephrostratigraphic record of large-magnitude eruptions in distal environments (i.e. Ionian Sea, Adriatic Sea) reveals that the knowledge of the Campi Flegrei volcanic record is largely incomplete. This has important implications in the quantification of recurrence times of explosive activity and in volcanic hazard assessment, due to the increased probability of large-magnitude events.
The aim is to provide a deeper knowledge of the dynamics and dispersal of past large-magnitude eruptions in the central Mediterranean area, thanks to the correlation of distal and proximal deposits from large-magnitude eruptions and the reconstruction of the volume, magnitude and eruption dynamics. With this regard, through the determination of ash shape, particle size and componentry for morphoscopical aim, it is possible to provide models of ash dispersal, sedimentation and settling velocity. A model of ash dispersal in the atmosphere can be obtained using 2D or 3D ash-dispersal Eulerian models (i.e. HAZMAP or FALL3D). These studies are fundamental to reconstruct the eruptive parameters, and to assess the hazard related to ash dispersal in the atmosphere.
Thus, a better understanding of poorly documented events in the Campi Flegrei volcanic activity

appears to be essential to provide future eruptive scenarios. In fact, the genesis and ash dispersal modeling of these poorly known eruptions are still lacking. Further studies to model their dispersal, eruption parameters and dynamics must be carried out to know their scale and the hazard of similar eruptions in the future.

Cryptotephra layers in marine sequences of the Ross Sea, Antarctica: implications and potential applications

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Marine sediments of Antarctica contain tephra, fragmented material produced by explosive eruptions of Antarctic volcanoes and widely dispersed by wind. Tephra are preserved especially when sequences suffer small disturbance and sedimentation rates are high. If fingerprinted, dated and linked to a volcanic source, tephra become time-synchronous markers for independent correlations between geological archives. Tephra are also significant for volcanological reconstructions to derive the type, magnitude, age and recurrence of eruptions. Tephra record can be significantly extended by examining successions for the presence of cryptotephra (non-visible tephra). These are essential to increase the number of eruptions recognizable of any magnitude and in distal occurrences.

We present the preliminary results of the tephrochronology study of marine sediments sampled in the Ross Sea (Antarctica) in the framework CHIMERA (CryptotepHra In Marine sEquences of the Ross Sea, Antarctica) and GRETA projects (CoolinG oveR thE VicToria LAnd: resolving the Ross Sea response to continental climate change during the last two millennia), funded by Italian Programma Nazionale delle Ricerche in Antartide (PNRA). We studied (i) TR17-02, Anta98-13, Anta91-14 and Anta99-Cj03 sediment cores recovered from the Joides Basin, (ii) Abio38-c2 core from the Pennel Through and (iii) TR17-08 and HLF16-02 cores from the Edisto Inlet. These three sedimentary basins, which are located in the western Ross Sea, have different distances from the major active volcanoes of the Northern Victoria Land. Using magnetic susceptibility coupled to XRF and lithostratigraphic investigations, we detected several cryptotephra layers. These were further characterized by a detailed description of tephra texture, mineral assemblage, and single shards major and trace element geochemistry. The age of cryptotephra layers is based on accelerator mass spectrometry (AMS) radiocarbon dates performed either on acid-insoluble organic matter.

Results indicate that some of the studied cryptotephra originate from historical eruptions of Mount Rittmann and Mount Melbourne volcanoes and allow the definition of new tephra markers for the synchronization and correlation of different sedimentary records. Furthermore, some of the studied cores record the rapid, synchronous increase in the abundance of volcaniclastic particles as detrital material in marine sediments possibly linked to ice shelf breakup processes.

S03 - Poster

Fast morphometrical data acquisition on volcanic ash particles for the eruptive style detection: a multivariate statistics approach

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Morpho-textural analysis of volcanic ash is a key instrument to promote an increased understanding on the complex interplay between degassing, crystallization and fragmentation mechanisms that controls unsteadiness in the dynamics of low-to-mid explosive eruptions. In particular, several studies highlighted the links between the physical features of the ash particles (e.g., shape) and the different physical parameters that characterize magma prior, during and after explosive eruptions within different eruptive contexts, such as magma rheology, chemistry (i.e., magmatic evolution and volatile content), vesicularity, crystal content and also conduit geometry of the system. Considering these links, and based on the morphological and textural analysis of juvenile ash particles, important insights can be gained about the efficiency and the style of magma fragmentation useful to give interpretation on the eruptive dynamics.
In this study we apply a multivariate statistical analysis to a large database on the apparent projected ash shape (APASH) in order to test with a solid and unbiased method the informative potential of the ash shape in terms of the variable eruptive styles and contexts. Several volcanic ash samples, collected at different sites around the world, were selected in order to account for the natural variability commonly observed within the low-to-mid energy and unsteady eruptive contexts (Sakurajima, Japan; Copahue, Chile; Etna and Vulcano, Italy; Fuego, Guatemala; Sangay, Ecuador; Santa Ana, El Salvador). Analyzed ash samples were collected either on the field during ongoing volcanic crises and from well-defined stratigraphic sequences, in order to associate a specific eruptive style to each of the collected deposits. Samples were analyzed using a static particle analyzer (Malvern Morphologi 3Gs) in the Laboratories of the University of Florence, resulting in the automatic and rapid (on average, 45min/sample) determination of a set of 20 dimensionless shape parameters on a very large population of ash particles (more than 10^5 particles/sample). This allowed us to construct a very large database of morphological measurements and treat the data with a statistical approach in order to outline some general relationships between the eruptive context and the different measures of the APASH of the particles. Discriminant analysis roughly classify the large set of morphological information and outline some important data trends, which are consistent with the eruptive style and context. These preliminary results confirm the validity of the approach and suggest a new way for the development of semi-automatic strategies for volcanic ash monitoring and classification.

S03 - Poster

S04 - BEHIND THE SCENES: ADVANCED METHODOLOGIES TO UNRAVEL THE ARCHITECTURE, DYNAMICS AND TIMESCALES OF VOLCANIC PLUMBING SYSTEMS

Conveners:
Simone Costa, Maurizio Petrelli, Marisa Giuffrida, Gabriele Lanzafame, Andrea Cannata

Determining the State of Activity of Transcrustal Magmatic Systems and their Volcanoes

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Polygenetic volcanoes and calderas produce eruptions of a wide variety of magnitudes, chemistries, and recurrence times. Understanding the interplay between long- and short-term and deep and shallow processes associated with accumulation and transfer of eruptible magma is essential for assessing the potential for future eruptions to occur and estimating their magnitude, which remains one of the foremost challenges in the Earth sciences. We review literature and use existing data for emblematic volcanic systems to identify the essential data sets required to define the state of activity of volcanoes and their plumbing systems across their full transcrustal extent. We explore global eruptive records in combination with heat flux and other geological and geophysical data to determine the evolutionary stage of plumbing systems. We define a Volcanic Activity Index applicable to any volcano that provides an estimate of the potential of a system to erupt in the future, which is especially important for long-quiescent volcanoes. Our Volcanic Activity Index challenges the current (very loose) defintion of what is an active volcano and significantly enlarges the number of potentially active volcanoes on Earth. A focus on the Italian volcanoes shows that the all Quaternary calderas of the Roman Magmatic Province, as much as all the Aeolian arc volcanoes, should be considered potentially active and that the time laps since last eruption (e.g. last quiescence) by itself, even when compared to average recurrence times, is not a reliable indicator for the state of activity of a volcanic system.

S04 - Oral Presentation

Magma recharge and mush disruption control basaltic paroxysmal eruptions: the summer 2019 eruptions at Stromboli volcano (Italy)

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Stromboli volcano (Southern Italy) shows characteristic persistent Strombolian activity alternating with episodic lava effusion and more violent explosive events (major events and paroxysms). The latter usually occur at intervals of a few years. However, the two most recent paroxysms occurred at very short interval on 3 July and 28 August 2019. A degassed highly porphyritic (hp) magma is typically erupted during the normal Strombolian activity. A more mafic, hotter, volatile-rich magma with low phenocryst content (lp) is erupted only during the paroxysm, mingled with hp-products. These typical mingled hp-lp products were also erupted during the 2019 paroxysms.

Clinopyroxene phenocrysts exhibit marked chemical heterogeneities and complex textures. Diopsidic compositions (Mg# 80-90), recorded by mantle + rim overgrowth and rare antecrystic cores, are markers of more primitive, higher-T (~1175°C) lp magma injecting into a shallower, lower-T (~1155°C) domain of the plumbing system represented by the augitic compositions (Mg# 69-79) of the majority of cores and some overgrowth. The short timescales recorded by the diopsidic overgrowth (from 1 day to 54 days) testify a rapid response of the magmatic system to injections of new mafic magma(s) in the days prior the two paroxysms, pointing to a major role played by mafic injections in triggering the 2019 paroxysms. Efficient mush cannibalism during the previous years (i.e., 2003-2017) has determined a drastic reduction of the crystal mush leading to a fully rejuvenated plumbing system in less than two decades. This, in turn controlled the 2019 paroxysms, as also demonstrated by the good correspondence between timescale of pre-eruptive mafic recharges and monitoring data.

Decoding the textural and temporal zoning patterns of minerals provide vital information for the interpretation of magma dynamics and the effects on monitoring data demonstrating the power of petrological studies in interpreting patterns of surficial activity. Magma-mush dynamics exercises a key role in controlling eruptions style and magnitude at persistently active basaltic volcanoes.

S04 - Oral Presentation

Thermal and SO_2 measurements reveal shallow magmatic dynamics at Stromboli volcano

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Stromboli volcano is globally known for its persistent long-lasting activity sustained by steady, degassing-driven convective magma overturning in the shallow conduit. This persistent regime is characterized by a rate of magma supply to the upper feeding system largely exceeding the rate of magma eruption. We combine independent observations of heat (Volcanic Radiative Power; via satellite images) and gas (SO_2, via UV camera) fluxes in a temporal interval encompassing the summer 2019 eruptive crisis to characterize the regimes of shallow magma circulation. We show that, during the phase of ordinary strombolian explosive activity that preceded the unrest, the average magma input rate (0.1-0.2 m^3/s) exceeds the magma eruption rate (0.001-0.01 m^3/s) by about 2 orders of magnitude. In contrast, during the 2019 effusion, the magma input and output rates converge to approximately the same values of 0.2 to 1 m^3/s. We interpret this as evidence of a temporary suppression of the ordinary excess degassing regime during the effusion. The two parameters exhibit different trends during the effusive phase, with the peak in SO_2 emissions lagging behind the thermal emission peak by about one month. We take this observation as evidence for that lava outpouring dominates over magma supply in the conduit in the first phase of the effusive eruption. We additionally propose that this initial phase of the effusion leads to a decompression of the shallow plumbing system, ultimately causing ascent of less-dense, volatile-rich magma batch from depth and elevated SO_2 fluxes, culminating into a paroxysmal explosion on August 28. The continuous and in near-real time combined analysis of thermal and SO_2 flux time-series paves the way to improved understanding of shallow magmatic system dynamics at open-vent system, enabling a better capturing of the transition from explosive to effusive activity regimes.

Image-assisted analysis for unraveling textural and chemical features of volcanic rocks: A case study from the 2019 paroxysmal eruptions of Stromboli

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We present an advanced image processing strategy, based on the Q-XRMA software (Ortolano et al., 2018), for acquiring quantitative information on volcanic samples showing textural and chemical complexities as a result of intricate mechanical and/or chemical magmatic interactions. The new methodology has been tested on pumices and scoriae emitted during the July 3 and August 28, 2019, paroxysmal eruptions of Stromboli, whose textural and compositional heterogeneities reflect concomitant emission of two magmatic end-members, a low porphyric (LP) basalt and a high porphyric (HP) shoshonite [Giordano & De Astis, 2021; Viccaro et al. 2021]. Since pumice and scoria are strictly intertwined in individual ejecta, discerning between the coexisting fractions turns out to be a hard task, which requires meticulous, time-consuming analytical work and data processing. In this contribution, we show that the composition of the two interacting magmas can be fully and easily discerned at the microscopic scale, even in samples with evidence of intense interaction processes (mingling vs. mixing). The image analysis by Q-XRMA was performed on mm-sized domains selected on thin sections, each reflecting the main features of HP or LP magmas, respectively. The software utilizes the Principal Components Analysis and the supervised Maximum Likelihood Classification for the multivariate statistical data handling of an array of X-ray elemental maps collected at the scale of selected micro-domains. This permits to parametrize of textural and chemical features of volcanic rocks in a few steps, distinguishing among various rock constituents, such as vesicles, crystals, and glasses, extrapolating the associated modal abundances, and imaging chemical variations within the glass portion in great detail. In particular, we focused on the compositional variability of glasses to quantitatively discern between LP and HP magmas in individual micro-domains. Our elaborations evidence heterogeneous interaction from micro- to macro-scale, which can be the result of a fast, therefore incomplete, mixing/mingling of the LP and HP end-members. Furthermore, we are able to recognize subtle differences in the proportions of the two magmas constituting the products of both eruptions, being the LP basaltic magma more represented in the July 3 products with respect to those of August 28, 2019. These differences, in turn, might be a consequence of syn-eruptive mixing/mingling that involved smaller proportions of LP magma during the eruption of August 28.

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S04 - Oral Presentation

Kinetic crystallization of a high-K basalt melt undercooled in laboratory: Implications for the modeling of open-conduit dynamics at Stromboli (Aeolian Islands, Italy)

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Crystallization of igneous minerals is a fundamental process driving the evolution of magmas and eruptive styles of active volcanoes. Crystallization occurs through either (near) equilibrium or kinetically-controlled mechanisms influencing the chemistry of magmas and the textural characteristics of igneous rocks. Among other factors, the degree of undercooling (ΔT), the difference between the liquidus temperature and the actual temperature of crystallization, is critical. Experimental investigations on the effect of ΔT are essential to reconstruct the crystallization path of basaltic melts under kinetic conditions which are frequently encountered in open-conduit volcanic systems. Stromboli is a reference example for these types of volcanoes, due to its persistent activity and periodic changes of eruptive style. In this study, we examine the effect of ΔT on the crystallization of basaltic magmas at Stromboli. The starting material is a high-K basaltic glass obtained from a low-porphyritic pumice erupted during the paroxysm of April 5, 2003. Experiments were performed in a non-end loaded piston cylinder at 300 MPa, 1050-1150 °C, nominally anhydrous and hydrous (2 wt.% H_2O) conditions, NNO +1.5 buffer and an imposed ΔT ranging from 10 to 162 °C. Textural features and chemical compositions of the experimental charges are investigated by synchrotron radiation X-ray microtomography (SR-µCT), scanning electron microscopy (FE-SEM) and electron probe microanalysis (EPMA). Experimental clinopyroxene shows textural and chemical dependence on ΔT. Particularly, clinopyroxene evolves from prevalently skeletal to dendritic with increasing ΔT. Clinopyroxene crystals become enriched in incompatible Ti and Al in concert with concurrent depletion in compatible Si and Mg. According to this cation exchange, the degree of ΔT is parameterized to derive a new predictive model for high-K basaltic melts and based on clinopyroxene composition only. Modeling results using natural clinopyroxene crystals provide new insights on the interpretation of open-conduit dynamics at Stromboli.

Long-term precursors to large explosive eruptions of Vesuvius: evidence from the opening phase of the Avellino Plinian eruption

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The deposits of distinct opening phases related to weak transient activity have been recognized frequently at the base of Plinian and Sub-Plinian eruption occurred all over around the world (i.e., Pululahua Eruption, Papale and Rosi 1993; Minoan Eruption, Santorini; 1815 Tambora Eruption, Sigurdsson and Carey, 1992; AD 79 Vesuvius Eruption, Sigurdsson et al., 1985; Cioni e al., 1992; 1991 Pinatubo Eruption, Rosi et alii, 2001; Laacher See, Germany, Schmincke et al., 1999). In general, the opening stages are recorded in the deposits as thin ash-bearing beds characterized by largely variable juvenile material and high lithic content. The volcanic products of these phases clearly record pre- and syn-eruptive processes and preserve information on the onset of magma ascent. Hence, geological evidence from the basal deposit, together with compositional and textural analysis, could help in the interpretation of short-term precursory phenomena as seismicity, ground deformation and gas emission, assuming a key role for volcanic hazard assessment as well as for monitoring purposes at high-risk volcanoes like Somma Vesuvius.
The Pomici di Avellino eruption was characterized by a distinct opening phase recorded in the stratigraphic succession by a double bedset made of alternate lapilli and ash layers referred as unit EU1 at the base of the magmatic Plinian deposit (units EU2 and EU3). The detailed study of the ejected products comprises morphological, textural and compositional analysis and it assumes a relevant role to understand modalities and rates of the eruption trigger. The basal deposit is characterized by a large heterogeneity of the juvenile material, with the identification of different components: white pumice, low-vesicularity clasts and dense blocks. Textural and petrographic characteristic of the groundmass, major and trace element compositions and residual volatile contents (Cl, F), strongly differ between the different juvenile lithologies, and between these and the products of the following climactic Plinian phase.
The occurrence of fractures hosting highly vesicular glass and cutting through phenocrysts and a largely crystallized groundmass is typical of dense blocks and could suggest the occurrence of pre-eruptive magma processes inducing decompression and rigid fragmentation into a cryptodome/shallow intrusion that experienced an intrusive-liquid replenishment just prior to eruption. The occurrence of chlorine-bearing mineral phases such as sodalite in both dense fragments and dense blocks and the lower Cl content characterizing the groundmass of these products, together with thermobarometric estimates confirm the pre-eruptive presence of batches of partially crystallized magma at shallow depth before the eruption. The simultaneous ejection of different types of juvenile material highlights the partial removal of the magma intruded at shallow level, followed by the withdrawal and consequent emission of magma from deeper and different portions of the deeper magma reservoir that fed the following Plinian phase. Preliminary data on elemental diffusion in phenocrysts rims suggest that magma intrusion at shallow level preceded the eruption of only a few tens of years. Thereby, our detailed volcanological study gives fundamental information to understand the processes favouring the initiation of the principal event and should be taken in account when considering the range expected precursors in case of unrest.

New insights into the recent magma dynamics under Campi Flegrei caldera (Italy) from petrological and geochemical evidence

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The Campi Flegrei caldera is considered the most dangerous volcano in Europe and is currently in a new phase of unrest (started in 2000 and still ongoing) that has persisted intermittently for several decades (main crisis occurred from 1950 to 1952, 1970–1972, and 1982–1984). Here, by combining the petrological and geochemical data collected in recent decades with numerical simulations, we place new constraints on the source(s) of the current dynamics of the volcano. In particular, we show that the measured (N_2-He-CO_2) geochemical changes at the fumaroles of Solfatara hydrothermal site are the result of massive (about 3 km^3) magma degassing in the deep portion (greater than/equal to 200 MPa, 8 km of depth) of the plumbing system. This degassing mechanism would be able to flood the overlying hydrothermal system with hot gas, thus heating and fracturing the upper crust inducing shallow seismicity and deformation. This implies that the deep magma transfer process (greater than/equal to 8 km) has been decoupled from the source of deformation and seismicity, localized in the first kilometers (0-4 km) of caldera-filling rocks. This information on magma transfer depth can have important implications for defining the best monitoring strategies and for forecasting a future eruption. Finally, this study highlights how petrological and geochemical data allow us to explore the dynamics of the deep portion of the plumbing system and thus trace the occurrence of recharge episodes, in a portion of the ductile lower crust where magma transfer occurs in the absence of earthquakes.

A data driven approach based on mineral chemistry unveils magma dynamics of long-lasting, low-intensity volcanic activity

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The most frequent volcanic eruptions worldwide are characterized by low intensity and magnitude. While in very proximal, often inaccessible areas, this activity may result in the emplacement of bombs and lapilli, medial and distal deposits mostly consist of ash-sized clasts. Due to their small dimensions (less than 2 mm), these cannot be easily employed to acquire specific geochemical data commonly used to gain insights into the plumbing system dynamics. Such lack of information hinders our capacity of using the entire eruptive record of volcanoes to understand magmatic processes. Yet, volcanoes erupting frequently can impact heavily communities located in their proximity, which requires alternative strategies to better outline their future behaviour. In this study, we chose the Palizzi Eruptive Unit (PEU) of La Fossa volcano (Vulcano Island, Italy) as a representative example of a long lasting eruptive sequence of ash-sized layers intercalated by the products of larger eruptions. We apply an unsupervised machine learning approach to gain information on the plumbing system dynamics and to elucidate the relationships between magmatic processes at depth and eruptive activity. We use hierarchical clustering (HC) to reduce the chemical complexity of core-to-rim clinopyroxene profiles, collected along the entire PEU stratigraphy, to sequence of clusters. HC shows that the composition of clinopyroxene is simplified by four clusters. The chemical differences between the clusters, their distributions in the different portions of the crystals and their mutual variations along the eruptive sequence, coupled with thermo-barometric constraints, allowed to recognize various cycles of mafic inputs during the PEU which reflect in different characteristics of the emplaced deposits. Our approach can be used to investigate eruptive sequences constituted essentially by ash beds, and it is widely applicable to provide a quantitative record of the relationship between the temporal evolution of the plumbing system and eruptive dynamics by linking the eruption stratigraphy and detailed crystal data. This perspective is essential to anticipate, both on short- and long-term, the dynamics and potentially the magnitude of impending volcanic eruptions at active volcanoes.

Physical constraints and magma dynamics of Mt. Etna rift systems

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Mt. Etna features an articulated plumbing system characterized by a central open-conduit, culminating with the persistent degassing summit craters, three rift-related lateral systems (S-Rift, NE Rift and W Rift) and the eccentric feeding system, characterized by disperse monogenetic cones.
In the last twenty years, most the eruptive activity occurred at the summit central craters and by consequence most of the recent petrological studies focused on the parametrization of the central open-conduit system. In this study, we move the focus to the NE Rift system, whose last activity dates back to the 2002-2003 eruption. Rift-related events are potentially more dangerous since they are often accompanied by energetic precursor seismicity and increase the probability of lava effusion at low altitude where towns and infrastructures are concentrated. Samples from this last eruption were examined and the new chemical data integrated with a comprehensive whole rock and mineral chemistry dataset from pre-historical and historical events.
Textural observations of the NE Rift products highlight a greater variability compared to magmas erupted from the central craters, in spite of a comparable mineral assemblage made of Ol, Cpx, Plg and Ti-Mt. High and low porphyritic lavas coexist in the same event and appear frequently mingled. Similarly, whole-rock composition varies from hawaiite-trachybasalt to benmoreite, in contrast with the rather homogenous trachybasaltic composition of magmas erupted from the central craters. Plagioclase phenocrysts show partially resorbed rims associated with an increase in An content or alternatively, alignments of melt inclusions near the crystal rim, related to a decrease in An content.
Thermo-barometric estimates based on Ol-Liq and Cpx-liq equilibria suggest that most of Ol and Cpx phenocrysts equilibrated at temperature comprised between 1140 to 1000 °C and pressure ranging from 10 to 2 Kbar, with a remarkably higher T/P path with respect to magmas erupted at the central craters. This suggests a magma crustal ponding zone between 4 and 2 kbar and a deep independent magmatic feed of the NE Rift. These results have been integrated by thermodynamic modelling through the energy-constrained model Magma Chamber Simulator able to compute the evolution of the magma via fractional crystallization in a polybaric and polythermal volcanic plumbing system. Results highlights that fractionation occur along the Ol-Cpx-Plag liquid line of descent in a range of pressure equivalent to those determined by the crystal-melt geobarometry.

Quantifying magma ascent velocity at basaltic volcanoes and its role on determining the explosivity of eruptions

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The role of magma ascent rate is fundamental in determining the explosivity of eruptions. Although the topic has been so far partly addressed at closed-system volcanoes producing large-scale eruptions, the issue is relevant even at open conduit volcanic systems, where low viscosity, basic magmas generally feed weak explosive and/or effusive activity. Quantitative relationships between ascent rate and eruption energy have not yet been properly assessed in these systems. In this study, three eruptions of different explosivity from the post-2011 Mt. Etna activity have been selected in order to quantitatively constrain the relationships between the observed explosive intensities and magma ascent rates. The chosen eruptive episodes are: 1) the paroxysmal episode of 19 February 2013 at the South East Crater (SEC); 2) the violent eruption of 3 December 2015 occurred at the Voragine Crater; 3) the flank eruption that affected the southeastern sector of the volcanic edifice on 24-27 December 2018. The volatile diffusion along olivine-hosted melt embayments has been used to constrain the kinetics of magma ascent. Through this technique we have measured the compositional gradients of volatile elements that are produced by diffusion from the inner part of the embayment toward the outer melt as a response of degassing-induced decompression during magma ascent. Results obtained by using this approach demonstrate how differences in the timescales of decompression-driven magma degassing are correlated with markedly distinct eruptive dynamics, even considering similar physical and chemical conditions of the magmas involved in the eruptions. The intense paroxysmal activity at Voragine Crater on 3 December 2015 was characterized by fast magma ascent (~0.36-0.74 MPa/s), slightly higher than for the less energetic paroxysmal eruption occurred at NSEC on 19 February 2013 (~0.14-0.29 MPa/s). Decompression rate calculated for the weak flank eruption of 24-27 December 2018 (~0.045-0.094 MPa/s) are one order of magnitude smaller than values obtained for episodes of lava fountaining. Our results indicate that the intensity of activity at Mt. Etna is strongly controlled by degassing kinetics, thus suggesting that the explosivity does not depend exclusively on the overpressurization of the shallowest reservoir due to injection of gas from the deepest levels of the plumbing system. This reflects how Mt. Etna is able to transfer magmas throughout the upper part of the plumbing system with different dynamics in a rather limited timespan, even when the same basic and volatile-rich magmas are involved.

S04 - Oral Presentation

Relating eruptive dynamics to mineral chemistry variability during the February-March 2021 sequence of lava fountains (South-East Crater, Mt. Etna)

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The South-East Crater (SEC) at Mt. Etna started a period of lava fountaining from December 13th, 2020, to February 21st, 2022, producing over 66 paroxysms. The activity went through an intense sequence from February 16th to April 1st, 2021, for a total of 17 paroxysmal events. The entire eruptive period was extensively monitored, providing a unique opportunity to relate the chemistry and texture of the erupted products to eruptive dynamics. We investigate the temporal evolution of the magmatic system from February to April 2021 by quantifying the variations of composition and texture of clinopyroxene throughout the eruptive sequence. Chemical zonation in minerals records processes occurring at inaccessible depths, providing an essential tool to identify and quantify magmatic processes preceding volcanic eruptions. The investigation of major element transects on clinopyroxene from five representative lava fountains over the entire sequence allows us to determine the relative proportions of deep-stored versus shallow-stored magmas which fed the paroxysmal activity. We use hierarchical clustering, an unsupervised machine learning technique, to quantify the temporal evolution of mineral populations and identify discrete pre-eruptive storage regions. For this purpose, we apply random forest thermobarometry to relate each compositional cluster to the pressure and temperature conditions in which it forms. Our results allow to establish quantitative relationships between mineral chemistry, textures, monitoring parameters and eruptive dynamics. This approach helps to better interpret the past activity of volcanic systems, which is key to anticipate their future behavior.

Novel insights into dynamics and timescales of volcanic processes from magma storage at deep crustal levels to eruption: the contribution of synchrotron X-ray diffraction, radiography and computed microtomography

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A series of in situ time-dependent high Pressure (HP) and high Temperature (HT) experiments were performed by using third-generation synchrotron radiation sources on basaltic volcanic rocks from active volcanoes in Italy.
In a first series of experiments the effect of pressure and temperature on the viscosity and the atomic melt structure of a synthetic anhydrous primitive alkaline basalt belonging to the Campi Flegrei Volcanic District (CFVD) was investigated to shed light on its mobility and ascent velocity from the source rock to the volcanic plumbing system at present day. The viscosity was measured in-situ at P of 0.7–7.0 GPa and superliquidus temperatures (T between 1335 °C and 2000 °C) using the falling sphere technique with the Paris-Edinburgh press combined with synchrotron X-ray radiography. Moreover, melt structure measurements of the alkaline basalt was conducted at nearly the same HP-HT conditions at which viscosity was measured, using in situ multi-angle energy dispersive X-ray diffraction. Measured viscosities of the alkali basaltic melt were scaled down to realist P-T regime underneath the CFVD along with its mobility and ascent velocity. Interestingly, when integrated with existing geochemical and petrological data, our results are consistent with those of the existing literature in locating the depth of the source rock to ~60-80 km.
A second series of in situ experiments was performed to study bubble growth, coalescence and permeability of an Etna basaltic magma at HP-HT under water saturated conditions. X-ray synchrotron radiography was combined with a unique Internally Heated Pressure Vessel (IHPV) to simulate magma storage and ascent within the crust at pressures below 100 MPa in presence of volatiles (H_2O). These experiments allowed us to capture and quantify bubble kinetics in basaltic magma at pre- and syn-eruptive conditions and are fundamental to improve our understanding of magma behaviour and mitigating the volcanic risk associated with basaltic systems.
Future studies will focus on performing in situ 4D synchrotron x-ray microtomographic experiments with our novel IHPV to investigate vesiculation and crystallisation at HP-HT for a range of natural mildly (basaltic) to highly (trachytic) explosive magmas with different volatile and crystal content at different cooling and decompression rates. 4D x-ray microtomography allows to accurately reconstruct the investigated samples at the micrometre scale and visualise and quantify their textural features in 3D with time.
All these in situ techniques represent invaluable tools to shed light on the physical and kinetic properties of magma, as well as on mechanisms and timescales of volcanic processes that were not investigated in previous studies based on conventional ex situ, quenched experiments and two-dimensional imaging techniques. The results of these investigations are

important to understand the behaviour of volcanoes and can be combined with other geosciences disciplines to forecast their future activity.

Constraining models of magma ascent with ground deformation data: an application to Etna eruptions

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Explosive eruptions can be hazardous phenomena, during which large amount of mass and energy can be transferred from a magma reservoir located in the Earth's crust to the atmospheric environment. Such transfer is affected by many factors. Past models of explosive volcanic eruptions have commonly assumed flows in undeformable cylindrical conduits, not taking account pressure-dependent deformation. More recent models indicate that marked fluctuations on extrusion rates result from strong feedback between magma pressure, dyke width, and flow rate.

Here we present CPIUD (Chamber PIU', plus in Italian, Dyke) [Costa et al., 2009], a steady-state isothermal numerical model for explosive eruption written in FORTRAN, that analyzes the coupled behaviour of magma chamber and a deformable conduit flow during the evolution of a sustained explosive eruption. In this model, the axes of the conduit vary with depth and the steady-state elastic deformation of the walls is evaluated by analytic solution that couples the cross-section area of the dyke with the magmatic overpressure. An important assumption of the model is the slow-varying pressure at the base of the conduit: this is justified by the longer time of the pressure variation in the dyke - order of hours - compared to the magma ascent time through the conduit which is of the order of minutes. Therefore, cross-section averaged variables can be used to describe magma flow in the conduit.

The model moreover considers melt and crystal compressibility, so the magma behaves as a compressible fluid. The chamber can be approximated assuming a spherical, elliptical, or cylindrical geometry, and the conduit can be described considering a pseudo-dyke assumption having an elliptical cross-section. Moreover, in the model are implemented different models of viscosity and multiple fragmentation criteria.

Here we present a new version of the code and a few application examples to recent Etna eruptions, well constrained from ground deformation observations (e.g., 2001 and 2002).

Our results show that volcanic conduit geometry has a strong control on the flow dynamics, and these can have feedback on the geometry itself. For these reasons, it is pivotal to integrate geophysical models and observations.

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S04 - Oral Presentation

The Marsili plumbing system and its magmatic evolution

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The Marsili seamount aligns NNW-SSE in the Southern Tyrrhenian sea and rises up to 3200 m from the seafloor (top at about 500 m b.s.l.). It mainly formed in the last 1 Ma on a ~ 10-12 km thick oceanic crust of the 2 Ma old oceanic Marsili back-arc basin. The lavas and tephras have composition ranging from basalts (IAB and OIB affinities [e.g., Trua et al., 2002]) to trachytes [Iezzi et al., 2014; Tamburrino et al., 2015]. Plagioclase is the main mineral phase followed by clinopyroxene and olivine.

Here, we use the equilibrium minerals-melt couples to retrieve thermobaric-, oxy- and hygrometric estimations. The equilibrium temperature T and pressure P were derived on clinopyroxenes chemical compositions and were used to constrain and calculate the H_2O content and oxygen fugacity (fO_2) in the pre-eruptive conditions. The T and P of crystallization of large clinopyroxenes are strongly related to the SiO_2 content of their respective bulk rocks. The estimated T decreases from about 1190 °C to 1000° C with increasing degree of evolution, i.e. moving from basaltic to trachytic systems. To the contrary, P of crystallization of clinopyroxene shows the opposite behaviour, being invariably lower than 400 MPa (depth 14 km) for basaltic rocks and high, up to 500 MPa (max depth is 17 km), in trachytic system. The intermediate rocks (SiO_2 between 54 and 59 wt%) display clinopyroxenes with crystallization at intermediate depth (7-14 km). The H_2O content is in the range 0-4 wt% and the fO2 is 0-3 log unit above FMQ buffer, irrespectively of the rock (lava or tephra) composition.

These estimated P-T conditions of crystallization of clinopyroxene and related depths suggest the occurrence of a complex plumbing system composed of vertically superimposed reservoirs at different depths up to about 17 km b.s.l. These reservoirs are filled with both SiO_2-poor and SiO_2-rich magmas, but the latter ones are located at higher depths. Furthermore, the retrieved P-T-H_2O-fO_2 conditions coupled with evolution of the bulk chemical systems confirm the predominance of fractional crystallization in Marsili magmas, and revealing, together with new Sr-Nd-Pb isotopic determinations, the occurrence of minor mixing events between OIB- and IAB-type source basaltic magmas.

This petrological reappraisal has been constrained with independent gravimetric and magnetic measurements and models; they indicate the presence of large SiO_2-rich reservoirs only at low crustal levels. By contrast, SiO_2-poor magma prevalently ascends and accumulates mainly at shallow crustal levels, just below the sea bottom. The recent (3-7 ka BP), deep and SiO_2-rich submarine eruptions reported in the Marsili central sector [Iezzi et al., 2014; Tamburrino et al., 2015] are probably linked to rapid remobilization from low crustal levels.

We emphasised that this petrological-geophysical approach may be applied to other back-arc volcanic complexes to shed light on their plumbing system. This unexpected situation suggest a general rethinking of the architecture of plumbing systems at spreading centres; the viscosity of SiO_2-rich magmas favours their stagnation at bottom, whereas hot and fluid basaltic magmas accumulate only a few km below the sea bottom or even erupt directly on it.

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Pre-eruptive magmatic processes leading to the 1650 CE explosive eruption at the Kolumbo submarine volcano, Greece

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Kolumbo is the largest of more than twenty submarine volcanic cones, aligned in the transtensional Anydros basin, one of the most seismically active zones in the South Aegean Volcanic Arc. Kolumbo explosively erupted in 1650 CE, causing the death of about 70 people on Santorini, which is 7km SW of the volcano. Explorative cruises employing ROVs discovered a high temperature (220°C) hydrothermal field with CO_2-rich discharges and accumulation of acidic water at the bottom of the crater (505m bsl), increasing the related hazard. A possible magma chamber was recognized below the crater by seismic data. It is fundamental to understand the behaviour of this volcano, and how its storage and plumbing system works, to correctly assess risk for nearby islands.

We present petrographic, geochemical and isotopic data of samples collected during the cruises and by divers, showing a high heterogeneity of both juvenile products from the 1650 CE eruption and fresh lithic clasts. Rhyolitic samples with mafic enclaves represent the juvenile products of the 1650 CE activity, characterizing different magmas interacting before the eruption. Rhyolites are compositionally homogeneous but show different structures: we distinguished White, Banded and Convoluted pumices and Dense juvenile samples. Plagioclase, biotite, orthopyroxene are the main mineral phases. Plagioclase, amphibole, clinopyroxene and olivine are found in the mafic enclaves, often characterized by the diktytaxitic texture. Minerals show a large compositional variability. Besides whole-rock geochemical and Sr-Nd-Pb isotope analyses, we conducted detailed petrographic, mineral chemistry and micro-analytical isotopic investigations on selected samples. Plagioclase chemistry shows distinct crystal populations in juvenile samples: a Low-An group (An15-25) for rhyolitic samples and a High-An group for the enclaves (An80-95). Some rhyolitic samples show also an intermediate An25-40 population, together with more orthopyroxene and higher-Mg# biotite than samples with only An15-25 plagioclases. The latter are instead richer in enclaves. Fresh lithic lavas were sampled; they can be subdivided in three groups with characteristic petrographic textures that are well reflected in their different chemical compositions. They can give information on the early history of the volcano and on how the rhyolitic magma could have been generated.

Our data suggest the presence of a complex storage system where the most evolved magma differentiated by assimilation and fractional crystallization, undergoing several inputs of mafic magmas. The early batches of new melts initially mixed with the resident ones, whereas the later arrivals only mingled with the rhyolitic magma, thus possibly representing the final trigger of the eruption.

Magma mingling and crystal recycling inside a shallow magma chamber during the last phase of magmatic activity at Nisyros volcano (Greece)

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Interactions between different magmas are common processes during the evolution of a volcanic system and reveal a complex dynamics in the plumbing system, in which refilling with mafic melt could also cause eruption trigger. One of the best evidences of magma interaction is the presence of mafic enclaves inside a more evolved host rock, testifying immiscibility conditions between different magmas coexistent in the same magma chamber.
Nisyros volcano shows many evidences of mingling/mixing processes during its volcanological evolution, and represents an excellent case study to explore the relationship between magmas and reconstruct the deep-to-shallow structure of the feeding plumbing system.
In particular, the two most recent eruptive events, the caldera-forming rhyolitic explosive eruption of the Upper Pumice and the successive effusive activity of the Post-Caldera Domes (PCD), emplaced a thick pyroclastic deposit and six rhyodacitic lava domes, respectively, both rich in mafic crystal-rich clasts or enclaves. However, these two eruptions show many differences in the abundances, petrographic characteristics, mineral chemistry and geochemical and isotopic signature of their enclaves, as well as in the intensity of the mingling process, testifying that the magma interaction conditions were different, possibly linked to a changing in the magma chamber dynamics and/or in the deeper feeding system structure.
Lava domes are highly porphyritic (up to 30 vol.%) with criptocrystalline to glassy groundmasses, whereas pumices are less porphyritic with at least 5 vol.% and glassy groundmass. Plagioclase is always the most abundant phenocryst. Magmatic enclaves of the PCD have hypocrystalline, diktytaxitic textures, with low porphyritic index (~5 vol.%) and a paragenesis dominated by acicular plagioclase and amphiboles. The crystal-rich clasts of the UP show, on the contrary, a strong heterogeneity in textures with a more variable paragenesis dominated by plagioclase with minor ortho- and clinopyroxene or amphiboles. Previous micro-Sr isotope studies have demonstrated that the PCD rhyodacites are linked to the previous more evolved UP rhyolites being hybrid magmas between the latter and new mafic melts [Braschi et al., 2012, 2014].
We have investigated in detail the textural characteristics and mineral chemistry of the products erupted by these two different activities in order to possibly unravel the variation of physico-chemical condition of the magma chamber and the refilling mafic system.
Our results have revealed the occurrence of strong mineral disequilibrium conditions due to extensive crystal transfers from the host to the enclave magmas (mainly macro-phenocrysts of plagioclase) and vice versa (through disaggregation of the enclave groundmasses releasing microlites of pyroxene, olivine, amphibole and plagioclase) generating micro-scale mingling, that increase from the UP to the PCD and from the oldest to the youngest domes. Moreover, the enclaves itself show many evidences of sub-enclaves and mafic aggregates indicating multiple mafic inputs and a possible deeper storage level in which early magma interaction processes may be occurred.
In general, the femic phases show compositions clearly out of the equilibrium conditions,

especially among the dome lavas, whereas plagioclase crystals show a bimodal composition, that well reflect their crystal size and textures. The application of geothermobarometers to pyroxene and amphiboles allows supposing a slight decrease in pressure conditions with time from the UP to the PCD and within the PCD activity, possibly caused by the rise up of the post-caldera magma chamber and the interaction level between the two magmas during the emplacement of post-caldera domes.

In this case-study the careful combination of a detailed mineral chemistry study, leading to define the equilibrium/disequilibrium conditions, and the application of geothermobarometer allow to reconstruct a complex process of magma interaction.

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Spatio-temporal reconstruction of the magma plumbing system of Fogo volcano, Cape Verde archipelago

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We use novel microthermometry fluid inclusions results, coupled with petrological information, to reconstruct the evolution of the trans-crustal magma plumbing system of Fogo volcano (Cape Verde archipelago). Fogo, likewise similar intra-plate volcanic islands, is characterised by a complex, vertically elongated magma plumbing system, consisting of different storage levels filled by small magma pockets separated by non-eruptive crystal-mushes. The depth of these storage zones, and their vertical arrangement, is not entirely understood. Our results, derived from analysis of pure CO_2 fluid inclusions hosted in olivine and clinopyroxene phenocrysts from both lavas and tephra, indicate the Fogo plumbing system has undergone important changes over the last 120 ky of volcanic activity. We show that, before the Mt. Amarelo collapse event (dated at 62-123 ka), fluid inclusions record magma storage zone at circa 19 ±0.9 km (557-595 MPa), and a shallower temporary ponding level at circa 17 ±0.7 km (497-529 MPa). Fluid inclusions in lavas of the early post-collapse stage (60 ka) testify for a downward shift of the magma plumbing system to a maximum depth of 23.7 ±0.9 km (700-740 MPa). Since the Holocene, fluid inclusions record pre-eruptive magma storage at 13-21 km (384-640 MPa), and a shallower area of magma stagnation between 9.4-12.5 km depth (248-380 MPa). In these shallow levels, more evolved phono-tephritic melts may form, as the lavas erupted during the more recent eruptive events (e.g., in 2014-15). We identify a possible upward shift of pre-eruptive magma storage conditions starting in 1951, as supported by the presence of low density inclusions and by the more evolved chemistry of post-1951 lavas. Our new findings will be integrated with on-going studies of pre-eruptive volatile contents in melt inclusions in order to model magmatic degassing and constrain magma ascent rates prior and during volcanic eruptions at Fogo volcano.

S04 - Oral Presentation

Modulation of a plumbing system by ice cover fluctuations. The Pleiades volcanic complex, Antarctica

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The timing of volcanic eruptions in glaciated terrains is potentially modulated by climate-controlled variations in the glacio-lithostatic load, that modify the pressure conditions acting on underlying volcanic plumbing systems. Thus, during the glacial periods, the magmas experience a prolonged residence time in the crust, which allow them to crystallise, differentiate and accumulate volatiles over a longer time span with respect to the non-glacial periods.
In Antarctica, the volcanic activity is occurring in glaciated regions since the Miocene. In northern Victoria Land, the volcanism occurred in both attenuated and thick cratonic lithosphere, during a Cenozoic rifting process. In detail, among the inland volcanic edifices built on thick crust, the Quaternary Pleiades volcanic complex (PVC) is made up of some 20 monogenetic, partly overlapping scoria and spatter cones, that erupted over the last 900 ka. The erupted products, cropping out from the ice close to the head of Mariner Glacier, vary in composition from hawaiite to trachyte, defining a complete mildly Na-alkaline differentiation trend. Mafic samples have OIB within-plate affinity and variable radiogenic isotopic ratios, supporting the hypothesis of open-system evolution with significant crustal assimilation coupled with fractional crystallization. The occurrence of a complete differentiation trend with large assimilation rate is unusual among alkaline monogenetic volcanic fields.
Samples from PVC, representative of the whole differentiation trend, have been investigated by means of electron microscopy, electron microprobe and laser ablation ICP-MS. The paragenesis of mafic-intermediate rocks includes dominant clinopyroxene and plagioclase along with minor olivine, while sanidine is the only feldspar in trachytes. Olivine and clinopyroxene commonly show glass inclusions with composition significantly more evolved (phonolitic-trachytic) with respect to their corresponding bulk rock composition. The olivine phenocrysts do not present significant compositional variation from core to rim, however they are characterised by significant resorption textures with deep embayments. Conversely, both clinopyroxene and plagioclase phenocrysts show complex textures characterized by coarse to fine sieve texture cores and compositionally zoned mantle and rims, often with a patchy and convoluted pattern.
These observations suggest that the magma firstly experienced a rapid decompression, followed by a prolonged residence time likely due to high ice load. During this time interval, resorption of early formed mineral phases occurred, probably enhanced by crustal assimilation processes, coupled with re-crystallization under isobaric conditions. This extended residence time allowed both the formation of the products representing the observed complete differentiation trend and the development of the complex microtextures of clinopyroxene and plagioclase. Finally, a late supply of magma led to the formation of reverse zoning and of further recrystallisation and resorption features. Machine-learning-based thermobarometric estimates consistently suggest crystallization of clinopyroxene and plagioclase at a pressure ranging from the crust-mantle interface (early crystallization) to shallow crust (late crystallization in a shallow plumbing system under glacial load). This petrological evidence

leads to hypothesize a pre-eruptive mixing process between a freshly injected mafic magma and a magma which resided for a significant time in the crust, probably due to the eruption lag associated to increased ice load.

Mafic recharge dynamics in Middle Triassic feeding systems of Dolomites (Southern Alps): comparison with active volcanoes

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The study of compositionally zoned crystals is a key approach for unraveling the geometry and dynamics of the feeding systems beneath active volcanoes with an important effect on the monitoring of volcanic risks. This kind of study in ancient volcano-plutonic complexes has the advantage of having the feeding system as an outcrop allowing a comparison between the model and the field evidence. In this respect, we present a detailed textural and compositional study on the zoning pattern identified in the clinopyroxene population of volcanic rocks in different Middle Triassic provinces of the Dolomites (Southern Alps) such as Predazzo, Mt. Monzoni, Cima Pape, and Sciliar. The zoning pattern is expressed by one or more high-Mg# and Cr_2O_3-rich diopsidic bands (Mg# 79-91; Cr_2O_3 up to 1.2 wt%) growing in between augitic cores and rims with lower Mg# and Cr contents (Mg# 67-77; Cr2O30.1 wt%). The diopsidic composition is also documented in some cores that appear resorbed and coated with augitic rims. Chondrite-normalized incompatible trace element patterns of the low-Mg# portions show Nb, Ta, Sr, Zr, and Ti negative and Th-U positive anomalies. The high-Mg# domains have similar patterns but lower trace element abundances. REE patterns in both high-Mg# and low-Mg# domains have a convex-upward shape and La/YbN from 1.3 to 2.1. Thermobarometric and hygrometric models made on Cima Pape crystals describe a periodic replenishment of a mush-like system composed of cold, H_2O-rich trachyandesitic magma (Mg#=43-45; T=1035-1075°C; H_2O=2.6-3.8 wt%), ponding at 7 to 14 km with more primitive H_2O-poor basaltic magma (Mg#=65-70; T=1130-1150°C; H_2O=2.1-2.6 wt%) accountable for the formation of diopsidic zones in the previously formed augitic crystals in the shallower trachyandesitic batch [Nardini et al., 2022]. Moreover, the presence of diopsidic resorbed cores could suggest mild remobilization of these antecrysts by the arrival of the new mafic input. The occurrence of these compositional zoning patterns through different volcanic centers in the Dolomites could suggest that mixing in the feeding system before the eruption was a common process among the main eruptive provinces of the Mid-Triassic magmatism. The availability of compositionally zoned crystals in these rocks opens the possibility to study the Dolomitic centers like active volcanoes using techniques never applied before in the Dolomites. Furthermore, the presence of outcrops of the magmatic chambers, as intrusive rocks, could be helpful to check the models in the field and compare them with those suggested on active volcanoes with crystals having similar zoning models (e.g., Stromboli). In summary, this new instrument on the Middle Triassic event in the Southern Alps can reveal new information that remained undiscovered for years and offers the chance to compare ancient volcanoes with active ones, like Stromboli and Etna.

S04 - Oral Presentation

Characterization of final eruptive stages on Filicudi Island (Aeolian Islands): the “Montagnola” Dome

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This study is focused on the geochemical characterization and petrologic investigations on the products emitted by the “Montagnola” dome, on the island of Filicudi (Aeolian Islands), active about 64 ka after a relatively long period of quiescence. Particular attention will be given to the eventual occurrence of a shallow magma reservoir and the processes of differentiation acting prior to the eruption, and on all dynamics leading to the generation of such unusual, until that time, eruptive style.

Starting from a detailed volcano-stratigraphic study accompanied by a new sampling of 15 rock samples. The volcanic succession is mainly made up by a pyroclastic basal sequence, mainly related to the opening phases of the system, and the carapace of the dome. Petrographic investigations have been performed by means of polarized microscope, whereas mineral compositions have been acquired through EMPA. Results has shown that An50-90 plagioclase is the most abundant mineral phase (50-60 vol%) followed by clinopyroxene (20 vol %) and orthopyroxene (10 vol %) while Amphibole (5 vol %) and Biotite (5 vol %) are observed only in dome samples. Whole rock investigations were performed by means of X-Ray Fluorescence. Result show compositions from trachyandesite toward dacites.

Geobarometric studies and modelling of crystal fractionation from the last previously-emitted sample at Filicudi, showed that magmas of Montagnola dome formed due to crystal fractionation of a previously intruded trachybasaltic magma within a reservoir ponding at a pressure of 420 MPa. Further study will be devoted to the identification of the mechanisms of trigger of the eruption and on the observed eruptive styles.

S04 - Poster

Exploring microstructure and physical properties of rocks from the Campi Flegrei caldera: a 3D/4D multiscale characterization

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The Campi Flegrei caldera is in an unrest phase since the 2005, manifested by increasing ground uplift, seismicity and hydrothermal activity. The seismicity mainly involves the first 3 km below the hydrothermal site of Solfatara-Pisciarelli, where an intensifying heating and pressurization is inferred by gas geothermobarometers. Moreover, studies based on geodetic data inversion generally localize the deformation source in this sector of the caldera. Different driving mechanisms have been proposed to explain the ongoing unrest, which can be summarized in two end-members: magmatic and non-magmatic unrest. In this frame, investigating the physical properties of subsurface rocks that host hydrothermal-volcanic systems can be valuable. In fact, they can largely affect local stress and strength, controlling seismic distribution, phreatic eruption triggering, as well as sill or dyke dynamics and emplacements.
Recent technological advances allow to characterize rocks in 3D and non-destructively in the digital rock physics framework. Rock samples are scanned by X-ray microtomography (micro-CT) to obtain digital rocks, then used to quantify microstructural parameters and estimate physical properties through numerical simulations. 3D imaging can be also calibrated using in-situ experiments (e.g., HT-HP mechanical tests) to better characterize the mechanical properties of rocks in 4D.
In this study we focus on the subsurface rocks of the Campi Flegrei caldera, examining cores extracted from 3-km-deep exploratory geothermal wells. The cores were collected according to the most representative stratigraphic levels and are dominated by tuffs alternating with minor lavas. Their mineralogical assemblage reflects different depth-dependent T-P conditions ranging from argillic alteration (150°C) to thermometamorphism (350°C). We explored methods to optimize the 3D/4D characterization of these challenging rocks. Particularly, a 3D multiscale imaging of rock cores was performed using micro-CT. We also employed high-resolution scans to enhance the quality of low-resolution scans of larger sample volumes through deep learning-based super-resolution approaches. Mostly, we set up a device to perform in-situ mechanical experiments and time-resolved (4D) imaging, able to provide compressive/tensile mechanical parameters and link rock behavior with microstructural changes. Preliminary data on microstructural parameters and on flow and mechanical properties of subsurface rocks from the Campi Fregrei caldera will be shown. The results will be used to better constrain recent seismic tomographies and earthquake distribution in this area, as well as to discuss their implication on the dynamics of magma batches potentially stored or ascending up to shallow levels.

Overlook into the Stromboli plumbing system: defining the spatial and temporal conditions of magma storage and transfer as prelude of paroxysmal eruptions

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Stromboli volcano is the site of persistent, low-to-mid explosive activity and a paradigm of open-conduit system volcano worldwide. Within this framework, the ordinary activity is sometimes interrupted by energetic manifestations that are known in literature as major explosions and paroxysm depending on the increasing intensity of the eruption. Numerous models have been proposed to explain the triggering mechanisms of paroxysmal eruptions at Stromboli, some of them focusing on the prominent role of bottom-up replenishment processes by magma and/or gas [Bertagnini et al., 2003; Métrich et al., 2010; Allard, 2010], others attributing a crucial role to dynamics affecting the shallow plumbing system and the uppermost portions of the conduits [Calvari et al., 2011; Ripepe et al., 2017; Viccaro et al., 2021]. Other recent studies have shown that the main factors for shifting the ordinary activity towards more energetic events are the ascent velocity of the LP magma, the minimum position level of the LP magma and the length of the LP magma column [Pichavant et al., 2022]. However, the peculiar eruptive behavior of Stromboli still makes difficult the understanding of mechanisms governing temporal variations between ordinary activity and violent explosions, both major explosions and paroxysms.
Aim of this work is to reconstruct the magma dynamics acting within the plumbing system and its correlation with the triggering of paroxysmal events. Therefore, we have acquired textural and petrological data on products erupted during the paroxysmal eruptions occurred at Stromboli volcano on 1930, 2003, 2007, July 3 and August 28 2019. On the same products we have hand-picked about 200 olivine crystals belonging to either LP or HP magmas, investigating their textural and chemical zoning in order to reconstruct the magma storage and transfer dynamics throughout the plumbing system prior to the paroxysm. The data are used to better constrain the magmatic plumbing system of Stromboli and highlight its variations over time from 1930 to present in terms of storage dynamics and timescales of magma ascent. Preliminary results show that core-to-rim compositional profiles on olivine crystals have almost constant forsterite contents in most cases or minor reverse zoning with Δ Fo ~2. On the basis of the plateaus identified at the core of olivine crystals, we have recognized six main populations representative of distinct chemical and physical conditions of crystallization throughout the plumbing system; they are namely: Fo_{71-74}, Fo_{75-78}, Fo_{79-82}, Fo_{83-86}, Fo_{87-91}. Thermodynamic simulations by Rhyolite-MELTS allowed to constrain the X-P-T-fO_2 conditions of formation of the analyzed crystals, which are the primary step for defining the kinetics of transfer among the different magmatic environments identified.
Our data have been elaborated either with standard models based on the Fe-Mg intra-crystalline diffusion, and advanced models using fast-diffusion volatile species in melt inclusions and embayments. The obtained dataset, which is also integrated with data resulting from gas monitoring and ground deformations, contribute to fix an updated working model for the Stromboli and should help for the identification of potential new precursory signals anticipating the most energetic manifestations at the volcano.

Olivine clinopyroxenite xenolith in the 2002-2003 lavas of Mount Etna

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The occurrence of olivine clinopyroxenite nodule in 2002-03 trachybasalt lavas from the NE fissure Mount Etna is here reported for the first time. The xenolith is formed by aggregates of large (millimetric) cumulus diopsidic, mildly forsteritic olivine, calcic plagioclase, Ti–magnetite, apatite, rhönite and glass inclusions, in order of decreasing abundance. Subidiomorphic olivine crystals can be considered as primocrysts. Microprobe analyses indicate moderate chemical zoning of the phases. This nodule indicates a crystallization stage of the Etnean magmas dominated by clinopyroxene and olivine, where plagioclase is still not a liquidus phase, not very different from that observed in relatively primitive magmas as those erupted in northern Etna, and the equilibration temperatures and pressures of the phases will provide very useful information about the depth of equilibration of the xenolith in the crust.
Intrusive xenoliths on Mt. Etna are quite uncommon [Lo Giudice and Rittmann 1975; Aurisicchio and Scribano 1987; Andronico et al. 2005; Corsaro et al. 2007] and they are usually found within lavas or pyroclasts emitted during the previously defined "eccentric" [Rittmann 1965] and more recently named "deep dyke-fed" eruptions [DDF, Corsaro et al. 2009 and references therein]. Ultramafic xenoliths were previously reported only in products from the Ancient Alkalic Lavas, [Aurisicchio and Scribano 1987] with a presumed cumulitic origin (dunites and wehrlites). Cognate xenoliths hosted in lavas of the 1763 ("La Montagnola"), 2001 and 2002-03 (South Fissure) eruptions have been recently investigated by Corsaro et al. (2014) and are gabbros with amphibole and either olivine or plagioclase. On the basis of textural, mineralogical and physical evidences, these authors ruled out a mantle origin.
The occurrence of rhönite is rare in the Etnean lavas [D'Orazio, 1994; Clocchiatti et al., 2004; Corsaro et al., 2006; Lopez et al., 2006] and is associated with amphibole. Amphibole is however absent in the xenolith.

Real crystal-chemical variations of spinel, plagioclase and pyroxene solidified at variable cooling rates in a tholeiitic basaltic system using EPMA maps

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The crystal-chemical variations of spinel, plagioclase and pyroxene phases have been redetermined by X-ray electron-microprobe (EPMA) maps to quantify the actual role of cooling rate [Iezzi et al., 2014; Giuliani et al., 2022]. They were experimentally crystallized from a basaltic liquid (MORB from Iceland) at cooling rate of 1, 7, 60 and 180 °C/h from 1300 to 800 °C, atmospheric pressure and air oxygen fugacity (fO_2) [Vetere et al., 2015]. Experimental products are made of pyroxenes, spinels and plagioclases crystals ± glass. As the cooling rate increases, the run-products became progressively richer in glass and pyroxenes, poorer in plagioclases, and the size of crystals decreases [Giuliani et al., 2020]. Systematic analytical approach [Iezzi et al., 2014] allow us to retrieve a detailed dataset (thousands of single point analyses per run-product) that further and strongly constrain previous outcomes [Giuliani et al., 2022].

As the cooling rate increases from 1 to 180 °C/h, spinel is progressively enriched in Al_2O_3 and, to a minor extent, MgO, and depleted in TiO_2 and FeO_{tot}. In pyroxenes, FeO_{tot} and Al_2O_3 increase, and MgO slight decreases as the cooling rate increases from 1 to 180 °C/h. CaO and MgO in pyroxene are distributed in 2 main clusters in the product solidified at 1 °C/h, and in a less prominent way at 7° C/h, revealing the occurrence both of cpx and opx at the lower cooling rate Plagioclases chemistry, instead, do not show straightforward paths with the cooling rate. The calculated cations in a.p.f.u. (atoms per formula unit) on measured oxides variations unveils several sharp relationships with cooling rate. As cooling rate increases: i) Al + Fe^{3+} increases while Ti and Mg + Fe^{2+} decrease in spinel, ii) Mg decreases whereas Fe^{2+} and Al increase in pyroxene and iii) Si, Fe3+, Mg and K increase whereas Al decreases in plagioclase. Importantly, several cations are linearly correlated with cooling rate, showing good statistics ($R^2 > 0.6$) and, thus, functional as geo-speedometers for basaltic rocks. This is mainly evident for Ti in spinel ($R^2 = 0.94$), K for plagioclase ($R^2 = 0.94$) and Mg and M1Al+Fe^{2+} for pyroxene (R^2= 0.83 and 0.98, respectively).

The observed distribution of cations and oxides confirm that the chemical variations of pyroxene, spinel and plagioclase solidified from basaltic melt are strongly related to the solidification condition. In particular, spinel sensu strictu seem to be favoured at higher cooling rate, with the Usp% decreasing as the cooling rate increases. At low rate of cooling, it is possible that orthopyroxene forms in coexistence with Ca-poor clinopyroxenes. An-rich plagioclases predominate at the lower cooling rate; this is mainly due to late segregation of plagioclase after spinel and pyroxene causing an increase of Al in the residual melt.

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A journey into the Monte Amiata mafic enclaves world: from fieldwork observations to chemistry

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Monte Amiata is a small Pleistocenic volcano emplaced in a short period of time between 305 ka and 231 ka [Laurenzi et al., 2015] and located in southern Tuscany at about 40 km NW of Vulsini volcanoes and ca. 12 km West of the Radicofani neck, where the Tuscan and the Roman magmatic provinces overlap. Its rocks range in composition from trachydacites to olivine-latites, and are grouped into three main complexes, corresponding to the three different phases of the volcanic activity: the “Basal Trachydacitic Complex”; the “Dome and Lava flow Complex”; the “Olivine Latite final lavas” [Conticelli et al., 2015; Marroni et al., 2015].
One of the most important petrographic features of Monte Amiata volcanic rocks is represented by the presence of rounded to sub-rounded fine-grained mafic enclaves, mainly found in the “Dome and Lava flow Complex” and characterised by cuspidate margins convex toward the host. Such mafic enclaves constitute proof of the mixing/mingling process that took place at Monte Amiata and possibly triggered the eruption of these highly viscous magmas.
Here, we present the results of our study about the origin, the evolution, and the distribution of the magmatic enclaves hosted by Monte Amiata lavas and domes. This is based on fieldwork observations, petrographic investigations and chemical analyses on whole rocks and minerals (sanidine, orthopyroxene, clinopyroxene, plagioclase, olivine, biotite, phlogopite, and oxides) of the mafic enclaves. Fieldwork observations, supported by image analysis, showed a variation of the outcropping percentage abundance and size variations of the magmatic enclaves within the different domes of Monte Amiata. In particular, the estimated abundance of the mafic enclaves varies between ca. 4.4% for Poggio Trauzzolo and Poggio Lombardo domes and ca. 1% in the case of the Poggio Pinzi dome. This suggests a variable degree of interaction between the magmas involved in the mingling process and, in some cases, it remarks the occurrence of the mechanical fractionation. Moreover, it was possible to verify that Poggio Pinzi dome, commonly considered the oldest dome, is characterized by the lowest outcropping abundance of mafic enclaves.
In addition, three main groups of mafic enclaves have been identified, whose distribution within the different domes seems to be influenced by the chemical composition of both the host domes and the mafic enclaves. Mineral phases of the enclaves often show resorbed and disequilibrium textures, pointing out complex processes of crystal recycle and exchange between the enclave and host magmas.

S04 - Poster

Modes and kinetics of magma storage and ascent across the Eastern and Northern Volcanic Zones of Iceland: the role of regional tectonics on the volcanic system dynamics

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In this study, we have defined and compared dynamics of magma storage and transfer throughout various reservoirs that have been detected along two main volcano-tectonic segments of Iceland, i.e. the Eastern Volcanic Zone (EVZ) and the Northern Volcanic Zone (NVZ). Lava and tephra samples from different volcanic systems, including the Laki, Ejafjallajokull, Holouraun, Eldfell on the EVZ and the Krafla, Ludentshaedir, Svenanja, Myvatn in the NVZ, have been collected and inspected under optical and electronic microscope for in-depth petrologic characterization. In particular, we focused on the textural and chemical variability of olivine crystals to detect the main storage zones and their preferential routes of connections within the Icelandic crust. Coexisting olivine populations that cluster in narrow compositional ranges have been used to identify common deep-seated magmatic reservoirs in which crystals initially nucleated and grew. Then, the chemical information provided by the olivine populations has been integrated with literature data relative to the hypocentre migration to allocate the detected reservoirs in the crust and define their spatial relationships. A more detailed pre-eruptive picture of magma movements has been finally obtained as the Fe-Mg zoning in olivine crystals was evaluated considering its time-dependent diffusive relaxation. By modelling the Fe-Mg diffusion in reverse and normal zoning profiles, we have calculated the timescales of crystal intrusion, storage, and remobilization at distinct crustal depths, with the aim of providing a thorough space-time reconstruction of the magma ascent history along the NVZ and the EVZ.

Our observations on storage zones and olivine zoning profiles indicate the presence of plumbing systems that are more articulated along the NVZ than in the EVZ, where olivine crystals may experience up to three storage events between nucleation and eruption, at depths of about 5-15 km b.s.l. Moreover, the comparison of temporal data for the two volcanic zones suggests overall longer (up to 427 days) timescales of magma storage across the NVZ sector compared to the time estimates across the EVZ (35 days on average). This study highlights how magmas emitted at volcanic systems of the two main volcanic zones of Iceland may undergo divergent, yet fairly complex processes during their transport in the crust, chiefly due to the presence of multilevel plumbing systems, on which regional tectonics appear to have little or no control.

S04 - Poster

Determining the depths and timescales of pre-eruptive processes before historical Monte Nuovo eruption (Campi Flegrei caldera, Italy)

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Campi Flegrei is one of the most populated caldera volcanoes on Earth and a detailed understanding of its sub-volcanic magma system and pre-eruption processes are essential for effective hazard mitigation. Of particular interest are the depths and timescales of magma storage, as this information can inform the interpretation of volcano monitoring data that is critical to civil protection. This study places new constraints on these important aspects of the Campi Flegrei magmatic system through detailed petrological analysis of clinopyroxene crystals produced in the most recent, AD 1538 Monte Nuovo eruption, which was preceded by important precursory activity at the Earth's surface, recorded in historical chronicles.
Through backscattered electron imaging (BSE) of >200 erupted crystals, we identified four texturally distinct clinopyroxene populations in Monte Nuovo eruption deposits, characterized by different zoning patterns. A small number of crystals preserve a thin evolved rim zone. Using BSE images as a guide, we characterised the full compositional diversity of these clinopyroxenes by electron microprobe analysis (EPMA). This data was input into the Python tool Thermobar [1] to find equilibrium matches with published Monte Nuovo whole-rock and glass data, and to determine clinopyroxene crystallisation pressures and temperatures using a geothermobarometer calibrated for alkali systems [2].
The compositional zoning preserved in the Monte Nuovo clinopyroxenes is consistent with an open magmatic system where mafic and felsic magma periodically mix. Our barometric modelling suggests that all the erupted clinopyroxene crystals formed at temperatures and pressures averaging at ~1000°C and ~2.5 kbar. These pressures equate to a magma storage depth of ~10 km, in agreement with a deep melt zone identified under Campi Flegrei by seismic tomography [3]. The crystals do not display evidence of crystallisation at shallow depths, suggesting that the erupted magmas did not undergo prolonged storage at the depth of recent bradyseismic activity. Hence, our data agree with previous studies [4] which have suggested that recent Campi Flegrei eruptions are fed by magmas ascending directly from the mid–lower crust and undergo minimal interaction with magmas that have stalled at shallow depths.
After constraining the structure of the Monte Nuovo magma system, we extracted compositional profiles across the outermost zones of clinopyroxene crystals; these rim zones are interpreted as recording the transfer of crystals from one magmatic environment to another, in the final stages of magma system development shortly before eruption. We used Fe-Mg diffusion modelling to constrain the timing of these pre-eruptive processes, giving robust temporal constraints which can inform the interpretation of current monitoring data at Campi Flegrei and provide important information for future eruptive scenarios.

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S05 - EQUILIBRIUM/DISEQUILIBRIUM PROCESSES DURING MAGMA ASCENT: NEW INSIGHTS FROM LABORATORY AND MODELLING STUDIES AND OBSERVATIONS OF THE NATURAL SYSTEM

Conveners:
Giuseppe La Spina, Paola Stabile, Michael R. Carroll, Margherita Polacci

The complex rheology of bubble-bearing magmas

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Volcanic activity consists of a wide range of eruptive styles, controlled to a great extent by the gas phase within magmas. The comprehension of the rheological behaviour of these mixtures of melt, crystals and bubbles is primary to understand the migration of magma within the volcanic systems. To date, scientific community focused mostly its attention to the investigation of the rheological behaviour of crystal-bearing magmas. The paucity of studies on bubble-bearing magmas is partly due to the greater challenges posed by the experimental procedure, mostly related to the outgassing of the gas phase during the experiments. So, a model for the comprehension of the rheology of the bubble-bearing magmas appears far from being available. The aim of this work is to understand the complex dependence of the viscosity on vesicles, temperature and strain rates, by performing suites of in situ degassing experiments on a rhyolitic magma at an experimental temperature of 850 °C, followed by uniaxial deformational experiments (constant strain rates of 5 x 10^{-5}, 10^{-4} and 10^{-3} s^{-1} through the Volcanology Deformation Rig at experimental temperatures varying from 720 to 800 °C.
Results show a complex pattern consisting in an initial increase of relative viscosity for low amounts of vesicles (0-20%), followed above the 20% threshold porosity, and for a constant strain rate, by a general decrease of viscosity.
A dependence of viscosity by strain rate, for constant porosity is also observed with viscosity decreasing as the strain rate increases, replicating therefore a non Newtonian - shear thinning behaviour.

Quantifying the Influence of Cooling Rate and Shear Rate on the Disequilibrium Rheology of a Basaltic Melt from Mt. Etna (Italy)

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Magmas often experience severe disequilibrium conditions during their migration through the Earth's crust and the subsequent emplacement on its surface. During their transport, magmas are subjected to a wide range of cooling and deformation rates, generating physico-chemical perturbations in the magmatic system able to inhibit or promote crystallization processes. Quantifying the magnitude and timescale of kinetic effects is essential to correctly constrain the rheological evolution of magmas and their ability to flow. Here we present a suite of cooling deformation experiments (CDE) conducted on a basalt from Mt. Etna (Sicily, Italy) to disentangle and model the concurrent effects of cooling rates (from 1 to 10 °C/min) and shear rates (from 1 to 10 s^{-1}) on the rheology of the system. The analysis of the temporal evolution of viscosity indicates that both cooling and shear rate strongly affect the onset of crystallization and achievement of a rheological cut-off over time, which represents the steep viscosity increase responsible for inhibiting magma flow. Both these rheological thresholds occur at lower temperature and earlier in time with increasing the cooling rate applied, as well as at higher temperature and earlier in time with increasing the shear rates. To reproduce the observed effects of crystallization on the apparent viscosity, we adopt a stretched exponential function that identifies two main crystallization regimes: i) a first shear-induced crystallization regime, characterized by a gentle viscosity increase and ii) a second cooling-dominated regime, marked by a steeper viscosity increase. The relative extent of these crystallization regimes strictly depends on the interplay between cooling rate and shear rate on the crystallization kinetics and suggest a first order control of the cooling rate and a subordinate role of the shear rate.

S05 - Oral Presentation

A comprehensive database of crystal-bearing magmas for the calibration of a rheological model

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In this work, we present a comprehensive rheological database including most of the existing data relevant for crystal-bearing magmas collected from the scientific literature, covering the entire range of natural volcanic conditions, in terms of crystal content (1–80%), crystal shape (aspect ratio R from 1 to 13), and strain rate (between 10^{-7} and 10^{2} s^{-1}). Datasets were collected and discerned as a function of the information which we considered necessary for building a general systematic model describing relative viscosity of crystal-bearing magmas, such as the apparent and melt viscosity, the crystal concentration, crystal shape, and the strain rate. The selected dataset was then used for modelling the relative viscosity of a liquid-solid mixture having different concentrations of particles with different R, subjected to different strain rates. The proposed model allows us to quantitatively describe the rheological behaviour of crystal-bearing magmatic systems.

S05 - Oral Presentation

In situ 4D dendritic crystallization in hydrous basaltic magmas: implications for magma mobility within the Earth's crust

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The majority of basaltic magmas stall in the Earth's crust as a result of the rheological evolution caused by crystallization during transport. However, the relationships between crystallinity, rheology and eruptibility remain uncertain because it is difficult to observe dynamic magma crystallization in real time. Here, we present in-situ 4D data for crystal growth kinetics and the textural evolution of pyroxene during crystallization of trachybasaltic magmas in high-temperature experiments under water-saturated conditions at crustal pressures. We observe dendritic growth of pyroxene on initially euhedral cores, and a surprisingly rapid increase in crystal fraction and aspect ratio at undercooling ≥30 °C. Rapid dendritic crystallization favours a rheological transition from Newtonian to non-Newtonian behaviour within minutes. We use a numerical model to quantify the impact of rapid dendritic crystallization on basaltic dike propagation, and demonstrate its dramatic effect on magma mobility and eruptibility. Our results provide insights into the processes that control whether intrusions lead to eruption or not.

S05 - Oral Presentation

Assessing the role of equilibrium thermodynamics in magma evolution by molecular dynamics and phase diagram calculations

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In recent years, atomistic and advanced computational methods applied to magmatological problems have demonstrated their unique ability to provide chemico-physical constraints to the complex evolution of magmatic systems by the calculation of multicomponent phase diagrams of petrological interest [Belmonte et al., 2017; Ottonello, 2021]. Even though the role of disequilibrium in magma dynamics and rheology is nowadays widely accepted, the equilibrium picture is often blurred by the lack of a physically-consistent thermodynamic description of solid-melt phase equilibria in multicomponent compositional systems. In other words, defining the role of equilibrium processes in model systems before assessing that of disequilibrium is a fundamental benchmark for a deep understanding of magma evolution in real volcanic systems. We present the results of theoretical simulations based on ab initio and classical molecular dynamics (MD) and computational thermodynamics of model magmatic systems (i.e. Na_2O-K_2O-CaO-MgO-Al_2O_3-SiO_2 system along with relevant mineralogical sub-systems) in broad range of P-T conditions. MD simulations allow to analyze the dynamics of atoms and molecules in a given solid or liquid system at any physical conditions. The atoms and molecules are allowed to interact in a simulation box for a fixed period of time (which usually spans from tens to thousands of picoseconds), then the dynamic evolution of the system, viz. the trajectories of atoms and molecules, are determined by numerically solving Newton's equation of motion for a system of interacting particles. Forces between the particles along with their potential energies are calculated by interatomic potential force fields or quantum mechanics DFT electronic structure calculations in classical and ab initio MD, respectively. Free energy differences of solid-melt exchange reactions along with enthalpy of fusion can be extracted from MD simulations by time averaging and integrating changes in total energy over a reaction path [Frenkel & Smit, 2001]. Equilibrium partitioning for major, minor or trace elements between the solid and the liquid phase can also be derived from the exchange equilibrium constants at any desired P and T conditions. Coupling MD results with hybrid polymeric models for silicate melts and ab initio DFT calculations for crystalline solids allows to define physically-consistent solid-melt equilibria in multi-component phase diagrams by computational thermodynamics. Some case studies related to the crystallization and melting processes of simple oxides and pyroxene phases (protoenstatite, orthoenstatite, low- and high-clinoenstatite, diopside) in model magmatic systems are presented and their implications for large-scale processes briefly discussed.

Acknowledgements Financial support by MIUR PRIN 2017 ("Oceanic Megatransforms: a New Class of Plate Boundaries", Prot. 2017KY5ZX8) and PRIN 2020 ("Dynamics and timescales of volcanic plumbing systems: a multidisciplinary approach to a multifaceted problem", Prot. 202037YPCZ) to D.B. is warmly acknowledged. The authors also acknowledge the CINECA award under the ISCRA initiative (ISCRA C Projects THOMMY - HP10CNF2NR and ECLIPSE - HP10CA2JUN) for the availability of high-performance-computing resources and support.

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Shallow syn-eruptive carbonate assimilation and its effects on vesiculation and eruptive behaviour - insights from 3D reconstruction of experimental samples

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Melt vesiculation, i.e. the process of bubble formation and evolution, is mainly controlling the eruptive behaviour. Vesiculation in magmas is often described by bubble size distributions and bubble number densities (hereafter BSD and BND respectively) in the eruptive products. High vesiculation results in high rates of magma expansion, which leads to magma fragmentation and explosive eruptions. The syn-eruptive assimilation of carbonate wall-rock and the related release of CO_2 pose an additional but often neglected volatile source. Since the solubility of CO_2 in magmas at shallow depths is extremely low, almost all of the released CO_2 is bound to form an additional vapour phase (i.e., additional bubbles will nucleate). Some studies suggest that this might be the cause for a change in eruptive style from effusive to explosive, especially for basaltic volcanism. Despite its importance regarding the hazard assessment, the kinetics of CO_2 release by syn-eruptive carbonate assimilation as well as its potential influence on vesiculation have yet to be investigated.

Here we present a first step towards resolving the kinetics of CO_2 bubble nucleation due to syn-eruptive carbonate assimilation in shallow depth. Our carbonate assimilation experiments were conducted at atmospheric pressure in open alumina crucibles, allowing degassing/outgassing of the released CO_2. The absence of decompression and the use of dry magmas allowed us to attribute all nucleated bubbles to the release of CO_2 from the ingested carbonate clast. The starting materials for the experiments are comprised of three different magma compositions (Phonolite, Shoshonite and Basalt) and two different limestone compositions (calcitic and dolomitic). The experiments were conducted at two different temperatures (1230°C and 950°C) and span an interaction timescale of 1-30 min, which is in line with magma ascent rates. The experimental products were then analysed and reconstructed via x-ray computed microtomography. From the 3D models the respective BSDs and BNDs for all experiments (diverse combinations of time, temperature, magma and limestone composition) were calculated. While temperature and limestone composition control the rate of CO_2 release in these experiments, the magma composition (and hence magma viscosity) seems to be controlling the vesiculation process (bubble nucleation and growth). With increasing magma viscosity, the amount of bubbles nucleated increase (higher BND) while the bubble sizes remain smaller (BSD towards finer sizes).

S05 - Oral Presentation

Relationship between edifice collapse and eruptive activity on instant time scales: insights from the Pacaya 1 ka and Cumbre Vieja 2021 eruptions

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Understanding whether volcanic eruptions can influence flank instability or if lateral collapses have a direct impact on volcanic eruptions is crucial for determining the chained hazards of unstable volcanoes. Here we present two basaltic volcanoes that were erupting during their flank failures. Pacaya volcano (Guatemala) experienced a dramatic collapse 1 ka BP, depositing a debris avalanche of c. 0.6 km^3, followed by a lateral blast westward. The growing cone of the Cumbre Vieja 2021 eruption lost nearly 5.5 x 10^6 m^3 due to a lateral collapse one week after the beginning of the eruption. Both were syn-eruptive cone failures, however Cumbre Vieja did not experience a lateral blast related to the collapse. We study the stratigraphy, components, grain size, pyroclastic texture and composition in glass and crystals shortly before, during and after these collapses. Our results are interpreted to determine magma viscosities and ascent rates to elucidate the role of magma decompression. Pacaya eruption shows a clear influence of unloading on the erupting magma, whereas for Cumbre Vieja the collapse seems to be magmatically controlled. We speculate that the modest pressure loss in the conduit was insufficient to trigger an explosive response by Cumbre Vieja, while at Pacaya was enough to trigger sudden microlite crystallisation during decompression that promoted a rapid rheological transition during magma ascent enhancing explosivity. These results are important to understand conditions leading to volcano instability and the potential impacts of lateral collapses on magmatic plumbing systems.

S05 - Oral Presentation

Crystallization kinetics in hydrous trachytic and latitic melts from Campi Flegrei

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Water saturated magmas, subjected to decompression induce H_2O loss from the melt which can be expected to crystallize due to the effects of H_2O loss on magma liquidus temperatures. The magma crystallization due to decompression may thus produce large changes in viscosity during magma ascent towards the surface and potentially influence eruptive styles (e.g., effusive vs. explosive). Hydrous basaltic magmas are able to crystallize rapidly even during fast ascent and decompression rates within conduits, promoting highly explosive eruptions [Arzill et al, 2019]. Trachytic and latitic magmas of Campi Flegrei (Naples, Italy) produced highly explosive eruptions in the phlegrean volcanic area, but the effect of crystallization on magma viscosity during ascent and on the eruptive style is poorly investigated. This study investigates the effect of continuous cooling and decompression on crystallization kinetics of trachytic and latitic melts through cooling and decompression experiments conducted in an internally heated pressure vessel (compositions more mafic than the trachy-phonolite studied by [Arzilli et al, 2016]). We conducted H_2O-saturated isobaric cooling experiments (continuous cooling at 0.125, 0.5, 3, and 12.5 °C/min) at P of 200 and 50 MPa, and isothermal decompression experiments (1.15, 6.92, and 23.03 MPa/min) at 975 °C and 200 to 50 or 25 MPa. Preliminary observations suggest that the presence of H_2O in these experiments aids the nucleation and growth of feldspar crystals compared with the dry case [Iezzi et al, 2008]. The results indicate that the effects of H_2O on crystallization kinetics in the more mafic trachytic and latitic melts discussed here could be slightly less than the effects observed for trachy-phonolitic melts [Arzilli et al, 2016]. However, this depends on the effect of water on the crystallization temperature of the individual phases and on crystallization kinetics which are controlled by melt water content and diffusivity.

Nanocrystallization in basalts: a chemical threshold between magmas from Mt. Etna and Stromboli

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An increasing number of studies are being presented demonstrating that volcanic glasses can be heterogeneous at the nanoscale. These nano-heterogeneities can develop both during viscosity measurements in the laboratory and during magma eruptions. Our multifaceted study identifies here total transition metal oxide content as a crucial compositional factor governing the tendency of basalt melts towards nanolitization: an undercooled trachybasalt melt from Mt. Etna readily develops nanocrystals whose formation also hampers viscosity measurements, while a similar but FeO- and TiO_2-poorer basalt melt from Stromboli proves far more stable at similar conditions. We therefore outline a procedure to reliably derive pure liquid viscosity without the effect of nanocrystals, additionally discussing how subtle compositional differences may contribute to the different eruptive styles of Mt. Etna and Stromboli.

S05 - Poster

Numerical modelling of sudden eruptive style transitions at basaltic volcanoes

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Abrupt transitions in eruptive style are common during eruptions at low viscosity basaltic volcanoes. The unexpected resulting activity may strongly affect volcanic risk, potentially damaging infrastructures and threatening people living in the surrounding area. The recent 19th September - 13th December 2021 Cumbre Vieja eruption on La Palma, Canary Islands, represents an ideal case where mechanisms underlying such transitions can be investigated. To this aim, we use our 1D steady-state numerical model for magma ascent, which accounts for the complex and non-linear coupling between changes in temperature, viscosity evolution, non-ideal gas behaviour, outgassing, and both crystallization and exsolution disequilibrium [1,2]. The results of the simulations will be integrated with field observations of the eruption to provide an improved understanding of eruption dynamics and forecasting in basaltic systems.

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S05 - Poster

Rheology of 2021 lava flows at Cumbre Vieja volcano (La Palma, Canary Islands, Spain)

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After half a century of quiescence, activity at Cumbre Vieja volcano (La Palma, Canary Islands, Spain) restarted with a spectacular flank eruption characterized by both high fire fountaining and effusive activity. The products emitted comprise tephra fall and lava flows, ranging from tephrite to basanite. Between September 19th and December 13th, 2021, the lava flows covered ~ 13 km^2, affecting more than 3000 buildings and paralyzing the viability and the essential activity on the SW sector of the island. This scenario highlights the importance of rheological data deriving from experimental studies of such low viscosity magma to better understand lava flow emplacement dynamics, hazard and mitigate risk.
We performed a detailed experimental study to characterize the rheology of the basanitic lava sampled between October 3rd and 7th in a Concentric Cylinder set-up. Starting from a superliquidus state of 1400 °C, a set of isothermal deformation experiments was carried out at different target subliquidus temperatures (from 1225 to 1175 °C) and fixed shear rate of 10 s^{-1} to investigate the near equilibrium viscosity. Moreover, a series of cooling deformation experiments were performed at different cooling-rates (ranging from 0.1 to 10 °C/min) and at constant shear rate of 10 s^{-1} with the aim to mimic the dynamic evolution of natural flowing lava through controlled cooling rate conditions. In isothermal deformation experiments, the steady state conditions (i.e., stable crystal contents) were achieved faster at increasing degree of undercooling, showing a progressive increase in the final viscosity values. In cooling deformation experiments, with increasing cooling rate applied, the onset of crystallization took place at progressively lower temperature over shorter timescales. The experiments performed at cooling rates from 0.1 to 1 °C/min were interrupted when viscous rupture (i.e., the transition from coherent flow to shear localization and physical separation) was observed. For the experiments conducted at higher cooling-rates (i.e., from 3 to 10 °C/min), the experimental runs were stopped when the stress limit of the device was achieved.
Results show that the thermal and deformation history plays a fundamental role on the kinetics of the crystallization hence modulating the capacity of lava to flow. The different viscosity paths observed at low and high cooling rates lead to a rheological decoupling between the slow-cooling core and the fast-cooling external part of the lava flows. This process would be key in promoting the transition from pāhoehoe to 'a'ā emplacement regimes, ultimately controlling the runout distance of lava flows.

S05 - Poster

Experimental constraints on fragmentation conditions of mafic magmas during large-scale, ignimbrite-forming eruptions

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Mafic magmas commonly erupt at intensities ranging from effusive to mildly explosive. More rarely, large-volume ignimbrite-forming eruptions do occur. Although the processes promoting mafic magma fragmentation, especially during large-scale eruptions, are still subject of studies, there is consensus on a key role of syn-eruptive crystallization. Mafic melts are characterized by low viscosities and, therefore, fast crystallization kinetics due to rapid chemical diffusion. Very rapid crystallization can dramatically increase magma viscosity, affecting magma rheological response and eventually leading to ductile to brittle transition (i.e. fragmentation).
Here we present an experimental dataset on the subliquidus rheology of basalts erupted during the 12.6 ka Curacautín ignimbrite eruption of Llaima volcano (Chile). Experiments were designed to investigate the effect of crystallization on the high T (1165-1200 °C) magma rheology across the ductile-brittle deformation window in a concentric cylinder apparatus under shear rates between 0.1 and 10 s^{-1}.
Crystallization-induced viscosity increase agrees with the predictions of melt-crystal viscosity models. Real-time viscosity monitoring also mapped the sharp transition from flowing as a coherent unit (i.e., laminar deformation) to tearing apart along surfaces sub-parallel to the direction of maximum shear (rupture process) recorded in the experiments by a significant drop in the measured shear stress. The conditions for rupturing are primarily controlled by crystal content, changing as a function of the degree of undercooling (which is the difference between the liquidus and the experimental temperatures). At low degree of undercooling (T > 1190 °C), the flow is perfectly viscous and the rheology is Newtonian. At larger degree of undercooling (T 1180 °C), the suspension viscosity shows a complex shear rate dependence (shear thinning) with the onset of rupture processes only at high shear rates. We demonstrate that this shear localization could occur over very short timescales during magma ascent and promote magma fragmentation during high-energy mafic eruptions.

S05 - Poster

Are volcanic melts less viscous than we thought?

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Volcanic eruptions represent one of the most dangerous natural hazards on Earth. Eruption styles range from effusive lava-fed fountains to explosive ash-producing eruptions capable to generate pyroclastic flows and destructive ash falls. Eruptive style is mainly controlled by the ability of the gas phase to escape the magma, where magma viscosity modulates how easy is for the gas to decouple from it. Therefore, magma viscosity is one of the most critical parameters required to understand magma evolution, transport, and eruptive style. Viscosity of magmas strongly depends on chemical composition, temperature, crystal and volatile content. Recent studies demonstrate that volcanic melts can be prone to crystallization and dehydration during viscosity measurements. We developed an experimental methodology combining differential scanning calorimetry (DSC), conventional viscometry and spectroscopy to accurately quantify the viscosity of the liquid phase for different compositions. We show that volcanic melts can be less viscous than estimations from commonly used empirical models. Finally, we discuss the impact of our results on numerical modelling of volcanic eruptions and magma dynamics.

S05 - Poster

S06 - LARGE ERUPTIONS MAGMA-CHAMBERS FORMATION AND EVOLUTION: IMPLICATIONS ON MAGMATIC PROCESSES, ERUPTION DYNAMICS AND ENVIRONMENTAL IMPACT

Conveners:
Sandro de Vita, Claudia D'Oriano, Ilenia Arienzo, Domenico Doronzo

Classification of ignimbrites and their eruptions

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The term "ignimbrite" probably encompasses the one of the largest ranges of deposit types on Earth, associated with the partial to total collapse of explosive eruption columns feeding pyroclastic density currents. Ignimbrites range from millions of cubic metres to thousands of cubic kilometeres in bulk volume and are associated with any kind of magma type (from basaltic to rhyolite, from crystal poor to crystal rich) and explosive eruption style (except the very low intensity hawaiian and strombolian eruptions).

Notably, even though caldera-related ignimbrites represent, along with flood basalts, the largest volcanic units on Earth, there is not a terminology which describes the related eruption style, with the common misconcept that these kind of catastrophic eruptions can be associated with the collapse of Plinian columns.

The last fifty years of research has largely focused on the sedimentology of ignimbrites emphasizing the dilute vs concentrated spectrum of pyroclastic density currents to reconstruct conditions at the flow boundary layer. However, such spectrum is scale invariant, so it can be found in any PDC deposit from minuscule to gigantic. As a consequence, there is no quantified classification scheme for ignimbrite types, as there is instead for fallout deposits [Walker 1973 and subsequent modifications], and this is a remarkable deficiency of modern volcanology. This has so far prevented the identification of standardized global descriptors for ignimbrites and the improvement of methods for the documentation of their characteristics (with the exception of descriptors of the local sedimentology), such as happened for fallout deposits.

Hence, despite some earlier attempts, ignimbrite types do not conform to eruption style nomenclature even though for many eruptions they represent the largest proportion (if not all) of the erupted materials.

We here explore and discuss global descriptors for a classification scheme based on the correlation of runout, areal extent, aspect ratio and volume from a compiled database comprising 92 ignimbrites, which then allows current understanding of pyroclastic flow dynamics to be considered.

Ignimbrites show remarkable power-law relationship between dispersal area/equivalent runout and bulk volume. Runout is directly related to increasing mass flow rate feeding the pyroclastic current. Volume is related to the magnitude of the flow event. We therefore propose that by measuring first order field observables such as bulk volume and dispersal area provides the opportunity to evaluate magnitude and intensity of related pyroclastic currents and, for large eruptions dominated by ignimbrites, of the eruption. The striking relationship between mass flow rates and runout is also corroborated by observation and numerical modeling.

Based on the relationships identified we propose that ignimbrites that originated from the partial to wholsale collapse of single point-source eruption columns, usually smaller than 1 km^3, are named "Vulcanian ignimbrites" and "Plinian ignimbrites" depending on the style of the eruption they are associated with.

Larger ignimbrites that originated from caldera-forming eruptions along ring-fault fissure vents should be regarded as related to a separate eruption style - with respect to the common Hawaiian-Plinian trend -, where the effect of increased mass flow rate due to ring-fissure vents is dominant and controls the dynamics of the resulting collapsing fountains and pyroclastic flows, irrespective of the kind of eruption style that preceded the onset of the caldera collapse. These are named “caldera-forming ignimbrites” and are further subdivided into small (1-10 km^3), intermediate (10-100 km^3), large (100-1000 km^3) and super (>1000 km^3), based on their increasing erupted volume. We suggest that stratigraphic complexity and temperature of emplacement of the ignimbrites further relate to varying caldera collapse style and especially to chaotic versus piston collapse, which control the geometry of the ring vents and variations in mass eruption and flow rates.

Volcanological and petrological characterization of the Golja Ignimbrite (Main Ethiopian rift)

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The Main Ethiopian Rift (MER) is an ideal natural laboratory to study magmatism related to rifting. The MER is an active magmatic rift that records variations in rift evolution from mature rifting in the north to less evolved rifting southwards. The Plio-Pleistocene volcanism in the MER is mainly characterized by eruptions of mafic products (i.e., transitional basalts) associated with cinder cones and lava flows, alternating with ignimbritic eruptions emplacing large volume of felsic products (i.e., peralkaline rhyolitic and trachytic pyroclastics) with the formation of large calderas. After widespread Miocene-Pliocene volcanism, the Quaternary magmatic activity became mostly localized in the MER axis, with products showing a typical bimodal composition (i.e., dominantly basaltic and rhyolitic composition) with a notable compositional gap, also known as the Daly gap, which remains a poorly understood aspect of the rift-related magmatism.

In this context, we present the first volcanological and petrological characterization of the Golja Ignimbrite, a crystal-poor (5% crystals of qtz+K-feld+pl+cpx+aen), low aspect ratio ignimbrite sourced from the MER floor, that crops out over ~400 km^2 and has an estimated bulk-tephra volume of ~100 km^3. The Golja Ignimbrite pyroclastic sequence is characterized from bottom to top by: 1) a coarsening upward basal fallout layer; 2) an obsidian vitrophyre with rare, scattered fiammae; 3) a weakly to partially welded, lithic-rich PDC deposit and 4) a thick, unwelded PDC deposit containing white and banded pumices together with black scorias.

Both density and welding degree are relatively low at the transition between the basal fallout and the vitrophyre (1.32 ± 0.03 g /cm^3) and reach their maximum in the vitrophyre (2.38 ± 0.02 g/cm^3), where most of the glass shards are not distinguishable from the groundmass glass. Subsequently, density tends to decrease up-sequence (down to 1.20 ± 0.01 g/cm^3 at the top), as indicated by the increasing occurrence of glass shards without a preferential orientation, glass spherules and vesicular juvenile clasts.

$^{40}Ar/^{39}Ar$ dating of single K-feldspars from a white pumice and a black scoria yielded and age of 1.159 ± 0.006 Ma relative to the Fish Canyon Tuff (FCs) sanidine age 28.02 ± 0.28 Ma (Renne et al., 1998).

The ignimbrite composition plots in a transitional field between the subalkaline and peralkaline series, which is typical of magmas associated with continental rifts. Compositional differences have been observed between the various juvenile clasts with rhyolitic white pumices and, trachy-basaltic to trachy-andesitic black scorias. Mingled, streaky pumices range between trachytes and rhyolites, while truly basaltic compositions were only found in melt inclusions contained in bytownitic plagioclase crystals. The presence of intermediate compositions is an uncommon feature for MER magmas and our data support that they are likely due to two different processes: fractional crystallization and mingling between magmas with strong compositional differences (i.e, basalts and rhyolites) occurring before eruption. Such evidence places important constraints on the evolution of large magma reservoirs in this peculiar geodynamic setting.

From deposits to physical parameters of large-scale energetic pyroclastic density currents: the case of the 39.8 ka Campanian Ignimbrite, Italy

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Interpreting the physical processes of large-scale pyroclastic density currents (PDCs) from their deposits is a critical issue in volcanology. In this study, we use the physical characteristics of the Campanian Ignimbrite (CI) to interpret the transport and emplacement dynamics of the pyroclastic density current. The high-magnitude 7.7-7.8, Campanian Ignimbrite PDC, related to the 39.8-ka eruption that formed the Campi Flegrei caldera (Italy), emplaced over an area of more than 6000 km^2 on land around the caldera, with an average final runout of about 80 km, and surmounted ridges higher than 1000 m above sea level at medial and distal reaches. The lateral decrease in size of both pumices and lithics across paleotopography suggests that the main transport system was dilute. The lateral and vertical mass distribution of the ignimbrite, related to the paleotopography, allows us to identify a density-stratified PDC, at least 1.5 km thick, with ca 60% of the material below 400 m of elevation and the rest above. We use thickness data, associated with different aggradation rates, to estimate the duration of the short-lived PDC (~20 minutes), and the relative mass flow rate of ~10^{11} kg/s. At the base of the dilute PDC, we recognize, due to the deposit characteristics, high-concentration undercurrents formed and interacted with the rough paleotopography, depositing a low aspect ratio sheet when on flat plains, but generating back-flows off ridges and channeling in paleovalleys. It formed massive valley-pond ignimbrite facies, even in rough mountain terrain, and the absence of veneer facies or deposits on steep slopes reflects a near-Newtonian rheology of the undercurrents, interpreted as fluidized dense granular flows unable to stop on slopes >10°. This work advances the interpretation of PDC deposits, which do not necessarily directly reflect conditions in the transport system, and it underlines the key role of pyroclastic deposits, which are the main tool to understand past eruptive dynamics.

Reconstructing Pyroclastic Currents' Source and Flow Parameters from Deposit Characteristics and Numerical Modeling: The Pozzolane Rosse Ignimbrite Case Study (Colli Albani, Italy)

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In this study, we apply a two-dimensional, transient depth-averaged model to simulate the inertial flow dynamics of caldera-forming pyroclastic currents, using the available data about the Pozzolane Rosse ignimbrite (Colli Albani, Italy) eruption (460 ka, 63 km^3 DRE). By performing an extensive set of numerical simulations, we test the effects of the initial parameters of the pyroclastic current (Richardson number, mass flow rate, initial flow density) on simulated deposit characteristics which can be compared with selected ignimbrite field observables, including the deposit dispersal along topography, the maximum distance from source, the deposit thickness, the grain size distribution at different distances, and the emplacement temperature. Results permit us to quantify the first-order dependency of the flow runout on the mass flow rate, and of the deposit thickness decay pattern on the initial mixture density. By using the results of the parametric study we reconstruct the source parameters of the Pozzolane Rosse ignimbrite constrained by the ignimbrite depositional characteristics, including the mass partition into the co-ignimbrite cloud. Despite uncertainties associated with the complex, non-linear interplay between the flow variables, the single-layer, depth-averaged model demonstrates to be suitable for simulating inertial pyroclastic currents, such as those generating large-scale caldera-forming ignimbrites, providing a tool for reconstructing the eruption source parameters from deposits characteristics, and to assess pyroclastic currents' hazard for future eruptions.

S06 - Oral Presentation

The 79 CE eruption of Vesuvius - lesson from the past and future perspectives

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This work is a comprehensive review of the 79 CE Plinian eruption of Vesuvius, carried out through multidisciplinary approaches, integrating historical, stratigraphic, sedimentological, petrological, geophysical, paleoclimatic, and modelling studies dedicated to this famous and extreme event. The critical review has been combined with new data, spanning from proximal to ultradistal findings of the 79 CE eruption deposits throughout the Mediterranean. The study adopts different investigation approaches and follows the temporal evolution of the 79 CE eruptive events, from the magma chamber supply to the deposition in proximal and distal areas, by focusing on three macro-categories, historical aspects, products, and processes. It has allowed first to compile a full database of all findings of the eruption deposits, then to relate them to the genetic thermo-mechanical processes, and lastly to better assess both the local and regional impacts of the 79 CE eruption in the environment. In addition, it highlights a number of open issues that will be more deeply addressed in the future, although the 79 CE eruption of Vesuvius is one of the best studied volcanic eruptions. In fact, the comprehensive study done in this work has opened to phenomenological aspects that are worth of further investigations. Various aspects for volcanic hazard assessment of Plinian eruptions, particularly of the size of the studied one, are highlighted from the tephra distribution and modelling points of view, as these extreme natural phenomena can have a larger impact than previously thought [Doronzo et al. 2022, Earth-Science Reviews, 231, 104072].

Reconstructing the pre Campanian Ignimbrite (39 ka) activity of Neapolitan volcanoes: first stratigraphical results of boreholes drilling in proximal and intermediate-distal areas of the Campi Flegrei caldera

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In the framework of the INGV – Pianeta Dinamico project, the research theme TIFEHO (Trachytic Ignimbrites magma-chambers Formation and Evolution in the pre-HOlocene history of the Campania volcanic area) has the main goal of understanding the growth and evolution of the deep magmatic feeding system prior to high magnitude, caldera-forming eruptions, originated from the Campania volcanic area. In order to reconstruct the volcanic activity prior to Campanian Ignimbrite eruption (39 ka), two boreholes were drilled in the Ponti Rossi area of Naples (50 m a.s.l.) and at Acerra (25 m a.s.l.), about 16 km northeastward, down to 113.2 m and 65 m of depth from the ground level, respectively. Here, we present the preliminary results of the stratigraphic analysis of the cored sediments together with some paleo-environmental implications. In both sites, grain-size, textural and structural characteristics of pyroclastic deposits reflect both fall and pyroclastic current emplacement mechanisms. As a whole, deposits vary from grain-supported beds of angular, coarse-to-fine lapilli, to matrix-supported ash deposits with a variable amount of rounded to sub-rounded lapilli, dispersed into the matrix. From a lithological point of view, deposits are composed of both pumice and scoria juvenile fragments and different types of lithic clasts (e.g. lava, skarns, intrusive and metasomatic rocks). At Ponti Rossi, cored sediments are composed of primary pyroclastic deposits, separated by paleosols and/or sandy, lithic-rich, reworked material. In this site, 31 pyroclastic units older than the Campanian Ignimbrite were recognized. Their thickness ranges from few centimeters to tens of meters. The thickest unit is 21.5 m thick, while the thinnest one is only 10 cm thick. Paleosols are characterized by different degrees of evolution, with thicknesses between 5 and 60 cm, varying from very mature and dark brown in color to less mature and light brown in color. Some paleosols grade from dark brown at the top to light brown-yellowish at the base and often contain juvenile fragments and thin sandy intercalations. The presence of well-developed paleosols suggests the persistence of sub-aerial conditions in this area. A first hypothetical correlation, absolutely preliminary, was also attempted between the stratigraphy of the survey just concluded and the stratigraphy of previous drillings, carried out in the same area. The correlation was made exclusively on the basis of general lithology. The main problem in the correlation is the notable difference in the number of pre-Campanian Ignimbrite units recognized: 31 in the recent survey and only 11 in previous drillings. This difference may be due to the technique and quality of the core drilling. The recent core drilling has been characterized by a recovery percentage close to 100% allowing to sample almost undisturbed units only a few centimeters thick that may have been lost in the previous core drilling.

At Acerra, 12 pyroclastic deposits underlying the Campanian Ignimbrite have been recognized, having thicknesses from centimeters to meters. The thickest pyroclastic unit is 7 m thick while the thinnest one is 10 cm thick. Silty to clayey, locally sandy, palustrine and marine sediments are intercalated, at different depth, to primary pyroclastic deposits. Palustrine sediments, 3.5 m thick, are intercalated in the pyroclastic sequence between 36.5 and 40 m of depth, while marine sediments containing very abundant shells, having a total thickness of 11.15 m, have been found between 43.15 and 54.4 m of depth, intercalated by a 10 cm thick pyroclastic bed at 45 m of

depth. The alternation of pyroclastic deposits grading upward into paleosols and marine/palustrine sediments testify sea level oscillations through time and repeated variations from sub-aerial to transitional/marine paleo-environment.
Although still preliminary, our results show a very rich volcanic stratigraphy represented by a conspicuous number of pre-Campanian Ignimbrite pyroclastic units that testify a remarkable volcanic activity in the Campanian area associated to a complex paleo-environmental evolution. Further investigation through sedimentological, geochemical, petrological and paleontological analyses will be carried out on collected samples from cored sediments in order to shed further light on the history of the Campanian volcanic area.

Timescales of mingling preceding the Zaro eruption at Ischia

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The Zaro eruption (Ischia island, Southern Italy; 7 ka) emplaced a lava complex, in which the main flows host abundant mafic to felsic enclaves. Based on petrographic, geochemical and isotopic characterization, previous investigation allowed hypothesizing that a mafic magma mixed/mingled with a trachytic one, destabilizing the magmatic system and favoring the eruption. Detailed mineral composition analyses have shown that the zoning pattern of clinopyroxene is characterized by two main compositional populations, each formed in a specific magmatic environment, characterized by a well-defined range of temperature and pressure. One population pertains to a more evolved, crystal-rich trachyte, and the other to a possibly volatile-richer shoshonite of deeper origin. Geological records suggest that the shoshonitic magma contributed to only a very limited amount of the erupted material.
To unravel the processes that triggered the eruptions, and their timescales, we have modeled the injection of a small volume of the shoshonitic end-member into a relatively shallow (pressure $p = 2$ kbar), vertically elongated trachytic reservoir.
Chemical constraints, pressure-temperature conditions of the interacting magmas are obtained from the petrological analyses. Equilibrium thermodynamics predicts a very limited amount of exsolved volatiles within the two magmas, that can thus be effectively described as incompressible fluids with specified melt viscosities. Inclusion of different amounts of crystals, as observed in the field, controls the viscosity of the multiphase magmatic mixtures. The deep shoshonitic magma has a lower density at the reservoir pressure, therefore a gravitational instability favors the dynamical interaction.
The evolution of the system has been modeled using MagmaFOAM, a numerical framework based on OpenFOAM, specifically designed to describe magmatic fluid dynamics under different conditions. Simulation results show that buoyancy triggers efficient convection and mingling of the shoshonitic melt into the trachytic reservoir. The two end-members mix efficiently on time scales that vary from days to months, depending on their physical properties including density and viscosity, in turn controlled by their crystal and volatile contents.
Pressure-temperature-composition trajectories of crystals within the convecting systems are tracked in space and time to obtain synthetic compositional zoning profiles. Comparison with petrological observations provides the best fitting simulated scenarios in terms of sizes and physical properties of the magmatic multiphase mixtures.

S06 - Oral Presentation

The TIFEHO research theme in the framework of the INGV Pianeta Dinamico project: a window into the past of the Phlegraean Volcanic District

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The main objective of TIFEHO is to reconstruct structure, growth and evolution of the magmatic feeding system(s) of some of the highest magnitude eruptions of the Campania volcanic area. For the TIFEHO purposes, we selected the eruptions of Campanian Ignimbrite (CI - 39.88 ± 0.17ka) and Mount Epomeo Green Tuff (MEGT - 56.0 ± 1.0ka), along with the products of the eruptions that slightly preceded these two events. The objectives of this project have been pursued by carrying out activities both in the field and in the laboratory. These include a comprehensive study of the existing literature along with new geological, geomorphological, stratigraphic, volcanological, structural and geophysical investigations and the collection and preparation of samples for geochemical, sedimentological, paleomagnetic and geochronological analyses. These activities are aimed at: improving the description of the volcanic stratigraphy; defining the sedimentological characteristics of the products exposed in proximal areas; reconstructing the main magmatic and deformational events that preceded, accompanied and followed volcanic eruptions, caldera collapse and resurgence and investigating magma chamber processes, through melt inclusions studies, diffusion chronometry and numerical simulations
A field survey has been performed in several Campi Flegrei, Ischia, Procida and Capri localities for the characterization of volcanic sequences and sampling of the products belonging to the eruptions that preceded the CI and MEGT.
Two drillings of c. 80 and 110 m have already been performed in the eastern part of the city of Naples (Ponti Rossi) and near the city of Caserta (Acerra), respectively. The analyses of samples from both proximal sequences and cores are employed for the reconstruction of tephra sequences in both proximal and intermediate areas and for the recovery of information on the paleoenvironment. $^{40}Ar/^{39}Ar$ dating of alkali-feldspar from most of the recognized tephra layers allows to reconstruct the volcanism that preceded CI and MEGT and to identify the possible proximal equivalents of the distal stratigraphic markers (e.g., C-22, X-5 and X-6) recognized only in the distal marine and terrestrial successions.
Moreover, the deep structure of the Campanian Plain and the morphological characteristics of the main structures acting during the deformational events that accompanied and followed the studied eruptions have been investigated through reprocessing and reinterpreting gravimetric, seismological and deep drilling data, and through detailed aerial photogrammetry, respectively, in the areas of Ischia and Campi Flegrei and in selected areas of the Campanian plain.
TIFEHO has a multidisciplinary character and will benefit from the cross participation of researchers from different institutions. It aims to create a motivated and collaborative scientific community, made up of researchers / technologists from INGV and Italian and foreign universities, dealing with the different aspects of volcanology and petrology.

S06 - Poster

How does an eruption start?
The AD79 Pompeii eruption of Mt. Somma-Vesuvius (Italy)

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The eruptive history of Mount Somma-Vesuvius is characterized by large Plinian and Subplinian eruptions. These high intensity events are generally characterized by a succession of different eruptive phases: a brief opening phase; a Plinian phase, with the formation of a stable to unstable convective plume; a final phase mainly characterized by collapsing clouds related to phreatomagmatic activity. Studies of these explosive eruptions are generally based on the products of the paroxysmal phases, so not allowing an accurate evaluation of timing and dynamics of the processes involved in the initial stages of magma ascent to the surface. Conversely, the study of the very initial deposits of these eruptions may represent a unique witness to unravel the mechanisms of eruption trigger and the dynamics of the final magma ascent before eruption starts. The deposits of the opening phase of the AD79 eruption, Mt. Somma-Vesuvius (Italy) testify for a short-lived phreatomagmatic phase, producing an accretionary-lapilli-bearing fall ash with an eastward dispersal and proximal pyroclastic density current deposits. The peculiar character of this event which precedes the paroxysmal Plinian sequence is well recorded in the large variability of the products within the thin basal deposit. Preliminary coupled geochemical and textural analyses of the samples evidence the concurrent ejection of different types of juvenile material (white pumice, grey pumice, streaky pumice, dark scoriae) and of variable lithics population (lava, altered scoriae, marble, carbonates, skarns). The detailed compositional study performed on the juvenile material shows important differences respect to the products of the paroxysmal event, suggestive of a trigger mechanism for the eruption which involved the whole body of the magma reservoir. Textural data on the juvenile material help to constrain the dynamics of the eruption onset, as well as data on volatile contents in melt inclusions and residual glasses.
Timing and dynamics of eruption onset, as derived from the study of the products of the very initial deposits of large eruptions, represent a fundamental information to decipher the possible paths of unrest and eruptive reactivation at dormant volcanoes.

S06 - Poster

Magma chamber dynamics during the Green Tuff (Pantelleria, Italy) eruption: insights into the evolution of a peralkaline mush zone

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The geological history of Pantelleria is characterized by several explosive eruptions that blanketed the entire island. Among these, the Green Tuff eruption (45.7 ± 1 ka), the last caldera-forming event extruded 0.3 to 3 km^3 DRE of pantellerite magma and a small volume of trachyte. The Green Tuff eruption was followed by the extrusion of a series of post-caldera trachyte lavas compositionally similar to the Green Tuff trachyte and with many features of a re-mobilized mush-zone, such as a strong enrichment in large alkali feldspar phenocrysts. We investigated two samples of the Green Tuff trachyte and nine of post-Green Tuff Montagna Grande trachytes, all characterized by high crystal content (up to 40 vol%) with alkali feldspar as the dominant mineral followed by clinopyroxene and olivine. In this study, we use the whole-rock major- and trace-element and melt inclusions analyses, combined with textural studies. Alkali feldspars generally show some degree of resorption in their inner shells, resorption that is more pronounced in the alkali feldspar of Green Tuff trachyte and decreases with increasing host rock peralkalinity. Cathodoluminescence microscopy and electron microprobe (EMP) analyses reveal complex zonation in alkali feldspar where potassium, calcium, and barium are the key elements to depict a scenario about the origin and dynamics of trachytic mush zone, its interaction with pantellerite melts and their role in the caldera and post-caldera evolution of Pantelleria magmatic system. Relevant inferences can be made to unravel the complex processes of a peralkaline magmatic system in the transition from metaluminous to peralkaline.

S06 - Poster

Stratigraphic and geochemical investigations of pre-Campanian Ignimbrite (39.85 ± 0.14 ka) and pre-Monte Epomeo Green Tuff (56.0 ± 1.0 ka) volcanic sequences at Procida and Monte di Procida

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In the Neapolitan volcanic area, the occurrence of diffuse Plinian fallout and ignimbrite deposits outcropping stratigraphically below the deposits of the Campanian Ignimbrite (CI; 39.85 ± 0.14 ka, Campi Flegrei) and Monte Epomeo Green Tuff (MEGT; 56.0 ± 1.0 ka, Ischia island) suggests that the past volcanic activity was conspicuous and characterized by large events. Despite this significant activity, volcanism preceding the CI and MEGT is somewhat poorly investigated. The majority of these products has been found as distal tephra layers in several lacustrine, marine and continental successions, but has not been well characterized in near-vent outcrops because of the difficulties encountered in identifying and sampling suitable deposits.
The lack of a systematic collection and analysis of stratigraphic, volcanological, petrological and geochronological data on many of these proximal deposits does not allow the definition of their source areas and emitted volumes.
In the framework of INGV-TIFEHO project, a field survey has been performed at Acquamorta cliff (Monte di Procida) and at Ciraccio and Pozzo Vecchio localities (Procida) for characterizing the volcanic sequences and sampling the products underlying CI and MEGT deposits.
At Acquamorta, a thick pyroclastic sequence underlies the Campanian Ignimbrite. Four pyroclastic units just below the Campanian Ignimbrite were sampled. Such units are composed of both fall and pyroclastic current deposits. The lowermost unit 1 is made up of a coarse pumice lapilli fall deposit underlying a pumice-rich, massive ignimbrite, grading upward into a paleosol. Small lenses or pockets of a primary grey ash embedded into the paleosol represent the unit 2. Unit 3 is a well stratified deposit composed of an alternation of fine to medium pumice lapilli fall beds and light grey ash beds containing few very fine pumice lapilli. The uppermost ash bed is darker, contains scoria juveniles and grades upward into a paleosol. Unit 4 is formed by a basal, fine pumice lapilli fall deposit underlying a light grey, massive ash bed. This unit directly underlies the Campanian Ignimbrite via interposition of a paleosol.
At Ciraccio, a complex sequence of seven pyroclastic units composed by an alternation of fall and pyroclastic current deposits crop out. From the base upward: unit 1 consists of a clast-supported, massive, poorly sorted fallout deposit, made up of pumiceous lapilli to ash and rare blackish to gray, lithic clasts. This deposit underlies a blackish/dark laminated deposits (unit 2) composed of an alternation of dense scoriaceous lapilli and ashy layers; the sequence grades upward into a paleosol. Unit 3 is a massive, slightly sorted, clast-supported fallout deposit, made up of coarse, angular and poorly vesicular pumices, dark, reddish and yellowish lithic clasts and obsidians; in the middle, the unit is characterized by an alternation of slightly laminated ashy layers. A thin paleosoil separates this unit from unit 4, that is a 10 cm thick fine to medium pumice lapilli fall bed. The unit 5, which overlies a thin paleosoil, is a 4.5 m thick massive, clast-

supported fallout deposit made up of pumice lapilli and bombs and reddish to yellowish lithic clasts. Towards the top, this unit contains a thin yellowish ashy layer that underlies a 70 cm thick coarse grained deposit made up of pumice lapilli with variable vesicularity degree and heterogeneous lithic clasts. Unit 6 is a 60 cm thick deposit formed by laminated ashy beds underlying a massive tuffaceous deposit. Unit 7 is a 1.8 m thick massive, clast-supported fall deposit made up of porphyritic pumice lapilli and blocks and heterogeneous lithic clasts; a 50 cm thick dark to yellowish, slightly laminar, ashy bed lies on top; this bed underlies a thin clast-supported reverse-graded fall deposit made up of pumice lapilli. The sequence underlies the deposits of the Breccia Museo, belonging to the Campanian Ignimbrite.

At Pozzo Vecchio, part of the same sequence outcrops: in particular, units 5 to 7 have been described and sampled. Moreover, here, a matrix-supported, massive, ashy to lapilli tuff deposit, made up of blocky to lapilli juvenile fragments, scoriaceous clasts, heterogeneous lithic clasts and syenites, rests on top of unit 7 and underlies the Campanian Ignimbrite.

Rocks sampled from the described sequences have been observed under microscope and fully characterized in terms of lithological components. Selected samples have been analyzed by acquiring major and minor elements composition on matrix-glass of pumice clasts, through EMPA. In this way, the deposits have been characterized detail. This allowed attributing some of them to specific Campi Flegrei and Ischia events preceding the CI and MEGT eruptions.

The correlation with volcanic products recognized in proximal and distal sites also provides a better reconstruction of the volcanism prior to the main caldera-forming explosive events of the Neapolitan area.

Geochemical and isotopic characterization of old (>39 ka) tephra from the Phlegraean Volcanic District outcropping at Capri island

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The Campania Plain (South Italy) has been the site of volcanism for at least 300 ka years. Nevertheless, most of the knowledge of the volcanism of this area is based on studies of events occurred in recent period, e.g., last 15 ka. Little is known about the volcanic activity preceding the Campanian Ignimbrite (CI; 39.85 ± 0.14 ka) eruption, the highest magnitude event occurred in the Campi Flegrei.
In the framework of the TIFHEO project, aiming at reconstruct the evolution of the magmatic feeding system of the high magnitude eruptions originated in the Campania Volcanic area, a field survey of volcanic units older than the CI was performed on Capri Island, which is one of the intermediate to distal area of dispersal of Campi Flegrei and Ischia volcanic products. For the first time, several volcanic units have been recovered in the northern sector of Capri and investigated for volcanological and geochemical features.
The exposed sequence includes primary volcanic and colluvial deposits, separated by paleosols and/or unconformity or erosional surfaces. Primary volcanic deposits are four pumice lapilli- and ash-fallout beds, variable in thickness from few cm to tens of cm. Juvenile fragments are light-grey, variably vesiculated to silky, subaphiric pumice with rare phenocrysts of sanidine, and dense glass fragments. Lithic content is variable and includes mainly dark lava fragments. The sequence is closed by a fifth fine-to-coarse ash deposit, laminated for contrasting grain-sizes, with embedded centimetric to subcentimetric pumice clasts, porphyritic with feldspar and pyroxene phenocrysts. This deposit overlies a reworked layer including archeological findings dated between the 4th century B.C and the Roman age, and is in turn overlaid by a very coarse talus breccia with carbonate clasts.
$^{40}Ar/^{39}Ar$ radiometric dating of unaltered sanidine phenocrysts from two of these units gave ages that allowed constraining the emplacement of the tephra between 51.8 ka and 40.08 ka. Samples belonging to all the units of the investigated stratigraphic sequence have been analyzed by acquiring the major and minor elements composition on glass from pumice clasts, through EMPA. Moreover, on the same samples, the $^{87}Sr/^{86}Sr$ isotopic composition of whole rocks and feldspars has been analyzed.
Age, chemical composition and Sr-isotopic ratios of the investigated products allowed to correlate these intermediate to distal tephra to proximal deposits that have been previously well characterized and attributed to volcanic activity pertaining to the post- Monte Epomeo Green Tuff eruption (56.0 ± 1.0 ka) at Ischia island and to pre-CI and CI at Campi Flegrei. The correlation is also supported by the chemical composition among the newly sampled products and those belonging to different outcrops and to a drilled core from the Campi Flegrei area. The uppermost ash-to-coarse ash layer, which lies above a historical reworked deposit, is still under examination and can be correlated with one of the eruptive events of the Phlegraean Volcanic District recent volcanic activity.
The recognition of the oldest tephra and the attribution to specific eruptions from Campi Flegrei and Ischia provides a better reconstruction of the eruptive history related to large explosive

events occurred in the Phlegraean Volcanic District and this knowledge will be useful for better understand the evolution of these complex magmatic systems prior to and following the formation and empting of large magma reservoirs.

S07 - TOWARDS A MULTIDISCIPLINARY APPROACH TO UNDERSTAND THE ORIGIN AND DYNAMICS OF PAROXYSMS AT BASALTIC VOLCANOES

Conveners:
Ida Di Carlo, Massimo Pompilio, Michel Pichavant, Nolwenn Le Gall

Volcanic gas constraints on the trigger mechanisms and incubation timescales of basaltic paroxysms

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Persistent open-vent activity at Etna and Stromboli volcanoes in Sicily is frequently interrupted by powerful paroxysmal events that range in style and size from sequences of lava fountaining episodes (at Etna) to short-lived but violent vulcanian blasts (at Stromboli). Interpretation of the causes the lead to such events is challenged by complex genetic processes and (at Stromboli) deep trigger. However, consensus has been reached on a central role played by the exsolved magmatic gas phase in acting as key eruption trigger. Here, we review volcanic gas time-series acquired at both Etna and Stromboli using permanent instrumental volcanic gas networks to demonstrate distinct paroxysm's trigger mechanisms and incubation timescales at the two volcanoes. On Mt. Etna, we use volcanic SO_2 flux observations derived from a permanent UV camera system to show that the paroxysmal sequences taking place at its South-East Crater (SEC) are preceded by clear acceleration in SO_2 degassing occurring over periods of months to weeks [Lo Bue Trisciuzzi et al., 2022, this volume]. From this, we propose that initiation of a paroxysmal sequence is triggered by progressive pressure build-up in a shallow (>3 km) reservoir, as caused by early (deep) degassing of a Low Porphiricity (LP) basaltic magma [Aiuppa et al., 2021, Sci. Adv.]. This accumulating foam would initially leak passively (for days/weeks) until a over-pressure threshold is reached, at which the LP magma+gas mixture is suddenly (in hours) erupted in a major explosion/paroxysm.

S07 - Oral Presentation

Pre-explosive ground deformations induced by normal Strombolian and paroxysmal activities at Stromboli volcano

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Eruptive activity of basaltic volcanoes is characterized by the persistent activity of intermittent mild explosions well-known as Strombolian eruptions. More violent explosive activity, paroxysms that occasionally interrupt the normal Strombolian activity, whose triggering mechanisms are still a matter of debate. In summer 2019, Stromboli volcano produced two paroxysmal events on 3 July and 28 August. Our ground deformation data recorded during these paroxysmal activities shows a similar inflation phase preceding each explosion [Ripepe et al., 2021]. The duration and amplitude of this inflation trend scale with the eruption magnitude, suggesting that common explosive dynamics obey the scale-invariant conduit process among normal, major and paroxysmal explosions [Ripepe et al., 2021]. However, the pressure source that generates ground deformations at Stromboli has not been well constrained, especially for normal activity, mainly because of its small amplitude (poor signal-to-noise ratio) and a limited number of instruments. Here, we report data analysis of the ground tilt network deployed within a close distance (~1 km) from the eruptive craters to estimate pressure sources responsible for normal explosions and paroxysm. We analyzed more than 800 events of ground tilt associated with the normal activity during July 2014 recorded by three temporary tilt stations and two permanent borehole tilt stations to investigate characteristics of pre-explosive inflation induced by the normal activity. We also analyzed pre-explosive inflation of the 3 July 2019 paroxysmal explosion recorded by one borehole tilt station and five seismic stations. We invert the pressure source using a finite element method code COMSOL Multiphysics 5.3a (https://www.comsol.com) for calculating theoretical ground tilts to include complex effects of the steep topography of the volcano. Independent inversions with a spherical source for each explosive type show that, in spite of the different intensities, both normal and paroxysmal explosions share a common pressurized source. We then jointed those data of normal and paroxysm to improve the constraints on the source. The joint inversion results using an ellipsoidal source show the optimal source with 100-150 m large located at ~300 m depth beneath the eruptive vent. The source is interpreted as a shallow magma chamber, or upper part of the conduit beneath the plug, filled with gas-poor, crystal-rich stagnant magma ejected during ordinary explosions and supported by a convective magma column [Metrich et al., 2001; Suckale et al., 2016]. We demonstrate that this source can also explain the ground deflation recorded during a flank effusive eruption on 5 August 2014, implying that the explosive and effusive dynamics involve the same shallow portion of the feeding system. The estimated pressure change of the source is well correlated with the volume of magma ejected during the explosive eruptions and effusive outflow.

S07 - Oral Presentation

The 19 July 2020 eruption at Stromboli: insights into the magmatic system feeding high-energy activity at an open-conduit basaltic volcano

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Stromboli is well-known for its periodic, ordinary activity that has been persistent for the past 1400-1800 years. On sporadic occasions however, Stromboli's ordinary activity is interrupted by more violent events that are characterised by higher erupted mass and energy and pose a threat to the island's population and tourists. Those eruptions involve the highest duration, mass and energy and are generally classified as paroxysms, with the most recent events that occurred in 2003, 2007 and 2019. Eruptions with characteristics intermediate between paroxysms and ordinary activity are commonly termed major explosions. While there is abundant literature discussing the mechanisms, dynamics and source regions that underlie both paroxysms and ordinary activity, these factors remain poorly constrained for major explosions. This is particularly crucial with regards to key parameters such as source region, dynamics that lead up to the eruption as well as the associated timescales, which constitute fundamental information when it comes to improving existing early-warning systems.
The 19 July 2020 eruption provides an excellent case study to discuss the processes that control major explosions and paroxysmal activity given that it was characterised by the emission of an important amount of juvenile products. Here we focus on the low porphyritic ejecta that represent the contribution of the deep magmatic component. We provide a detailed geochemical characterisation of melt inclusions, olivine crystals and matrix glass, which is subsequently integrated with data from the monitoring network. Major element data on melt inclusions and matrix glass is combined with olivine compositions to constrain magma source and ascent dynamics, suggesting that both differ from typical paroxysms. Water and carbon contents in melt inclusions and embayments are combined with sulphur and chlorine compositions and are used to estimate entrapment pressures, allowing to constrain the source region as well as the degassing history of the feeding magma. Furthermore, modelling of Fe-Mg diffusion in olivine zoning profiles provides time constraints that are coherent with observations from the degassing regime of the plume.
The integration of this geochemical-petrological dataset with observations from the monitoring network provides new insights into the source and ascent dynamics of the magma feeding major explosions at Stromboli and adds further understanding to the fundamental discussion on magma systems that feed paroxysmal activity at open-conduit basaltic volcanoes.

The 2019 basaltic Vulcanian eruptions of Stromboli

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Stromboli is an active, open conduit mafic volcano, whose persistent mild Strombolian activity associated with degassing at near-magmastatic conditions is occasionally punctuated by much stronger explosions, known as paroxysms, which instead involve the fast rise and eruption of deeper magma.
During summer 2019, the volcano unexpectedly produced one such paroxysm on July 3, followed by intense explosive and intermittent effusive activity culminating in a second paroxysm on August 28. In both cases, similar to previous paroxysms, deposits were made not only by high porphyritic magma (HP) commonly intepreted as the degassed and crysallised magma resident in the shallow conduit during the persistent strombolian activity, but also by low porphyritic magma (LP) commonly interpreted as the deeper magma which triggers the paroxysm.
As the term paroxysm is only qualitative and does not conform to any known codified volcanic style, we discuss criteria to describe deposit and eruption characteristics in order to better classify such strong and short lived explosions at Stromboli.
Visual observations and the analysis of the fall deposits associated with the two paroxysms allowed us to reconstruct ballistic exit velocities of up to 160 m/s. Plume heights of ~ 8.4 km and 6.4 km estimated for the two events correspond to mass eruption rates of 1.1×10^6 kg/s and 3.6×10^5 kg/s, respectively. This is certainly an underestimate as directional pyroclastic flows into which mass was partitioned immediately formed, triggering small tsunamis at the sea entrance. The mass of ballistic spatters and blocks erupted during the July 3 event formed a continuous cover at the summit of the volcano, with a mass calculated at ~ 1.4×10^8 kg.
The distribution of fall deposits of both the July 3 and August 28 events suggests that lapilli-sized pyroclasts characterized by terminal fall velocities 10–20 m/s remained fully suspended within the convective region of the plume and did not fall at distances closer than ca 1700 m to the vent.
Bubble size distribution and number density allows to constrain the decompression rates associated with the explosions and agree with the mass eruption rates estimated independently from plume heights.
Based on the impulsive, blast-like phenomenology of the eruptions, the mass eruption rates, as well as the deposit distribution and type, we propose to classify paroxysms at Stromboli as basaltic Vulcanian in style, and we discuss possible triggering and eruption mechanisms.

Precursors of paroxysmal activity at Stromboli volcano through machine learning applied to seismo-acoustic features

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Machine learning techniques can successfully contribute to geophysical data analysis focused on the definition of the state of activity of a volcano and the recognition of changes in its eruptive style. We applied machine learning to highlight changes in the persistent eruptive activity of Stromboli over a period containing the paroxysmal crises of 2019 [Giudicepietro et al., 2022, Remote Sens.].
Two paroxysmal explosions occurred in Stromboli on 3 July and 28 August 2019, the first of which caused the death of one person and some injuries. On 3 July an effusive activity also began from the summit of the volcano. A previous study [Giudicepietro et al., 2020, Sci. Rep.] highlighted medium-term seismic precursors of the paroxysmal activity. In particular, the authors defined the VLP size parameter, which had shown significant variations before the paroxysm of 3 July 2019. To investigate the causes of the variations of the VLP size before the paroxysmal crisis, here we applied an unsupervised machine learning technique to analyse the seismo-acoustic features of the persistent explosive activity of Stromboli.
We considered data over 10 months (15 November 2018–15 September 2019), including the paroxysms. We applied a Self-Organizing Map (SOM) clustering of the seismic and infrasonic features to group events generated in similar conditions. Then, to associate specific eruptive behaviours to the seismo-acoustic clusters, we compared the SOM analysis results with the images recorded by thermal and visible cameras, and with the ground displacement measurements obtained by Ground-Based Interferometric Synthetic Aperture Radar (GBInSAR) devices.
First, we selected a set of seismo-acoustic events produced by the ordinary Strombolian explosions. To avoid an unreasonable number of events in the dataset (typically Stromboli produces about 300 explosions per day), we selected one event for each half an hour, to form our dataset. In particular, to choose the most significant events, we selected the explosions that were characterised by the largest VLP signal each half an hour, to be sure that our analysis is applied to appropriate explosive activity samples. We obtained a dataset including about 14,300 selected seismo-acoustic events.
For the feature extraction phase, we adopted a new approach. An efficient feature extraction method for seismic and infrasonic data typically considers the spectral content and the waveform of the events (the characteristics that the analysts visually examine to classify seismograms, for example, to distinguish a local earthquake from a regional one or a teleseism). Often, spectrograms expressed in compressed form and waveform functions calculated on sliding windows are used to analyse events with impulsive onset. However, in this case, the signals of our interest are the VLPs (0.05–0.5 Hz), in which an impulsive onset cannot be recognized. Thus, we designed novel methods for seismic and infrasonic feature extraction, that are independent of the picking of a transient signal onset.

Once the signal preprocessing for feature extraction was done, we applied the SOM method. This analysis identified three main clusters, which we called Red, Blue, and Green. The three main clusters showed different occurrences with time indicating a clear change in Stromboli's eruptive style before the paroxysm of 3 July 2019. In particular, the cluster Blue became strictly dominant in the two months before the 3 July paroxysm.

Finally, we compared subsets of events belonging to the main clusters (Red, Blue, and Green) with the recordings of the fixed monitoring cameras and the GBInSAR measurements, and found that the clusters are associated with different types of Strombolian explosions and different deformation patterns of the summit area. In particular, we found that the cluster Blue was associated with gas explosions, with height in the range of 10–20 m and little or no ash and ballistic emission. These bursts may not be detected by the camera recordings and infrasonic signals, whereas they are evident in the VLP seismic signals (filtered in the 0.05–0.5 Hz frequency band). Therefore, we discovered that the paroxysmal phase of 2019 was preceded by a significant variation of the eruptive style, which was characterised by the prevalence of powerful gas explosions for at least two months before 3 July.

The results of the experiments we performed increase our ability to distinguish the different Strombolian mechanisms and suggest new opportunities to improve the monitoring of Stromboli (and other volcanoes) and early warning for paroxysms.

Team: Flora Giudicepietro, Sonia Calvari, Luca D'Auria, Federico Di Traglia, Giovanni Macedonio, Teresa Caputo, Walter De Cesare, Gaetana Ganci, Marcello Martini, Massimo Orazi, Rosario Peluso, Giovanni Scarpato, Laura Spina, Teresa Nolesini, Nicola Casagli, Anna Tramelli and Antonietta M. Esposito.

Paroxysmal explosive activity at Mt. Vesuvius during the 1906 and 1944 eruptions

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Paroxysmal volcanic eruptions periodically characterize the volcanic activity of open conduit volcanoes. In populated areas these violent explosions may be highly hazardous when they take place with little warning, if are not preceded by clear geophysical and geochemical signals.
Thus understanding why and how these paroxysmal explosions occur, remains one of the major challenges of volcanology. In fact the trigger for such sudden shifts in the eruptive regime has been generally attributed to various mechanisms (such as magma chamber and/or conduit processes; changes in vent geometry; magma/water interaction etc.), however it remains poorly understood for many eruptions.
Fundamental information on subsurface magma behavior and its influence on eruptive style can be obtained by the compositional and micro-textural studies on volcanic rocks. In this work, we investigate glass volatile contents and microlite textural characteristics to shed light on evolving conduit conditions and associated explosions during the 1906 and 1944 paroxysmal activity at Vesuvius volcano.
Both these eruptions were fed by mafic magmas and characterized by an initial mild effusive activity followed by an explosive phase that rapidly culminated in a paroxysmal explosion during which the eruptive column reached its maximum altitude and ash carried by the wind was deposited at long distances from the volcano.
In this study volcanic ash samples collected during the different phases of the 1906 and 1944 Vesuvius eruptions are analyzed in order to obtain information on the eruptive dynamics. Although the detailed mechanisms are poorly understood, changes in eruptive style during an eruptive cycle are considered to be related to variations in magma ascent rate, higher velocities being associated with more violent activity and arrival of magma from depth.
We found that in spite of the uniform composition of phenocrysts and groundmass glass, the analyzed volcanic samples show different textural characteristics in microlites, depending upon the stage of the eruption they belong to. Particularly, groundmass texture shows high crystallinity associated to larger prismatic microlites during the first phases of the eruption, while shifting toward low values of crystallinity and size of microlites that became progressively became also more skeletal.
These changes are due to the partial collapse of the deeper parts of the plumbing system as testified by the high abundance of lithic fragments (including also skarn, clinopyroxenites, dunite) observed in the corresponding volcanic deposits. This process caused a pressure drop at the top of the underlying magma chamber and then the fast extrusion of a larger volume of magma in a short time.
The obtained results are compared with the witnessed description of the volcanic activity at the time of ash sampling, to identify the correlation between geochemical and textural features and the eruptive dynamics. Thus the available numerous historical records and eye witness reportage allow us to evaluate the impact of these paroxysms on the environment as well as the relative human responses that can constitute important lessons to present day hazard managers.

S07 - Poster

Investigation of tiltmeters produced by different manufacturers

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Monitoring sudden unexpected violent eruptions such as basaltic paroxysms and phreatic eruptions is crucial to understanding the eruptive dynamics and forecasting volcanic eruptions. Ground deformation is generated by magma or fluid transportation beneath the surface and thus is useful for detecting the eruptive precursors [Maeda et al., 2017; Ripepe et al., 2021]. Because these eruptions are generally small and occur in a short time, ground deformation is detectable by highly sensitive instruments such as tiltmeter, strainmeter and seismometer, which generally show uncertain behaviour [Agnew, 1986]. Thus it is important to understand the response of instruments as a fundamental of monitoring. However, few studies compared the response of tiltmeters produced by different manufacturers [Anderson et al., 2010]. Here, we investigate the response of different tiltmeters to clarify their usability for capturing volcanic activity (normal Strombolian) and non-volcanic phenomena at Stromboli volcano.

Pinnacle 5000T tiltmeter with a nominal resolution of 1 nrad is deployed at a depth of 5.5 m at the station OHO, which is located at an elevation of 600 m and ~1 km SE from the craters. This station has been operative since 2007 and used for the Early Warning system for paroxysms [Ripepe et al., 2021] since 2019. The tilt record is smoothed by an internal Sallen-Key type analogue low-pass filter with a cut-off period of ~30 s. In February 2022, we installed two Jewell LILY borehole tiltmeters with a nominal resolution of 5 nrad and an internal magnetic compass. One is OHS, 4 m-depth borehole at ~20 m apart from OHO. The other is installed at LHR, 6m-depth borehole at ~1.3 km ENE from the craters. Both instruments record X-tilt, Y-tilt, temperature and voltage. All tilt data is sampled at 1 sps and stored on a web server in real-time.

We analyzed data from February to May 2022 and concluded that all the instruments were operated correctly. Because raw tilt signals and their frequency spectra show more low-passed response of Pinnacle than LILY, we apply a digital low-pass filter equivalent to the analogue filter in Pinnacle to LILY to equalize their response. Filtered LILY and raw Pinnacle instruments appear to be coherent for diurnal tilt induced by tides and thermal stress of the ground [Bonaccorso et al., 1999], but the signal-to-noise ratio of LILY is still worse than Pinnacle. We used several teleseismic surface waves with a dominant period of 20-30 s to check the tiltmeter's response and orientation in the east-north coordinate. Comparison of the inflation-deflation tilt cycles associated with normal explosions [Genco and Ripepe, 2010] between co-located Pinnacle (OHO) and filtered LILY (OHS) instruments shows that the seismic VLP (Very-Long-Period) signal is visible in LILY. However, gradual inflation ~200 s before an explosive onset with ~10 nrad is not visible due to its poor signal-to-noise ratio. We also found that the two different instruments respond to seismic shakings differently. Because the signal-to-noise ratio of LILY is worse in the broad frequency range, we conclude that the sensitivity of LILY is lower than that of Pinnacle, which masks tiny signals in a short period. Therefore, we suggest that Pinnacle is more favourable to be used for monitoring small (~nrad) and short-term (~minutes) eruptive activity because of its higher sensitivity.

As an alternative way to monitoring ground deformation, we designed a real-time derivation system of tilt from a seismic signal with four infinite impulse response (IIR) filters: decimation from 100 sps to 1 sps by averaging over 1 s; high-pass filtering of 3 h to remove accumulative drift due to integration and diurnal cycle; trapezoidal integration and magnification to convert velocity to tilt; low-pass filtering by the digital Sallen-Key filter. We validate the filter's performance using our seismic stations equipped with Güralp CMG-40T broadband seismometer with a natural period of 30 s deployed at ~30 cm depth. The noise level of the seismic-derived tilt is comparable to the amplitude of the inflation-deflation cycles, which consequently indicates smaller signal-to-noise than the borehole tiltmeter OHO. The filter well reproduces the ground inflation before the 3 July 2019 paroxysm reported in Ripepe et al. [2021]. Real-time running of the filter generally returns tilt signals with ~20 s delay from the actual clock. We suggest that real-time conversion of seismic-derived tilt may be a possible option for monitoring ground deformation because of its lower installation cost.

Investigating major and ordinary Strombolian eruptions via distributed acoustic sensing with fibre optics

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Distributed Acoustic Sensing (DAS) is a relatively novel and emerging technology to record seismic waves by means of the optical properties of light pulses propagating through fibre-optic cables. Tens of kilometers of fibres can be turned into a dense (meter-scale) network of single-component seismometers sensitive to the axial strain (or strain-rate), enabling the high-resolution reconstruction of the strain along the cable both in time and space. During the last decades DAS technology has spread widely in several geophysical fields of application from the oil-and-gas industry up to near-surface seismic surveys [Dou et al., 2017], earthquake seismology [Jousset et al., 2018] and volcanic monitoring [Nishimura et al. 2021] to name a few, and its usage in seismic monitoring is believed to become essential in forthcoming seismic networks [Fernandez-Ruiz et al., 2020].

During 2020 and 2021 we deployed a total of 3 km of fibre-optic cable in a 30 cm-deep trench along the northeast side of Stromboli volcano, with the objective to test DAS capability as a new monitoring tool in volcanic environments. Together with the fibre-optic, an array of high-frequency and broadband three-components seismometers was deployed as well. Both DAS and seismometers were active simultaneously for more than one month. DAS clearly recorded the seismic signals generated by the persistent explosive activity (together with volcanic tremor). On 06/10/2021 at 14:UTC a so-called Major Explosion was recorded as well.

We performed a benchmark comparison between the two different measurements. We applied a finite-difference relationship [Wang et al., 2018] for converting the particle-velocity as recorded by the inertial seismometers into strain-rate, observing a perfect agreement in phase and a good agreement in amplitude if compared with DAS strain-rate signals recorded at co-located channels along the fibre. This similarity is valid for signals associated with the volcanic tremor, the ordinary explosive eruptions and the Major Explosion. Analogue results were also obtained after converting DAS data into particle-velocity via three different methods: (1) F-K rescaling [Lindsey et al., 2020], (2) wavenumber-domain integration and (3) spatial-domain integration.

We evaluated the integration of DAS within the pre-existing monitoring network of the Laboratory of Experimental Geophysics (Università degli Studi di Firenze - Dipartimento di Scienze della Terra - Italy), i.e. with broadband seismomenters, tiltmeters and infrasonic sensors, in order to better comprehend the nature of DAS measurement and to investigate for strain precursors of violent explosions occurring at Stromboli.

S07 - Poster

S08 - NEW PERSPECTIVES IN DECIPHERING MANTLE GEOCHEMICAL, MINERALOGICAL AND SEISMIC HETEROGENEITIES

Conveners:
Antonio Caracausi, Jabrane Labidi, Giulia Marras, Vincenzo Stagno

New Inferences on Magma Dynamics in Melilitite-Carbonatite Volcanoes: the Case Study of Mt. Vulture (Southern Italy)

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This study provides the first micro-thermometric data of fluid inclusions in mafic loose (disaggregated) xenocrysts and ultramafic xenoliths in explosive products of the melilitite-carbonatite Mt. Vulture volcano (southern Italy). We found within ultramafic xenoliths pure CO_2 fluid inclusions hosted by olivine and clinopyroxene (Cr-diopside) with trapping pressures between 8.5 and 8.9 kbar, corresponding to a depth of 26-27 km, in proximity of the local crust-mantle boundary. In contrast, trapping pressures within the loose xenocrysts are up to 2.8 and 3.2 kbar (8-9 km). We estimated an ascent rate of the latest 141 ka old melilititic-carbonatitic magmas from the Moho depth to the surface in the range of few hours. Considering the ongoing degassing of mantle-derived CO_2 rich gases at Mt. Vulture, together with seismic evidences of the presence of low amount of melts at depth, and the tectonic control of the past volcanic activity, our study opens new perspective about the hazardous nature of the "quiescent" melilitite-carbonatite volcanoes.

S08 - Oral Presentation

The nature of the lithospheric mantle under La Palma (Canary Islands): New data on noble gases and CO_2 isotopes from the 2021 Cumbre Vieja eruption

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The 2021 eruption of the Cumbre Vieja volcano (La Palma Island) is a unique opportunity to investigate the volcanic phenomenon and the nature of the Earth's interior. In fact, many approaches have been tried in the island (seismology, gas and bulk-rock geochemistry, petrography, petrology and fluid inclusion studies) to determine the origin and the evolution of the actual volcanism. In view of the occasion, we collected samples of lavas and ultramafic xenoliths from different localities along La Palma (including the Cumbre Vieja volcano) with the aim of investigating the isotopic composition of noble gas and CO_2 in fluid inclusions and their relationship with the nature and evolution of the local mantle source. Our samples include a) lavas from the 2021 Cumbre Vieja eruption, b) lavas from 1677 San Antonio eruption (south of Cumbre Vieja), C) ultramafic xenoliths hosted in San Antonio lavas, and d) a 3 Ma old picrite erupted in the Taburiente caldera.
Studies previously published in the literature suggest that the volcanism observed in the Canary Islands is fed by a spatially heterogeneous mantle with a multiplicity of involved components: mantle plume, MORB-like mantle, recycled oceanic crust/lithosphere (HIMU) and an enriched mantle (EM). Through the study of stable isotopes (particularly noble gases) the mantle plume component (3He/4He > 9 Ra) has been only observed in the Dos Aguas geothermal field and in some lavas from the Taburiente caldera (northern La Palma; Pérez et al., 1994; Day et al., 2010; Day and Hilton, 2020); conversely, in the southern portion of La Palma (where the Cumbre Vieja volcano is located) both fluid inclusion and bubbling gas data indicate MORB-like signatures (3He/4He = 8 ± 1 Ra; Hilton et al., 2000; Gurenko et al., 2006; Day and Hilton, 2011).
Our preliminary results confirm the existence of a lower mantle component in the Taburiente picrites (3He/4He = 9.4±0.1 Ra) which agrees with the helium ratios previously measured in the Dos Aguas spring. On the other hand, MORB-like signatures were identified in the 2021 and San Antonio systems with 3He/4He values that vary between 7 and 7.5 Ra. In the case of ultramafic xenoliths, helium ratios vary between 6.5 and 7.2Ra and likely reflect an older and slightly more radiogenic mantle. The isotopic dichotomy between the Taburiente and San Antonio/Cumbre Vieja lavas is evident and may be explained by two different hypotheses: (i) the differences in Rc/Ra ratios indicate the existence of small-scale heterogeneities in the local mantle and/or (ii) the lower helium ratios observed in the Cumbre Vieja and San Antonio lavas are a result of a plumbing system processes, for instance, magma differentiation and degassing at the crust-mantle boundary or even deeper in the mantle, coupled to the production and accumulation of radiogenic 4He.

S08 - Oral Presentation

Multi-stage oxidizing events recorded by peridotite mantle xenoliths from the Hyblean Plateau: evidence from combined measurements of $Fe3^{+}$ in spinel, noble gases, and fluid inclusions composition

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Mantle xenoliths are powerful tools to investigate the redox state (i.e., the oxygen fugacity, fo_2) of Earth's mantle, a key variable that controls many processes occurring in depth like partial melting, metasomatism and deep volatiles cycle (C, H, O, N and S). At fo_2 conditions registered from spinel-peridotites distributed worldwide (from -2 to 0.5 log unit normalized to FMQ buffer), the available thermodynamic models predict CO_2 and H_2O as the main stable fluid, that can either exsolve or affect the melting temperature of the surrounding mantle. Direct evidence of volatile circulation in depth comes from fluid inclusions in silicate minerals like olivine, where the retained noble gasses (He, Ar, Ne) can give information about the signature of their source. This study aims to reconstruct the origin and the onset of the metasomatism of the mantle underneath the Hyblean Plateau (Sicily), investigating spinel-peridotites xenoliths through a multidisciplinary approach which included thermodynamic fo_2 estimation, chemical characterization of inclusions in olivine and noble gases signature.
We selected two harzburgites and five lherzolites sampled from the Miocene Hyblean tuff-breccia pipe of Valle Guffari (Sicily). Chemical and textural analysis were conducted by EMPA and SEM, $Fe3^{+}$/Fe(tot) ratio in spinel was measured by both in situ synchrotron (beamline ID8, ESRF, Grenoble) and conventional ^{57}Fe Mössbauer spectroscopy (Sapienza University, Rome). Inclusions in olivine were chemically characterized through micro-Raman (Milano-Bicocca University, Milano), while OH- bands were mapped by regular grids across olivine crystals (including inclusion trail regions) through micro-FTIR (beamline SISSI beamline, Elettra sincrotrone, Trieste). Noble gases isotopes (He, Ar, Ne) were analyzed on unaltered olivine grains by single-step in-vacuo crushing coupled with mass spectrometry (INGV, Palermo).
Pressure and temperature of equilibrium (0.9-1.2 GPa and 950-1050 °C, respectively) [Perinelli et al. 2008] along with the Fe^{3+}/Fe(tot) ratio in spinel (0.27-0.35) and chemical composition of spinel, olivine and orthopyroxene were used for fo_2 estimates according to Ballhaus et al. (1991) oxy-thermobarometer. Hyblean spinel-peridotites registered a fo_2 ranging between 0.8 and 1.7 log units (FMQ), higher than worldwide xenoliths, falling in the stability field of C-O-H fluids. The samples exhibit textural evidence of interstitial glass veins and olivines with dendritic trails of (metasomatic) melt and fluid inclusions. The micro-Raman analyses on inclusions show association of Mg-Ca carbonates ± sulfide ± sulfur ± CO_2 for the most reduced sample and Mg-Ca carbonates ± sulfates ± CO_2 for the most oxidized, associated with silicate glass, attributable to a CO_2-S-bearing silicate melt that experienced fractional crystallization and volatile exsolution upon decompression/cooling. The micro-FTIR mapping evidenced the presence of OH^- groups relative to hydration reactions occurred between H_2O in the fluid inclusion and the surrounding

olivine. The He, Ar, and Ne systematics reflect mixing with a recycled atmospheric component. The $^3He/^4He$ ratios, in particular, vary between 7.04 and 7.28 Ra, below the MORB range, attributable, following a previous study [Correale et al. 2012], to a HIMU-type mantle source.
The results of this study suggest the occurrence of multiple metasomatic events in the Hyblean lithospheric mantle, likely resulting in the onset of an oxidation-driven melting and consequent formation of a volatile-bearing (C, S, O, H) melt/fluid recorded as glass microveins.

Application of synchrotron micro-Mössbauer and micro-FTIR spectroscopy to analyze redox-driven processes recorded by mineral and melt inclusions

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The redox state of Earth's interior plays a fundamental role in petrological processes including magma genesis, metasomatism and deep volatiles cycle. To date, the redox state of the Earth's upper mantle has been constrained by studying mantle xenoliths (i.e., peridotites and eclogites) based on the relationship between Fe^{3+}/Fe(tot) ratios measurements of redox-sensitive minerals (i.e., spinel and garnet) through conventional and milliprobe Mössbauer spectroscopy [McCammon, 2004; Frost and McCammon, 2008]. However, due to the limited spatial resolution of these apparatus (> about 200 μm), the oxidation state of micrometric minerals as well as the role that interacting fluids might have on mineral redox equilibria can be difficult to address. A great improvement to the knowledge of the mantle redox state is represented by synchrotron Mössbauer spectroscopy (SMS) at beamline ID18 of the European Synchrotron Radiation Facility (ESRF, Grenoble) [Potapkin et al., 2012], where the spot area of about 3 x 8 μm^2 allows challenging micrometer-scale investigation of Fe^{3+}/Fe(tot) ratio in minerals.
Interestingly, redox of mantle rocks was shown to correlate positively with the amount of water that nominally anhydrous minerals (NAMs) like olivine can incorporate [Peslier et al., 2010]. For this, it is essential to combine data from the redox state of peridotitic rocks with OH^- bands quantification in olivine.
SISSI-Materials beamline of Elettra sincrotrone (Trieste) is equipped with a FTIR spectrometer coupled to collimated infrared radiation produced by the synchrotron light. This kind of set-up provides a high spatial resolution, aperture of 20 μm and excellent signal/noise ratio, impossible to be developed with a laboratory FTIR spectrometer, allowing to perform transects and grids to detect OH^- bands absorption through minerals. These measurements can help to clarify the mechanism of H_2O incorporation into the crystal structure as function of the redox state.
This procedure, e.g., the combination of micro-Mössbauer and micro-FTIR spectroscopy at synchrotron, was recently applied to spinel-peridotites from Vulture (Italy), where spinel crystals of about 10 μm are trapped in olivine crystals. Some preliminary results will be shown that combined analyses of Fe^{3+} in trapped spinel with thermodynamic predictions of the Fe^{3+} content expected at a given P-T-fo_2. The obtained data will be used to assess the possible local redox state of mantle and model the speciation of volatiles.

Nature of metasomatic agents in the mantle wedge beneath the Imbabura-Cubilche volcanic complexes, Northern Ecuador

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Diverse slab-mantle-crust processes control the generation of the Ecuadorian magmatism, as evidenced in geochemical models of the literature. Here we summarize new findings at Imbabura and Cubilche, two close volcanic complexes in Northern Ecuador, using new and earlier data.
The dataset comprises 90 analyses of major and trace elements (from Navarrete et al. 2020, and references therein), which reveal medium-K andesitic-dacitic (56.6 - 66.0 wt% SiO_2) magmatic suites at both complexes. Major and trace element systematics suggest shared reservoirs and/or plumbing systems beneath both complexes, consistent with contemporaneous activity in Late Pleistocene times and local tectonic context. Various petrogenetic models (Sr/Y vs Y, La/Yb vs Sr/Y, (La/Yb)N vs (Yb)N and Yb ppm vs SiO_2 wt%) were used to examine the calc-alkaline vs adakitic signatures of Old and Young Imbabura and Cubilche. Early lavas of the debris avalanche deposits from Old Imbabura gradually approaches the adakite field, whereas Cubilche and Young Imbabura products have clear adakitic affinity (i.g high Sr/Y, (La/Yb)N, Th/Nb and Th/La).
By selecting the less evolved lavas of Old Imbabura and Cubilche (high-Mg#: 52.0 - 60.1 and 4.0 - 5.7 wt% MgO), we exclude major crustal contributions in magma geneses and discriminate slab components that are incorporated into the mantle wedge. We compared the latter parameters in our Imbabura-Cubilche dataset to partition ratios of Ba/Th and Sr/Th vs (La/Yb)N and La/Nb vs Sr/Nb that identify two different slab components. First melt is characterized by a stronger "fluid" signature enriched in fluid-mobile trace elements (e.g., Ba/La: 45.6 - 91.8) and low contents in fluid-immobile (La/Nb: 1.9 - 3.5 and Th/Nb: up to 0.8) observed in Old Imbabura and Cubilche. Second is rich in fluid-immobile elements contents (La/Nb: 3.5 - 7.0 and Th/Nb: up to 2.8) and shows low fluid-mobile trace elements (e.g., Ba/La: 34.0 - 50.0) from Young Imbabura volcano.
These results indicate that Imbabura-Cubilche Volcanic Complexes rocks have a marked adakitic character: a mantle wedge metasomatized by a slab-derived aqueous fluid (Ba/Th >200) produced magmas that fed Old Imbabura and Cubilche, whereas Young Imbabura magmas are related to partial melting of a hydrous siliceous melts metasomatized mantle wedge.

S08 - Poster

The December 2018 eruption of Mt Etna: a geochemical study of melt inclusions

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The eruption of 24-27 December 2018 at Mt. Etna resulted from the intrusion of a N-S deep dike which splitted the entire volcano edifice and extended upward forming a smaller dike that emerged at the surface through two NW–SE fissures. The eruption, after an initial stage with lava fountains and ash clouds from the uppermost eruptive fissure, proceeded with quiet lava effusion within the Valle del Bove. Noteworthy, despite the low duration and the small lava volume, the 2018 eruption was associated to a very strong seismic swarm in terms of number of events and their energy.

With the objective to characterize the deep magma that fed this flank eruption, we focus the present study on the petrographic and geochemical characteristics of selected melt inclusions (MI) enclosed in olivines separated from representative lapilli produced during lava fountaining of the initial stage.

The studied rocks have a phenocrysts content (ol, cpx and plg)?30%. The minerochemical analyses allow the identification of two extremes end members:

- a primitive one is featured by phenocrysts Fo78, whose MI show SiO_2 =45.62 wt %, MgO=5.49 wt% and CaO/Al_2O_3=0.72
- an evolved one is characterized by phenocrysts Fo74 hosting MI with SiO_2=52.73 wt%, MgO=4.04 wt% and CaO/Al_2O_3= 0.34

Major and trace element content of MI show a clear affinity with the compositional features of recent eruptions (1997-2013), and in particular with 2001 and 2002-03 eruptions. Trace elements patterns present a typical enrichment in LILE and LREE, depletion in HFSE and relatively fractionated REE patterns: (La/Lu)N= 12.4 - 42.3, with positive anomalies in Sr (Sr/Sr*= 4.12 - 8.11) and Ba that could be due to assimilation of plagioclase-rich mushes/cumulates by the magma stored into the magmatic reservoir.

The 2018 MIs variability of the Ba/La (9.3 - 15.5), K/Nb (124 - 849), Ce/Nb (1.98-3.39), Rb/La (0.37-1.16) and Ba/Nb (10.87-25.64) ratios allowed to identify a mixing between two different magmas comparable to those emitted during (i) the 2001 Upper Vents and 2002 NF (Type-1) and (ii) the 2001 Lower Vents and 2002 SF (Type-2) eruptions, respectively. Also, the first type is compatible with a HIMU-MORB type heterogeneous source that partially modified its trace element composition during the time due to crystallization, whereas the second one represents a magma that suffered the influence of a crustal component and a partial assimilation of plagioclase into a shallow region of the plumbing system.

The helium isotopic ratio ($^3He/^4He$) from fluid inclusions entrapped into olivine phenocrysts shows a variability ranging between 6.5 and 6.6 Ra, which perfectly matches literature Etnean dataset and allows to hypothesize the influence of a bland crustal contamination.

Our results support a scenario where, some months before the 24 December eruption, a more primitive magma with an HIMU-MORB marker rose from depth into the shallower reservoir, then evolved by crystallization and mixed with the residing magma, this latter featured by a more marked crustal signature. During the above past months, the two magmas rested long enough into the reservoir to mix widely their fluid content but not that of trace elements, which partially keep track of their geochemical differences. Thus, the 2018 olivine-hosted MI appear to have captured two different magma batches whose lack of complete homogenization may imply a very fast ascent.

Geochemical and isotopic constraints for mantle heterogeneity feeding the recent magmatic activity of the Dilo-Dukana and Mega volcanic fields (Ririba rift, southern Ethiopian Rift)

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The involvement of different mantle domains in the genesis of mafic magmas in the Ethiopian Rift represents a common, critical process driving the evolution of magmatism through space and time, even at small scale, generating a large variability of the erupted products.
The Ririba rift is a specific transect of the Ethiopian Rift at the southern termination of the Main Ethiopian Rift and formed from the southward propagation of this latter during, or shortly after, the emplacement of subalkaline basalts that produced a widespread basaltic lava basement, at ~3.7 Ma. The rift-related activity was short-lived and ceased between 2.8 and 2.3 Ma, when deformation migrated westward into an oblique, throughgoing rift zone directly connecting the Ethiopian and Kenyan rifts. Rifting was then followed by the eruption of limited volumes of Late Pleistocene-Holocene alkaline basalts, associated to several, monogenetic volcanic centers, forming the Dilo-Dukana and Mega volcanic fields.
We provide new petrological, geochemical and isotopic data on the still poorly studied magmatic products emplaced by the volcanic activity of the Ririba rift with the aim to investigate the source, and its possible variation, of both the older Pliocene lava basement and the Late Pleistocene-Holocene alkaline basalts.
Major and trace elements well discriminate the Pliocene lavas from the other younger alkaline products, and show that the Dilo-Dukana and Mega samples always overlap in composition. On the whole the studied products display variable major and trace element contents compared to a limited variation in silica (43-46wt %) describing slightly defined trends. Regular and evident trends are instead observed comparing some incompatible trace elements (e.g., Rb, Ba, Zr, Nb) suggesting a prominent role of fractional crystallization in their differentiation.
Sr-Nd and Pb isotope results reveal that the products erupted in the two younger volcanic fields have quite homogeneous compositions and are well distinct from the older Pliocene basaltic lavas (as well as with respect to all the older magmatic rocks of the area).
This corroborates the evidence that the younger Dilo-Dukana and Mega products are well distinct from the Pliocene activity, and are characterized by a more prominent mantle-plume signature testifying that during time a different mantle domain is involved in the magma genesis.
In detail, among the younger products, isotopes display interesting slightly different behavior: the Dilo-Dukana products are isotopically more homogeneous whereas the Mega lavas and pyroclastics display a small but wider variability partially overlapping the Dilo-Dukana samples pointing to the occurrence of other minor processes.
Our results also indicates that the two young volcanic fields of Dilo-Dukana and Mega are fed by deep structures directly transferring mantle melts up to the surface, as also suggested by the large abundance of mantle xenoliths in the different products. This is directly linked to the hypothesis that the two volcanic fields are not related to the major faults of the Ririba rift, but are associated to different, deep, NE-SW-trending inherited structures which cut the roughly N-S boundary faults of the rift.

08 - Poster

S09 - VOLCANO-HYDROTHERMAL SYSTEMS AND RELATED HAZARDS: MULTI-DISCIPLINARY APPROACHES

Conveners:
Franco Tassi, Manfredi Longo, Dmitri Rouwet

Hydrogeochemistry of the Turrialba and Irazú "twin volcanoes", Costa Rica

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This study presents the first hydrogeochemical model of the hydrothermal systems of Turrialba and Irazú volcanoes in central Costa Rica, manifested as thermal springs, summit crater lakes, and fumarolic degassing at both volcanoes. Our period of observations (2007-2012) coincides with the pre- and early syn-phreatic eruption stages of Turrialba volcano that resumed volcanic unrest since 2004, after almost 140 years of quiescence. Peculiarly, the generally stable Irazú crater lake dropped its level during this reawakening of Turrialba. The isotopic composition of discharged fluids confirms their Caribbean meteoric origin. Four groups of thermal springs drain the northern flanks of Turrialba and Irazú "twin volcanoes" into two main rivers. Río Sucio (i.e. "dirty river") is a major rock remover on the North flank of Irazú, mainly fed by the San Cayetano spring group. Instead, one group of thermal springs discharges towards the south of Irazú. All thermal spring waters are of SO4-type (i.e. steam heated waters), none of the springs has, however, a common hydrothermal end-member. A water mass budget for thermal springs results in an estimated total output flux of 187 ± 37 L/s, with 100 ± 20 L/s accounted for by the acidic San Cayetano springs. Thermal energy release is estimated at 110 ± 22 MW (83.9 ± 16.8 MW by San Cayetano), whereas the total rock mass removal rate by chemical leaching is ~3,000 m^3/y (~2,400 m^3/y by San Cayetano-Río Sucio). Despite Irazú being the less active volcano during the past decades, it is a highly efficient rock remover, which, on the long term can have effects on the stability of the volcanic edifice with potentially hazardous consequences (e.g. flank collapse, landslides, phreatic eruptions). Moreover, the vapor output flux from the Turrialba fumaroles after the onset of phreatic eruptions on 5 January 2010 showed an increase of at least ~260 L/s above pre-eruptive background fumarolic vapor fluxes. This extra vapor loss implies that the drying of the summit hydrothermal system of Turrialba could tap deeper than previously thought, and could explain the coincidental disappearance of Irazú's crater lake in April 2010.

Mount Etna volcanic emissions signature on the chemical composition of bulk atmospheric deposition in Sicily, Italy

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Mt. Etna, on the eastern coast of Sicily (Italy), is one of the most active and most intensely monitored volcanoes on the Earth, widely recognized as a big source of volcanic gases, such as CO_2, SO_2, halogens, and many trace elements, including TCEs, to the atmosphere on a regional and global scale. Mt. Etna emissions account for a significant percentage with respect to the worldwide average volcanic budget and especially during eruptive periods, its products can be dispersed over great distances and influence the chemical composition of the atmosphere of even other continents. The current knowledge about the geochemical cycle of TCEs is still scarce, nevertheless, recent studies [Brugnone et al., 2020], evidenced a contribution from the volcanic activity for some of them (Te, Tl, and REE). Here we report the concentration values of volcanic gases and halogens, i.e., SO_4^{2-}, Cl^-, and F^-, and of TCEs, i.e., Te, and Tl, highly volatile elements typically enriched in volcanic emissions, in the bulk deposition samples acquired, on monthly basis, during three different research projects: (1) S.E.W., from July 2017 to July 2018; (2) CISAS, from June 2018 to June 2019; (3) H.E.A.V.E.N., started in March 2021 and still ongoing. All the collected samples were analysed for major ion contents and many trace elements by IC, ICP-OES, and ICP-MS. During the S.E.W. project, atmospheric bulk deposition samples were acquired through the installation of 3 bulk collectors, which were located on the eastern slope of Etna, i.e., the slope toward which the volcanic emissions are usually dispersed by the prevalent regional winds. During this period, Etna had shown ordinary outgassing activity, without the occurrence of eruptions with lava or ash emissions. Volume-weighted-mean concentrations of SO_4^{2-} equal to 3.37 mg L^{-1}, Cl^- equal to 6.87 mg L^{-1}, and F^- equal to 0.48 mg L^{-1}, with concentrations up to 12.74 mg L^{-1}, 44.80 mg L^{-1}, and 2.55 mg L^{-1}, were respectively measured. High concentrations of Te and Tl were measured especially near the central craters, at Citelli sampling sites, with VWM concentration of 0.012 μg L^{-1} and up to 0.129 μg L^{-1} for Te and VWM concentration of 0.122 μg L^{-1} and up to 0.978 μg L^{-1} for Tl. During the CISAS project, atmospheric bulk depositions were collected through a network of 11 bulk collectors, which were installed in the area of Siracusa, a town on the east coast of Sicily, about 80 km SSE of Mt. Etna, and in Milazzo, a town on the northern coast of Sicily. Between 24-30 December 2018, a major eruption of Etna occurred, characterized by lava fountains and ash emissions. The samples collected in the study area of Siracusa during the period straddling the eruptive event were characterized by high concentrations of SO_4^{2-} (up to 6.68 mg L^{-1}), Cl^- (up to 19.00 mg L^{-1}), and F^- (up to 0.88 mg L^{-1}). In the same samples, the maximum concentrations were 0.025 μg L^{-1} and 0.164 μg L^{-1} for Te and Tl, respectively, showing values one order of magnitude higher than the median concentrations measured in the samples of the other monitoring campaigns carried out in the same study area. The study area of Milazzo, due to the prevailing winds from the North direction during the period of the eruption, has not been affected by the volcanic plume, and therefore the signature of the eruption is not visible in the samples collected in that area. From March 2021 atmospheric bulk deposition samples were collected through a network of 10 bulk collectors, which were installed on Mt. Etna, at various distances from the summit craters and on different slopes of the volcano, near the city of Catania, in the Siracusa area and near the village of Cesarò, in the Nebrodi Natural Regional Park. Mt Etna experienced two long sequences of 53 short-living lava fountain episodes between December 2020 and March 2021 and April to October 2021. Other episodes occurred more recently, between February and May 2022. Volcanic emissions associated with these paroxysmal events have been dispersed over great distances, even reaching other continents (e.g., East Asia), and have been important contributors to the chemical composition of atmospheric deposition at all monitoring sites during the first year of the research. VWM concentrations of 3.26 mg L^{-1} (up to 189.60 mg L^{-1}), 5.78 mg L^{-1} (up to 244.60 mg L^{-1}), and 0.43 mg L^{-1} (up to 40.66 mg L^{-1}) were recorded for SO_4^{2-}, Cl^-, and F^-, respectively. High concentrations of Te and Tl were also recorded, especially at sites closer to the central craters of Mt. Etna, with VWM concentrations of 0.018 μg L^{-1} and 0.121 μg L^{-1} and values up to 0.369 μg L^{-1} and 2.101 μg L^{-1}, respectively. In conclusion, close to active volcanic areas, but also at considerable distances from the vents, especially during high-magnitude eruption events, volcanic emissions must be considered among the major contributors to the chemistry of the atmospheric bulk deposition.

The key-role of submarine calderas in the development of hydrothermal systems: new findings from Palinuro and Brothers seamounts

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Seafloor hydrothermal vents are arguably the most intriguing and fascinating geological features investigated by scientists studying the deep oceans over the last four decades. Understanding these systems has important implications from a biological, geological and volcanological perspective, and may provide important insights into metallogenic processes. Calderas are morphological depressions resulting from the collapse of a magma chamber following large eruptions and are commonly found in subduction-related tectono-magmatic regimes, such as arc and back-arc settings. These volcanic-related structures represent important environments for the formation of many hydrothermal ore deposits, such as porphyry copper, epithermal, polymetallic vein and massive sulphides.

In this study, we compare the magnetic models of two hydrothermal systems associated with submarine calderas from different geologic settings. These two case studies are: the Palinuro Volcanic System, located in the Southern Tyrrhenian Sea, SW of Italy, and the well-constrained example of Brothers volcano, located along the Kermadec arc, NE of New Zealand. These volcanoes occur in different geodynamic settings but show similarities in the development of their hydrothermal systems, both of which are hosted within calderas. We present a new integrated model based on morphological, geological and magnetic data for the Palinuro caldera, and we compare this with the well-established model of Brothers caldera, highlighting the differences and common features in the geophysical expressions of both hydrothermal systems. We build a model of demagnetised areas associated with hydrothermal alteration derived from 3D inversion of magnetic data. Both these models for Brothers and Palinuro show that hydrothermal up-flow zones are strongly controlled by caldera structures which provide large-scale permeability pathways, favouring circulation of the hydrothermal fluids at depth.

S09 - Oral Presentation

Geochemistry of REE and trace elements in shallow hydrothermal vents at Panarea island (Italy)

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Exploration of Shallow hydrothermal Vents (SHVs) is usually focused on analysis of major chemical species while contents of trace and Rare Earth Elements (REE; lanthanides and yttrium) play an important role as tracers both of natural and anthropic geochemical processes.
Here we show some recent progresses concerning the study of trace elements and REE geochemistry in natural system focusing on their geochemical behavior in SHVs (shallow sea-water hydrothermal vents) in the surrounding area of Panarea Island (Eolian Island, Italy).
Samples were collected from several submerged vents at different depth (5-40m) and analyzed for Al, V, Cr, Mn, Fe, Co, Ni, Zn, As, Cd, Sb, Ba, Pb, Th, U and REE in a temporal range going from June 2015 to October 2021. All concentrations were measured by ICP-MS after triethylamine-assisted $Mg(OH)_2$ preconcentration-coprecipitation method [Arslan et al., 2017].
Physical-chemical parameters in discharged volcanic fluids span in a wide range of values: pH 2.7 - 8.2 and -235 - 186 mV for pH and Eh respectively; this great variability in pH and Eh values is responsible of the variations in concentrations of Fe, Al, Mn and Σ REE (total REE concentration) as an inverse correlation in observed between pH and Fe-Al-Mn and between pH and Σ REE.
ΣREE concentrations are also characterized by great variability, spanning from 19.1 to 24696.6 ng l^{-1}, the maximum value of which is higher than the reference value of Σ REEsw up to three orders of magnitude.
In these fluids, the pH values play a controlling role on the precipitation/dissolution of solid phases, inducing a fractionation of REE. The positive correlation between the total amount of REE and Fe-Al-Mn in fluid samples shows the simultaneous variations of these elements linked to co-precipitation and adsorption onto the surface of oxide and oxyhydroxide of Fe, Al and Mn involving strong process of REE scavenging [Censi et al., 2007; Bau and Koschinsky, 2009]; as a consequence, Fe, Al, and Mn are responsible of the abundance REE dissolved in hydrothermal fluids.
REE Patterns normalized to chondrite show two different trends and according to the pattern shapes, waters could be classified in two groups:
group-1 (LREEn/HREEn > 1) showing a decreasing trend from La to Lu, due to carbonate complexation of REE as usual in sea water and group-2 (LREEn/HREEn 0.6) have been calculated respect the well documented Ce anomaly in seawater (Ce/Ce* =0.2) [4]. Probably the redox condition (Eh 0 mV) do not allow the oxidation of Ce(III) to Ce(IV), as a result the preferential scavenging activity over REE(III)s is inhibited [Alibo & Nozaki; 1998].
All these evidences demonstrate that the contamination of discharging fluids and consequent formation of Fe, Al and Mn-bearing minerals controls the fractionation of REE and trace elements. As a result, the fate of trace metals and REE is mainly conveyed by both processes of scavenging onto newly forming Fe-Mn-Al-oxyhydroxides and carbonate complexation.
The suggested model provides important details on the fate of trace metals and REE discharged by shallow hydrothermal vents showing the interactions between hydrothermal fluids and seawater, demonstrating the chemical composition is controlled by contamination of discharging fluids and the typical process of oxidation and co-precipitation occurring in seawater.

S09 - Oral Presentation

The shallow hydrothermal brine of Panarea: preliminary characterisation of the acoustic signature

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Passive acoustic may represents a sustainable and safe method for long-term investigation of hydrothermal vents, as direct measures can be challenging due to the extreme environmental conditions (high temperature and acidic fluids) as demonstrated in the recent past [Heinicke, et al. 2009, Longo et al. 2021]. We present preliminary results of short-term monitoring of the submarine hot hydrothermal spring located inside the hydrothermal field near Bottaro, an islet about 2 km E of Panarea island, in the NE sector of Aeolian arc (Aeolian Island, Italy). The so-called Black Point shows peculiar characteristics compared to the surrounding field; it is characterised by extremely high temperatures close to 140 °C, very low pH (with values centred around 2.8-3.5) and dark/brown fluid emissions from the vent [Italiano and Nuccio, 1991, Müller 2011].

In this regard, the main scope of present work is to describe for the first time the spectral signature of the shallow hydrothermal brine using non invasive passive acoustic methods and to provide a useful and long-life tool to track the flow rate evolution along the time.

The hydrophone was moored in the proximity of the thermal emission, at 1 metre height from the hot fluid emission. High resolution acoustic records were obtained using a smart hydrophone icListen SA9L-ETH, an autonomous, battery and storage equipped instrument, able to collect and store digitised audio frames in the frequency band [1 - 12.800] Hz.

The short-time deployments provided a panoramic view of the investigated phenomena, highlighting the mitigation effects superimposed by tidal and hydrostatic load.

The application of various methods of spectral analysis and metadata extrapolation permitted to identify different energetic frequency peaks, diverging from the ambient background noise, in the range [6 - 6500] Hz, depicting distinct features in terms of bandwidth and energy levels. The bandwidth extension, comprising both infrasonic and audible bands, suggested the coexistence of different source mechanisms, as previously highlighted in different deep hydrothermal sites [Little et al. 1990, Crone TJ at al. 2006, Smith and Barclay 2021].

Afterwards, the analysis of the PSDs of each record emphasised the temporal evolution of both the power spectral levels and the frequency peaks during the observing period.

The first results obtained show that the selected contributions are persistent and almost constant. Significant variations on the time series were observed in the frequency range between 4500 and 6500 Hz, where frequency shifts occurred, testifying a behaviour change of the hydrothermal vent out of the natural forces. Furthermore, vibrational induced signals and the presence of tonal components, due to the conversion of seismic energy into acoustic waves along the solid-liquid interface, were identified, underlying the complexity of mechanisms and the hidden information that can be extracted from the hydrothermal area. The ongoing research demonstrates how a deep understanding of the acoustic sources could shed light over the behaviour of the hydrothermal reservoir, acting as a powerful proxy to identify flux change induced by magmatic contribution over long-term deployments.

S09 - Oral Presentation

Numerical simulations for the characterization of phreatic events on Vulcano Island

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Starting from September 2021, Vulcano Island has been affected by a crisis, still ongoing, in which high levels of CO_2 degassing were observed both in the crater area and at the base of the La Fossa cone, thus involving areas such as Vulcano Porto, the area of Grotta dei Palizzi, the Camping Sicilia sites and the base of the Forgia vecchia. The crater area was also characterized by high levels of SO_2 degassing. The crisis was characterized by anomalous temperature values at the fumaroles on the edge of the crater and by high flow rate of CO_2, which reached about 2000 t/d in the crater area. The strong degassing caused a temporary ban of overnight stay in some area between November and December 2021. The chemical composition of fumarolic gases has also undergone a change, reaching about 26% of CO_2 concentration, well above the about 5% measured during quiet periods [Selva et al., 2020]. An increase in the local seismicity of the crater area was also observed, and VLP events whose source has been estimated at a depth of about 750 m b.s.l.. The current crisis was also characterized by a rapid growth in ground deformation both in the radial component, whose expansion is centered in the area of the Fossa crater, and in the vertical component. The observed unrest signals have given rise to the concern of a possible phreatic explosion [Stix and de Moor, 2018] in the summit area and/or in the Vulcano Porto area, for which the Vulcano Island is currently constantly monitored. Such explosions are characterized by a rapid expansion of fluids due to sudden heating or decompression, and they may be linked to the rapid vaporization of liquid water, a phenomenon known as flashing. Landslides or injection of hot fluids can both cause a phreatic explosion. To better constrain the conditions that may favor the onset of these events, we simulated the vaporization of a shallow aquifer under selected initial and boundary conditions.

The conditions that favor the phase transition of liquid water to vapor, the speed with which it occurs and the overpressures that arise, were evaluated by numerical modeling, using the finite volume code MUFITS [Afanasyev, 2012; 2013a; 2013b]. A parametric study was carried out by injecting for a year hot fluids into a surface aquifer at a temperature close to the boiling point of water. The main parameters explored concern the permeability of the porous medium (considering a more permeable (10^{-13} m^2) and a less permeable (10^{-15} m^2) permeability configuration), the injection temperature of the fluid, the rate of fluid injection and the composition (H_2O only or H_2O+CO_2) of the fluid. Simulation parameters were chosen over a wide range in order to evaluate their influence on the phase transition and the speed with which that transition took place.

The simulations show that the injection of the hot fluid causes an increase in temperature and pressure at the source and the formation of a gaseous phase. The results suggest that high values of permeability, injection temperature and flow rate, as well as the presence of CO_2 in the injected fluid, favor, in principle, a faster expansion of the gas-dominated region.

In particular, (1) high values of the injection temperature accelerate the phase transition which begins and is completed at lower temperatures and pressures; the rapidity of the phase transition allows at the end of the simulation to reach higher pressure and temperature values than the values reached with the injection of a fluid at lower temperatures; (2) high flow rate values allow for a faster transition. The transition begins and is completed at higher pressures and temperatures as the amount of fluid injected increases; (3) low permeabilities favor pressure increases comparable to those favoring the fracturing of the porous medium; (4) the presence of CO_2 in the injected fluid allows a rapid transition that begins and completes at higher pressures and temperatures.

Influence of vent geometry and grain size distribution on the dynamics of phreatic eruptions

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In the last decade, a number of well observed events (Te Maari, NZ, 2012; Ontake, JP, 2014; Whakaari, NZ, 2019), some of which with dramatic consequences in terms of injuries and fatalities, have raised the interest of researchers on phreatic eruptions, and on the limited knowledge on the factors controlling their dynamics. Despite the different terminology used literature, we can identify phreatic eruptions as sudden, violent explosions originated by the rapid expansion of pressurized hydrothermal fluids located at low depths beneath the surface, without the direct involvement of fresh juvenile material. The dynamics of such eruptions are characterized by the rapid acceleration of a mixture composed by gas and rock fragments, whose release originates thin ash fallout deposits, ballistic blocks, and in some cases dilute and relatively cold pyroclastic currents. The solid fraction associated to phreatic activity includes rocks of the host system and those overlying it, although a low fraction of juvenile fragments can occasionally be ejected.

Despite phreatic activity has limited impact areas and volumes with respect to magmatic eruptions, it can represent a real threat in touristic or densely populated areas. The need of defining possible areas affected by this type of activity is for these reasons crucial for assessing the potential effects on local population and infrastructure.

Recent field and experimental studies highlighted the role of temperature and pressure within the system prior to the eruption as fundamental in determining the explosiveness of the event, since they control the decompression work of the fluids. Not less important are water liquid fraction within the system, which affects the released energy, and physical-mechanical parameters of the host rocks (i.e., lithology, porosity, permeability, strength) that may favor or limit the process.

Here we present a set of simulations of phreatic eruptions to investigate the influence of two additional parameters, such as vent location and geometry and grain size distribution, that may control the dynamics of these events, thus their variable impact. The evaluation is discussed for eruptive sources located on Vulcano island (Aeolian Islands, Italy). Simulations are run with the new numerical model OpenPDAC developed at INGV of Pisa, which is based on the previous PDAC model used for simulating explosive eruptions (Neri et al., 2003; Esposti Ongaro et al., 2007; de' Michieli Vitturi et al., 2010).

The outcomes show the role of the different investigated parameters on the characteristics of the simulated phreatic events, such as the height and lateral expansion of the eruptive cloud, the area and maximum distance reached by ballistic particles, the generation mechanism, and the direction and runout of pyroclastic currents. In spite of the limitations imposed by the modelling approach (e.g., loose constrain of initial parameters, model assumptions, complexity of the real cases), our work contributes to elucidate the major factors controlling the dynamics of phreatic eruptions. Furthermore, it may represent a contribution for the definition of possible eruption scenarios at Vulcano island.

S09 - Oral Presentation

Modelling and filtering of Etna soil CO_2 flux time series by mean of wavelet method

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The monitoring of soil CO_2 has become very important in recent years because it allows to better understand the variations of volcanic activity in terms of recognizing episodes of volcanic unrest and precursors of eruptive periods. However, the dynamics of soil CO_2 is quite complex and depends on many different factors acting simultaneously. One over all is given by the climatic-environmental variables which influence the CO_2 output resulting in a series of marked periodic variations of the signal. To remove such effect and isolate the "volcanic" component of the signal, we propose the application of the wavelet technique for the spectral analysis in the time-frequency domain. This method has been tested on long-lasting soil CO_2 time series recorded by the monitoring network operating at Mt. Etna volcano. This network (ETNAGAS network) is operational since the early 2000s and in 2011 the network reached its present-day configuration which includes 14 sites distributed across the volcanic edifice.

The CO_2 flux time series from Mt. Etna represent a unique data set because of the continuity of observations (here we investigate data from January 2011 to March 2019) and also because of the availability of the climatic information recorded at the same sites (air temperature, atmospheric pressure, and relative humidity). Many of the sites show a main peak of the wavelet power roughly corresponding to the annual cycle (i.e. 340 to 370 days). When it is present, these annual cycles are continuous over the whole period. Sub-ordinate periods of shorter duration occur at some sites. These may vary from ~70 to ~300 days and they are not always continuous over the whole observation period. Even shorter periodicities (less than ~100 days) with limited durations (usually some months) emerge at some sites. The periodic components of the signals can be modeled from the wavelet analysis by calculating the waves corresponding to each single discrete frequency, modulating them according to their own power spectrum. The reconstructed components can therefore be used to filter the raw signals.

Moreover, the cross-wavelet analysis highlights common periods between the CO_2 signals and each of the climatic variables. Results indicate that the time series are highly correlated and the joint annual cycle is continuous over the analysed period and for all the variables, even though it is characterized by a different power. In a narrow band (20-days) corresponding to the maximum value of the cross-wavelet power we computed the phases of CO_2 series and of the climatic series. The resulting phase differences are constant, or almost constant over time. Comparing the results at the different monitoring sites, the behaviour of the climatic variables appear to be consistent through time but site-specific (i.e. controlled by local factors). Summing up, the annual cycle of CO_2 flux is affected by the climatic variations over a year, even though their synchronicity may vary.

Finally, given the information about the phases and phase difference of the joint annual period, we analytically calculated the theoretical harmonics of the climatic variables at two sites of the monitoring network. To account for their relative influence, the amplitudes of these harmonics (one for each of the three climatic variables) are proportional to the maximum values of the average cross-wavelet power in the same band. This value is a measure of the similarity of power between two series and it is independent from the length of the series. The sum of the harmonics, normalized in the interval 0-1, is then compared to the flux of CO_2, showing a clear correspondence of the yearly minimum and maximum. This signal obtained from the climatic variables can be used as a baseline to predict the seasonal trend of the CO_2 output and, therefore, to evaluate anomalies in real-time. It also may be useful to reconstruct missing portions in the data in case of temporary malfunctioning of the CO_2 sensors.

Revealing spatio-temporal variations of soil CO_2 at Mt. Etna volcano

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Volcanic gases provide information about the magmatic processes and represent useful eruption predictors. For this reason, also the monitoring of diffuse soil CO_2 has become very important in recent years. A devoted monitoring network, called "EtnaGAS network", records continuously since the early 2000s the soil CO_2 flux at Mt. Etna volcano. The network includes 14 sites that are almost uniformly distributed on the flanks of the volcano, and today long and continuous time series are available. The network basically covers homogeneously the lower half of the volcanic edifice, extending from the outer peripheral areas up to ~1,700 m a.s.l. (out of 3,300 m of the entire volcano). Furthermore, the angular distribution of the nodes is sufficiently uniform (the average angle between adjacent stations with respect the central crater is ~28).

Data used for this research result from the processing proposed by Liuzzo et al. (Geochem. Geophys. Geosyst., 2013), which proposed a technique to filter and combine the measurements of the soil CO_2 network at Etna. From 14 distinct time series, a unique signal representative of the state of the whole volcano is calculated. The unified signal is based on the assumption that even if the signal at each site can vary depending on its position on the volcano and on the local high-frequency noise, however, the sum of the signals will enhance the resonance effects of the shared sources among the sites (i.e. volcano-related sources); conversely, it will cancel out all the other possible sources ascribable to local effects. This approach led to easier interpretations of the potential link between the CO_2 volcanic emissions and the volcanic activity on Etna volcano, and proved to be effective to recognize several seismo-volcanic anomalies in the signals. With further elaboration of data, additional information regarding also the spatial and temporal variations of the CO_2 flux series can be retrieved. In this research, we transformed the data by means of a linear scaling. The necessity to scale the data derives from the possibility to compare the data from the various sites, namely that a given value assumes the same meaning at all the sites. The linear scaling does not alter the frequency distributions, and it is a procedure widely adopted also to treat CO_2 signals. The adopted scaling uses as constants a measure of central tendency (i.e. the median) and a measure of dispersion, in particular the spread of the middle half of the data (i.e. interquartile range). Such scaling procedure of the soil CO_2 flux series allows to represents the variations according to the positions of the monitoring sites. In particular, daily data are displayed to highlight the spatial variations considering the altitude of the monitoring sites, the distance from the main, active craters, and the azimuthal direction between the monitoring sites and the main craters. Moreover, the occurrence of spatial variations is evaluated at different temporal scales. First, long-term variations have been investigated considering the whole series spanning through nine years (2011 to 2019). Then, variations have been also explored for yearly windows and for short-term bi-monthly windows in correspondence of a period of marked activity of the volcano (2018-2019).

The variations affecting absolute elevation and the distance from the main volcano axis appear to be uncorrelated with the unified signal. This is probably due to the coverage of the network with respect to the dimension and position of the magma chamber at Etna. Conversely, we

found evidence of directional dependence of the unified signal which can be highlighted by means of azimuthal representations. The stations with shorter angular distances have usually very similar behavior. Conversely, pairs, or groups of stations, exhibit uncorrelated values of the daily curves even though they are at a short distance. The occurrence of preferential directions in the CO_2 soil flux at Etna can be interpreted as the effect of volcano- scale changes in the permeability as a consequence of the deformation involving the entire volcanic edifice and which are accommodated along main tectonic lineaments. Therefore, these deformations can either promote or, on the contrary, prevent the soil gas to be released in some portion of the volcano. All this information can be framed with the volcano-tectonic dynamics during the eruptive period and can provide detailed insights of eruptive mechanism.

Multidisciplinary and multilayer study of the 2022 Hunga Tonga-Hunga Ha'apai main eruption

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The Hunga Tonga volcano has been active since its first historical eruption in 1912 with an underwater explosion. After the explosive eruption of December 2014, it emerged with a tuff cone that explodes connecting the islands Hunga Tonga to the north-east and Hunga Ha'apai to the south-west. In 2022 January 15th, this submarine volcano showed a spectacular phenomenon with unexpected global effects. The violent explosion destroyed the volcanic island and produced a large plume seen from different satellites. So, we analysed the eruption with a multidisciplinary and multilayer study, distinguishing the different energy released on the lithosphere and on the atmosphere. Starting from the lithosphere, we conducted a seismological study of the acceleration and extrapolated the expected magnitude of the event with the Revised Accelerated Moment Release, R-AMR method [De Santis et al., 2015]. Rising to the atmosphere, we analysed the atmospheric parameters related to thermal radiative interaction with surface: skin temperature, air temperature, outgoing longwave radiation, lightning activity, cloud cover, relative humidity, ozone and surface pressure. Finally, we focused our attention to the ionospheric disturbances revealed by ground observatories, ionosonde data and satellite data. Magnetic observatory data were also analysed in conjugate point and centred to the volcano to search for a possible effect of the eruption in the magnetic field. Furthermore, a detailed study of the power spectral density was carried out, applying a fast Fourier transform to observe its fluctuations at satellite altitudes. The foF2 ionospheric parameter was analysed using a global ionosonde network, even if the geomagnetic storm of this period influenced the signal. In addition, we found a singular effect in the International GNSS Service Total Electron Content (TEC) daily data, possibly correlated to the volcanic explosion and a strong signal in Search Coil Magnetometer (SCM) indicating the influence of the great eruption.
From all these observations, we can confirm that this unique eruption evidenced Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) effects.

S09 - Poster

Petrography and geochemistry of Secca del Capo seamount (Aeolian Islands): a preliminary study

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Secca del Capo is a submerged volcanic edifice set in the central sector of the Aeolian Archipelago (Southern Tyrrhenian Sea), about 5 km NE of Salina Island. The summit of the seamount is placed at a depth of 8 meters below the sea level, while the base of the edifice is about 500 m b.s.l. The present study aims to assess, for the first time, a petrographic and geochemical characterisation of the volcanic rocks of this submerged volcano, sampled by expert divers at depth between 16 and 42 m b.s.l. at three different points.

The sampled rocks are porphyritic lavas with a mineral assemblage dominated by plagioclase and subordinate orthopyroxene and clinopyroxene. The composition is rather homogeneous, with most samples falling in the andesite field, and showing a calc-alkaline affinity. Slight variations in terms of major and trace elements are observed with depth. As a whole, the results indicate petrological and compositional affinities with the emerged portions of the islands of the central sector of the Archipelago, and particularly with the nearby island of Salina. Mineral textures and compositions suggest a complex history of multi-level storage and raise of the magma before the eruption(s).

Understanding groundwater circulation in active volcanic areas for the assessment of possible involvement of fresh and thermal waters in triggering phreatic explosions at Ischia (Italy)

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In active volcanic areas, the knowledge of groundwater circulation is fundamental for understanding the interaction between water and the magmatic system in case of re-alimentation of the shallow reservoir, and for assessing the possibility of phreatic explosions occurrence. The discrimination of shallow and deep flowpath is still an issue today, especially in volcano-tectonically active islands, making it difficult to estimate aquifer geometry and groundwater flow patterns.
Assessing the variations in space and time of groundwater circulation in volcanic islands is of paramount importance in the description of the hydro-geo-thermal system, and implementation of hydrogeological, geochemical, and volcanic monitoring systems. In fact, the reliable reconstruction of the groundwater potentiometric surface in such composite aquifer systems can enable the identification of the most advantageous strategies for both sustainable use of groundwater resources and management of volcanic risk.
Field data collection is the starting point in defining reliable conceptual hydrogeological models, and the reconstruction of the potentiometric surface is an important boundary in many groundwater flow models. Nevertheless, the potentiometric surface configuration is often poorly known due to the high variability of the hydrological properties of volcanic and non-volcanic deposits and to the small number of exploitation wells in the inland island areas.
Groundwater mapping, described by water table elevation in a phreatic aquifer or by piezometric surface elevations in a confined or a leaky one, is a useful tool for summarizing both field and desk investigations of hydrogeological structures. The interpolation of one kind or another (e.g., linear) of water level data, measured at the same time in the available observation wells of a given aquifer, allows contours of the potentiometric surface to be drawn. Therefore, many softwares have been developed for drawing contour maps, and properly designed and constructed mathematical models are able to predict the water levels by solving the partial differential equations which govern the groundwater flow.
Geospatial technologies have become an effective tool for monitoring, mapping, and modelling water resources as well as for volcanic risk evaluation and management and emergency planning, due to their capability to store, retrieve, analyze, and display data that are characterized spatially or geographically. One of the fundamental functions of Geographical Information System (GIS) is the automation of cartographic workflows and the potential to integrate and analyze the large number of spatial and temporal variables derived from monitoring of active volcanoes. In such a multidisciplinary study this process facilitates the integration of information and simplifies the identification of interrelationships between different phenomena.
In active volcanic islands piezometric mapping based on existing, even sparse water level data is a key tool able to guide and optimize field activities and improve the capabilities of the monitoring system. The most common interpolation methods for groundwater mapping are Inverse Distance Weighting (IDW), Natural Neighbor (NaN) and Kriging (K). IDW and NaN are

"deterministic" estimation methods, while Kriging is a "stochastic" method.
Despite the widespread use of GIS technology for analyzing main groundwater variables, and for their interpolation and representation by continuous surface (mapping), there are currently no guidelines on which spatial interpolation procedures are most suitable for developing the potentiometric surface in relation to the features of the water level observation network and factors that may affect the distribution of hydraulic heads. Conversely, several studies compare and analyze the progress of spatial interpolation techniques in environmental studies.
With regard to the very active Ischia Island (Italy), in this work we illustrate a GIS-based hydrogeological approach to identify the most accurate interpolation method for mapping the potentiometric surface in complex hydrogeological terrains.
The proposed approach has been applied to the existing dataset (1977-2003) stored by the Istituto Nazionale di Geofisica e Vulcanologia. Based on a careful geological and hydrogeological survey, a total of 267 wells, from 5 to 250 m in depth, were processed. The data pre-processing involved four meteorological time series data (1922-1997) and six long records of piezometric water levels (1930-1994). As a result, knowledge of the delineation of rather homogeneous stratigraphic and volcano-tectonic structures at the basin-scale has improved. Thus, new more reliable potentiometric surfaces of four main geothermal areas closest to the coast were produced, during both dry and wet seasons. The reliability of the processed potentiometric surface was then validated by comparing the spatially continuous data with complementary field data.

S10 - PROXIMAL AND DISTAL VOLCANIC MONITORING USING REMOTE SENSING SYSTEMS: NOVEL PRACTICES, APPLICATIONS AND INTEGRATIONS

Conveners:
Stefano Corradini, Gaetana Ganci, Luca Merucci, Giuseppe Salerno, Letizia Spampinato

Remote sensing of volcanic clouds: the legacy of Prof. Frank Silvio Marzano

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Volcanic clouds are fascinating phenomena, very complex to retrieve and study. They can be associated with weak, transitional or strong plumes with different features and behaviour. They can contain a large amount of volcanic particles with highly variable size, ranging from microns to centimetres, and shapes that mostly reflect the fragmentation mechanisms operating during an eruption. Several phenomena associated the volcanic clouds remain largely unconstrained (e.g. particle aggregation, sedimentation fingers, lightning) and are the topic of many studies and researches. During recent years, new remote sensing techniques have been developed and extensively used to expand our understanding of volcanic clouds. They span from radar to lidar, visible and thermal cameras and satellite sensors. In this work, we wish to remember the life and the extensive work of Prof. Frank Marzano (1963-2022), a pioneer in the application of meteorological radar to volcanic clouds. Frank was the Director of the Centro di Eccellenza CETEMPES and Full Professor at the Dipartimento di Ingegneria dell'Informazione, Elettronica e Telecomunicazioni (DIET) of the University in Rome. Since 2006 he studied volcanic clouds using different remote sensing techniques. He analysed the eruptions of different volcanoes worldwide such as the 2010 Eyjafjallajökull and the 2011 Grímsvötn eruptions in Island and the 2015 Calbuco eruption in Chile. He also worked on the analysis of several lava fountain events at Etna, mainly focused to the estimation of eruption source parameters and the development of effective early warning strategies. In 2020 Frank was included in the database of the Top 2% Scientists in the world from the Stanford University. His life and dedication to the study of volcanic clouds is inspirational for new advancements in this field.

S10 - Oral Presentation

Spatio-temporal evolution of SO_2 fluxes detected from a network of two ultraviolet cameras, and insights on the magma degassing (Stromboli Volcano, Sicily)

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We report on high frequency (~0.5 Hz) systematic measurements of the SO_2 flux at Stromboli, covering a 1-year long observation period (June 2017-June 2018), and obtained by a network of two permanent UV cameras using the same unmanned algorithm, and imaging the plume from two different viewing directions. SO_2 flux time-series derived from the two UV camera systems exhibit an excellent match in their weekly-long fluctuations, demonstrating the robustness of the automatic UV camera method in quantifying and characterizing the volcanic SO_2 emission patterns and trends. Our high-temporal resolution SO_2 records resolve individual strombolian explosions as transient repetitive gas bursts produced by the sudden release of over pressurized gas pockets and scoriae. Calculations show that such explosive degassing activity accounts for ~10% of the total SO_2 emission budget (dominated by quiescent degassing) during mild regular open-vent activity. We show that the temporal variations of the explosive SO_2 flux go in tandem with changes in the total SO_2 flux and in VLP seismicity, implicating some commonality in the source processes controlling quiescent degassing and explosive activity. We also find substantial swings in degassing activity in between the South-West/Central (SWCC) and the North-east (NEC) craters, the two active degassing sources inside the Stromboli's crater terrace. We find that the SO_2 fluxes from SWCC and NEC crater oscillate coherently, but those from NEC oscillate more widely, and are more sensitive to the changes in volcanic intensity. We interpret this as due to preferential gas/magma channeling into the structurally weaker north-eastern portion of the crater terrace in response to increasing supply rate of buoyant, bubble-rich magma in the shallow plumbing system.

S10 - Oral Presentation

Integrating Ground-based and Satellite Volcano Monitoring techniques applied to gas emissions from fumarole vents and from the ground at La fossa Caldera (Vulcano, Aeolian Islands, Italy)

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Recent studies [e.g. Girona et al., 2022; 2021] suggest satellite data as a powerful tool to study surface thermal anomalies, providing a useful way to monitor the thermal evolution of restless volcanoes by remote platforms. Infrared observations allow the characterization of surface temperature fields, signaling impending changes in activity, and subsurface processes generating thermal anomalies [e.g. Mannini et al., 2019; Silvestri et al., 2016; Vaughan et al., 2012].
Compared to ground-based monitoring systems that provide continuous data on a more restricted area, remote sensing provides data at discrete intervals but spanning wider areas. Because of this, thermal remote sensing is mostly applied on active lava flows and explosive eruptions, while a systematic quantification of time and space variation of thermal anomalies has not become a procedure usually applied on close conduit volcanoes during solphataric activity, despite the increased availability of remote sensing data.
Here we present methodologies and practices resulting from the integration, comparison, and validation of thermal monitoring data, from both ground and remote sensing systems, collected on a close conduit volcano during solphataric activity (on the Island of Vulcano, Aeolian Archipelago, Italy).
On a close conduit volcano, the fluid phase generated by thermodynamic processes cannot be freely dispersed in the atmosphere, because fluids interact with ground waters and soil system before being released, partially by the convective output of fumarole vents and partially by diffuse degassing over wider ground surfaces. Surface thermal anomalies are the evident effect of this permanent fluid release, so an inclusive monitoring method, systematically repeated in the long-term may be useful to herald the approaching disequilibrium conditions of the volcanic system, by detecting relevant transfer of energy and mass towards the surface. The ground-based monitoring systems provide almost continuous time coverage and higher accuracy, but with limited aerial coverage. This is the case of the temperature monitoring network of the fluid release and diffuse degassing in the summit area of the La Fossa cone.
The ground-based long-term time series of a few monitoring sites have defined the typical behavior of the hydrothermal system, pointing out the intensity of some periodical modulations and highlighting some other periods of time with critical alteration of the dynamic equilibrium, usually characterized by the gentle emission of fluids in the condition of stationary convection. The outlet temperature from the most intense fumaroles monitored continuously on top of the La Fossa cone changed from the maximum value of 540 °C to the minimum value of 250 °C, while in the same period another fumarole has oscillated between 670 °C and the actual value of 111 °C.
On the other hand, we can obtain a synoptic view of the investigated area by relying on multispectral satellite observations to ensure global spatial density measurements, albeit with lower spatial and temporal resolutions. In our case, data acquired by the Visible Infrared Imaging Radiometer Suite (VIIRS) at 375 m spatial resolution, spanning the period from January 2021 to

now, were processed with an automatic algorithm developed to detect thermal anomalies and compute the correspondent radiant heat flux. The VIIRS images allow following the most intense phases of the thermal activity. In particular, we present the thermal variations registered from June 2021 onwards.
These preliminary results show good agreement between ground and satellites confirming the complementary nature of the two techniques.

Integrating mineralogical and geomorphological analyses: a first application to the highly active hydrothermal discharge area of Pisciarelli in the Campi Flegrei volcanic field (Italy)

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This research explores relations between acidic sulfate alteration, geostructural framework and geomorphological changes that can be observed at active volcanic hydrothermal systems. The target area is Pisciarelli in the Campi Flegrei volcano, where a diffuse acidic sulfate alteration and hydrothermal dynamics have been described at the least since Roman time and are growing through time since 2012 causing a progressive deterioration of landscapes. Terrestrial Laser Scanner (TLS), photogrammetry of proximity survey, geological field trip, mineralogical and geochemical analysis with Optical Microscopy (OM), electron microscopy and energy dispersive micro-analysis (SEM-EDS) and X-Ray Diffraction (XRD) to characterize (and monitoring) altered rock outcrops, were repeatedly carried out in the area. We present the multi-temporal acquisition and analysis referred Terrestrial Laser Scanning (TLS) datasets (2014 survey) with 3D point clouds obtained from the Structure for Motion (SfM) photogrammetry (2021 survey) by a high-resolution digital camera aimed at evaluating volumetric changes, on the mostly damaged fault scarp. For each survey we obtained a vertical Digital Elevation Model (DEM) and a true color RGB orthomosaic that has provided the setting of the area at the different times and its evolution through their comparison. Changing sites have been examined in the field and characterized for mineralogical and geochemical purposes. Our methodological approach appears promising to evaluate evolution and rock fall susceptibility of solfataric terrains subjected to hydrothermal dynamics.

S10 - Oral Presentation

Quantifying thermal emission from open vent multicraters system using a multisensory space-based approach: Stromboli and Etna case studies

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Volcanic space-based thermal remote sensing is broadening its limits with the availability of new sensors with different temporal and spatial resolutions. Open-vent activity, with its constantly active magmatic processes sourcing a significant amount of heat and feeding mild explosive activity and thermal emissions, could be investigated by using different InfraRed satellites, leading to a continuous, homogenous, and multispatial constraints of thermal activity and offering a great improvement to monitor and understand dynamics of open-vent behaviors. In this work, we investigate 8 years of thermal activity (2013-2021) of Stromboli and Etna volcanoes (Sicily, Italy), two iconic open vent volcanoes exhibiting permanent thermal signals, combining data acquired by moderate (MODIS) and high spatial resolution sensors (20 -30 m), such as SENTINEL 2 Multi Spectral Instrument (S2) and LANDSAT 8 Operational Land Imager (L8), in the MIR and SWIR spectral regions, respectively. We focused our analysis during periods of thermal ordinary activity, excluding emissions related to lava flows, effusions, paroxysms, and major explosions. The multisensory approach allows to (i) map variations of thermal emissions location in summit areas, (ii) calculate mutual thermal budgets of different vents, and (iii), remarkably, to estimate heat flux values produced by single craters, comparing the Volcanic Radiative Power (VRP, in Watt) and the Volcanic Radiative Energy (VRE, in Joule) measured by MIR-MODIS with the Thermal Index parameter recorded by SWIR analysis using S2 and L8 dataset. The results are compared with the most important eruptive events that recently occurred at Stromboli and Etna, and we found that the thermal signals are in accord with the occurrence of higher intensities events such as effusion, explosion, and paroxysms. In addition, the multiyear thermal analysis seems to indicate long-term changes in the thermal budgets, in connection with the increase of explosivity and possibly revealing variations in magmatic supply rate feeding shallow activity. Using multiple space-based InfraRed datasets, we can perform a multiyear quantification of heat fluxes from every single crater on Stromboli and Etna, which represents a great improvement for monitoring purposes, with a possible dedicated space-based algorithm able to track in near real-time the heat flux produced by vents and the thermal budget on multicraters contexts.

Integrated use of satellite instruments for real-time monitoring of Etna emissions

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In recent decades, satellite remote sensing has become an essential tool for monitoring volcanic activity, particularly in the most remote regions of the Earth. Nowadays satellite monitoring of volcanic eruptions has become an effective tool for mitigating risks on the local population and on airspace, as well as for analyzing the processes associated with the preparatory phase of an eruption.

Satellite remote sensing systems operate in different spectral ranges, with different resolutions and spatial/temporal sensitivities. For this reason, only an integrated use of these different characteristics will make possible a continuous and reliable monitoring of the volcanic activity both during the quiescent and the eruptive phase.

In this work the measurements of various geostationary and polar satellite instruments such as SEVIRI (MSG), MODIS (NASA-Terra/Aqua), and TROPOMI (Sentinel-5P) were used for real time monitoring of Etna. The products obtained were validated using ground and satellite instrumentation.

The results obtained demonstrate the ability of satellite systems to monitor volcanic emissions in different phases and in real time, thus offering a powerful tool to mitigate the volcanic risk on population and airspace.

S10 - Oral Presentation

Doppler Radar Monitoring of Mt. Etna Explosive Activity

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The monitoring of explosive volcanic activity can be done in any weather condition by using the radar remote sensing technique.

Here we describe the realisation of a system aimed at continuously monitoring the explosive activity at the summit Mt. Etna craters, composed of two main components: a S-band pulse Doppler radar and a real-time analysis tool.

The radar system is the VAPORS-S (Volcanic Ash and Plume Observation by Radar System in S band), designed with the purpose of observing the pyroclastic materials emitted during an eruptive volcanic event. It is installed in the shelter "La Montagnola", located at about 2700 metres above sea level and 3 km from the active volcanic vents. In particular, the antenna is directed to illuminate the volume just above the South-Eastern Crater.

The real-time analysis tool was developed for the Monitoring Room of the Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo. It starts by acquiring the Doppler spectra, which are the basic data coming from the radar; each spectrum stores the measured decibels relative to the reflectivity factors (dBZ) of sensed remote objects for each Doppler velocity (from -150 m/s to 150 m/s). Then, this data is cleaned, processed and converted into four time series, one for each range bin. These time series contain the dBZ values over time, which are a proxy of the volume of the pyroclastic materials that are reflecting back the radar pulse in that moment. Therefore, the time series rise during an eruptive event, and the range of assumed dBZ values depends on the type of eruptive activity, permitting us to detect the occurrence of strombolian activity and its possible evolution to lava fountains.

This tool, which operates 24/7, improves the capacity to detect explosive activity at Etna volcano, which is strategic for the task of the observatory to inform air traffic controllers, under the ENAC assignment. For this duty the observatory is issuing within a few minutes the VONA (Volcano Observatory Notice for Aviation) messages on the explosive activity that produce volcanic ash dispersal in the atmosphere, for improving aviation safety.

S10 - Oral Presentation

Detection and Parametrization of Volcanic Plumes from Visible-Wavelength Images with PlumeTraP: Application to Plumes Associated with the 2018 Sabancaya Eruption, Peru

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Tephra plumes from explosive volcanic eruptions can be hazardous for the lives and livelihoods of people living in the proximity of volcanoes. Monitoring and forecasting tephra plumes play essential roles in the detection, characterization and hazard assessment of explosive volcanic events. However, advanced monitoring instruments, e.g., thermal cameras, can be expensive and are not always available in monitoring networks. Conversely, visible-wavelength cameras are significantly cheaper and much more widely available.

We propose an innovative approach to the detection and parametrization of tephra plumes, utilizing videos recorded in the visible wavelengths. Specifically, we have developed an algorithm with the objectives of: (i) identifying and isolating plume-containing pixels through image processing techniques; (ii) extracting the main geometrical parameters of the eruptive column, such as the height and width, as functions of time; and (iii) determining quantitative information related to the plume motion (e.g., the rise velocity and acceleration) using the physical quantities obtained through the first-order analysis. The resulting MATLAB-based software, named Plume Tracking and Parametrization (PlumeTraP), semi-automatically tracks the plume and is also capable of automatically calculating the associated geometric parameters [Simionato et al., 2022, doi: 10.3390/rs14071766].

Through application of the algorithm to the case study of Vulcanian explosions from Sabancaya volcano (Peru), we verify that the eruptive column boundaries are well recognized, and that the calculated parameters are reliable. The obtained results were also used to characterize and classify strong plumes at Sabancaya. Our results show that plumes at Sabancaya have a transient behaviour, characterised by similar times of pyroclasts-and-gas release and of full development of the plume, that is typical of Vulcanian explosions. We found that two types of plumes occur at Sabancaya volcano. Plumes characterized by initial velocities > ~10 m/s which then rapidly drop and constantly slow down with time were classified as starting plumes or rooted thermals. Conversely, plumes that after smaller initial velocities (~ 5-10 m/s) show an acceleration in rise velocity before slowing down again were defined as starting jets dominated by buoyancy.

Thus, the developed software can be of significant use to the wider volcanological community, enabling research into the dynamics of explosive volcanic eruptions, as well as potentially improving the use of visible-wavelength cameras as part of the monitoring networks of active volcanoes. Furthermore, PlumeTraP could potentially find a broader application for the analysis of any other plume-shaped natural or anthropogenic phenomena in visible wavelengths.

A new radar-based statistical parametric model to quantify the mass eruption rate and uncertainty in various wind conditions

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Accurate forecasting of volcanic ash dispersal during explosive eruptions requires the determination of various eruption source parameters (ESPs), e.g. Mass Eruption Rate (MER, QM hereinafter). Still today the QM retrievals in near real-time is a considerable challenge due to limitations both of specific sensors employed in the eruptive events observations and of current numerical/parametric models used to derive information. On the other hand, the top plume altitude (HTP), is the easiest ESP to quantify during an eruption and often used to estimate QM. In the last decade, many eruptive events of Mt. Etna, Italy, have been detected by the polarimetric doppler X-band radar, located in Catania, about 30 km far from the summit craters. The volcanic plumes (reaching a maximum altitude of 15 km above sea level) were mostly fed by lava fountains lasting a few hours.
Here we describe the first statistical parametric model, based on a Monte Carlo Markov Chain (MCMC) approach, to directly derive QM as a function of both top plume altitude (HTP) and wind velocity (vW). The QM and HTP data, used to calibrate the model parameters, are independent, entirely radar-based and have been retrieved from 32 eruptions of Etna. In this way we have identified the statistical parametric relationship to derive the QM from HTP and wind velocity that maximizes the likelihood of our completely ground-based radar observations. The MCMC approach allows estimating the inherent uncertainties on the model parameters, accounting for the errors on the radar-based observations. In this view, the added value of the proposed methodology is that we can calculate a confidence interval for the derived QM.
We compare the QM resulting from our statistical model (in terms of 95% confidence interval) with those derived from a consolidated model, known in literature, ingesting environmental features (e.g. wind velocity). This new relationship lends itself to be extended to other ground-based radars for monitoring other active volcanoes around the world. In this way the new parametric model can corroborate scientists to better understand and quantify eruption activities in near real time and thereby can help them to better quantify volcanic hazards and possibly mitigate their risks.

S10 - Oral Presentation

Real-time estimation of Mass Eruption Rates of tephra plumes at Mt. Etna from fixed-pointing Doppler radar

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Estimating eruptive source parameters during explosive eruptions is a major challenge in terms of hazards and risk assessment. These inputs are essential to initialize tephra dispersal models and forecast the impact of ash, gas and aerosols in the atmosphere and plumes and tephra deposits. These paroxysms were analyzed using the 23.5 cm wavelength Doppler radar (UHF VOLDORAD-2B, OPGC) integrated into 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. An outstanding achievement of the MEDSUV and EUROVOLC european programs is the retrieval of the Mass Eruption Rate (MER) in real-time from just the radar echo power and maximum Doppler velocity measured near the emission source. The radar-derived MER proxy was calibrated against an ascent model based on plume heights observed for the 2011-2015 paroxysms, leading to radar-derived climax MER from 2.96×10^4 to 3.26×10^6 kg s-1. Inferred Total Erupted Masses (TEMs) of tephra allowed quantitative comparisons of the relative amounts of emitted materials among all paroxysms. When present, the steady climax phase is commonly found to release about 3/4 of the TEM. 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. The next step is to implement operationnally the radar retrievals in real-time into dispersal models in order to refine forecasting and better mitigate associated risks.
The open-access data base of radar records and products, available from the OPGC (http://voldorad.opgc.fr/) and EPOS gateways, is widely used by the scientific community to investigate the source term parameters, eruptive processes, modelling of volcanic products dispersal, and sensors intercalibration.

S10 - Oral Presentation

Analysis of high-resolution DEMs from UAS to estimate the distribution of ash-fall out and ballistics from Etna's 2021 paroxysmal events

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Mt. Etna is a composite basaltic stratovolcano characterised by quasi-persistent activity at its four summit craters and quite frequent events from fissures along its flanks. In the last years, Etna eruptive activity mostly occurred in the summit area and in particular at the South East Crater (SEC). Between December 2020 and October 2021, the SEC produced more than fifty episodes of Strombolian activity and lava fountaining (paroxysms), with up to two events in 24 hours, feeding lava flows towards east, south and southwest and causing ash fallout in the surroundings of the volcano and the fall of large ballistics in the proximal area. Several Unoccupied Aerial System (UAS) surveys were performed for monitoring the morphological variations of the summit craters and quantifying the eruptive products. In particular, lots of images were acquired during each survey and processed with Structure from Motion (SfM) techniques to extract Digital Elevation Models (DEMs) and orthophotos at a spatial resolution as high as 5 cm. Data processing, through a Geographic Information Systems (GIS) software, enabled geomorphological analysis at a high resolution never before achieved for Etna volcano. Final results were the measurements of the thickness of the ash fallout deposits in the proximal and distal areas, as well as the spatial distribution of large ballistics in the proximal area. Since thousands of tourists, visit the affected area especially in the summertime, these results are useful for hazard evaluation. Moreover, these measurements could also be used to support studies and numerical simulations of the distribution of fallout deposits from explosive eruptions.

Long Range Infrasound Monitoring of Yasur Volcano

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The atmospheric injection of gas and material produced by an explosive volcanic eruption determines a rapid compression of the atmosphere, which subsequently propagates as longitudinal elastic waves (sound). The size of the source, generally greater than tens of meters, and its duration, longer than few seconds, result into an emitted signal that is particularly rich in low frequency (f 100 km) is efficient in recording and characterizing volcanic events. For the purpose of our study, detections from Yasur volcano (Tanna Island, Vanuatu) registered at a source-to-receiver distance of 400 km by the IS22 infrasound array, located in New Caledonia and part of the Comprehensive nuclear Test Ban Treaty (CTBT) International Monitoring System (IMS), were studied for a period of eleven years (2008-2018). The predominantly explosive Strombolian activity of this volcano makes it a perfect subject to be studied by infrasound technology. Detections are modulated according to the seasonal variation of stratospheric winds and corrected for attenuation accounting for real atmospheric specification between the source and the receiver to retrieve the pressure at the source: next, they are used to evaluate long term (yearly) and short term (hourly) variations of activity over the period of analysis.
Results are eventually compared with thermal anomalies recorded by the MODIS (MODerate resolution Imaging Spectroradiometer) installed on NASA's Terra and Aqua satellites and computed by the MIROVA hotspot detection system.
We show that even at regional distances (400 km) it is possible to follow the fluctuations of ordinary explosive activity during periods of optimal propagation of infrasonic waves in the atmosphere. In addition, we show that, when the signal is recorded, the time resolution retrieved from the analysis allows following variations of activity at hourly time scale, thus representing a valuable source of information, in particular in areas where local geophysical observation is missing.

Quantification of SO_2 emission rate by hyperspectral imaging

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The quantification of volcanic SO_2 amounts form active volcanoes represents a key feature in volcanological monitoring as it provides important and useful information regarding the volume of magma involved in the dynamics of the volcanic plumbing system. Currently, quantification of SO_2 is carried out in the electromagnetic radiation in the Ultraviolet (UV) region. UV radiation arises from the scattering of solar radiation in the high atmosphere, therefore SO_2 quantification are confined only over daylight. Contrary, as the Infrared (IR) spectral region is a thermal electromagnetic band by exploiting the temperature difference between the volcanic gas and the atmosphere, allowed quantification of the SO_2 emission even during the night. The CIMAVOLC (Compositional Infrared iMAging of VOLCanic emissions) project funded by INGV under the Ricerca Libera 2021, focus on the quantification of SO_2 emitted over the ordinary explosive activity of Stromboli through spectroscopy techniques in the infrared region. The project consists of a partnership between the INGV-Osservatorio Etneo and the Nucleo Regionale Avanzato NBCR of Palermo, of Corpo Nazionale dei Vigili del Fuoco (VVF). Joint filed surveys are planner by carrying out remote observations using the Bruker Hyperspectral imaging (HI90), supplied by the NBCR Nucleus of the VVF of Palermo together with UVCamera, UV spectroscopy and OP-FTIR from OE-INGV (sez. Catania). Here, we present the preliminary results of data collected during a phase test carried out at Mt. Etna.

S10 - Poster

Study of the cross-correlation between infrasonic and seismic signals generated during the 2-5 December 2015 Etna explosive activity

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Volcanic explosive activity is a powerful source of both seismic and infrasonic wavefield. As a matter of fact, the volcanic explosions, due to the abrupt gas release, produce a compressive stress that is transmitted both in the ground and in the atmosphere, in the form of seismic waves and infrasound respectively.
Volcanic tremor and infrasound produced by volcanic explosive activity are closely related. Indeed, the volcanic tremor recorded by a seismometer is the result of several components with different origin, reflecting both deep magma movements and shallow explosive dynamics. One tremor component corresponds to infrasound which is transmitted locally in the ground and converted to seismic waves, due to seismo-acoustic coupling. Therefore, understanding the relationship between tremor and infrasound is a key point to further investigate the explosive dynamics.
We present the cross-correlation study between infrasound and seismic ground velocity generated during the 2-5 December 2015 eruptive explosive activity of Etna Volcano, Italy, when 4 episodes of lava fountain occurred. We analysed infrasonic and seismic data recorded by a infrasonic sensor and a colocated seismometer deployed on the southern rim of the Valle del Bove at a distance of ~ 5.5 km from the summit craters.
The analysis of the seismo-acoustic data revealed that each lava fountain episode is characterised by a recurrent trend, with the transition from the initial strombolian phase to the sustained lava fountain being accompanied by a marked change in the infrasonic emission, passing from a series of isolated infrasonic transient to a higher amplitude and lower frequency quasi-monochromatic continuous infrasonic oscillation recorded during the fountaining event. In contrast, with the eruptive phase transition, only a sharp amplitude increase is observed in the volcanic tremor, without any evident change in the seismic waveform and frequency content.
The cross-correlation function between infrasonic and seismic signals was then computed along the entire period of analysis. Results show that the seismo-acoustic cross-correlation progressively rises during the intense strombolian activity phase preceding the lava fountain, while it abruptly collapses as soon as the sustained lava fountain phase begins. This trend is observed for all four analysed episodes, suggesting that the seismo-acoustic cross-correlation patterns are strictly dependent on and reflect the volcanic activity occurring at summit craters, thus highlighting the potential of using the seismo-acoustic cross-correlation for investigating the dynamics of explosive volcanic activity.

S10 - Poster

Monitoring of Indonesian volcanoes with I06AU infrasound array

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Detecting and notifying ongoing volcanic explosive eruptions can support the activities of the Volcanic Ash Advisory Centres (VAAC) in their contribution to the International Airways Volcano Watch. However, local monitoring systems are missing on many active volcanoes. Here, the use of a global monitoring that, even with lower reliability, can allow a fast response. Many studies have shown so far the utility and potential of long-range infrasound monitoring for this aim, but still open questions remain concerning the real efficiency and reliability of such a system.
In this study we investigate the potential of the infrasound network of the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) to detect volcanic explosive eruptions at large distances. We apply a procedure based on the Infrasound Parameter (IP) calculated from a single array to selected volcanoes by accounting for realistic infrasound propagation conditions.
The procedure was applied to data recorded by the I06AU infrasound array (Cocos Island) between January 2012 and December 2019 and targeting Indonesian volcanoes at source-to-receiver distances ranging between 1000 and 2000 km, where activity from 11 volcanoes was reported in the period of analysis with an energy spanning from mild explosions to VEI4 eruptions.
The system reliability was evaluated from the ratio between real ones and the total number of notifications provided from I06AU array for each volcano.
The IP was calculated following previous studies and improved with new constraints accounting for the source strength and signal persistency. These allowed us to improve significantly the system reliability for events VEI3 or greater and strongly reduce the number of false alerts. Still, undetected explosive events remain due to unfavorable propagation conditions and unresolved ambiguity due to short spacing among volcanoes with respect to the array. We propose to solve this last issue by considering volcanic sectors rather than single volcanic edifices. Instead of a notification for a single volcano, an alert for an area of interest could be issued to draw the attention and trigger further analysis of satellite images by the VAACs.
This study is performed to improve the Volcanic Information System (VIS) proposed and developed in the framework of FP7 and H2020 ARISE projects.

S10 - Poster

Quantifying thermal anomalies on active volcanoes: a comparison between MIROVA and FIRMS algorithms

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Volcanic activity causes the variation of numerous geophysical and geochemical parameters that characterize the state of a volcano. Among these, the satellite-derived radiant power is increasingly used to detect signs of unrest, to follow the evolution of an eruption and to mitigate the hazard once the activity has started. In this work, we compare the Volcanic Radiative Power (VRP) provided by the Middle Infrared Observation of Volcanic Activity (MIROVA) algorithm, with the Fire Radiative Power (FRP) distributed by the Fire Information for Resource Management System (FIRMS). In particular, we compare the VRP/FRP timeseries retrieved by the two algorithms by analyzing both the Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) datasets. These analyses were carried on for several volcanoes showing different type of activities (e.g. lava flows, lava lakes, lava domes) and located in different environments. As a whole, the obtained timeseries and regression curves suggest that the datasets processed by both MIROVA and FIRMS systems are comparable and provide quite consistent estimates on the radiant power sourced by volcanic eruptions. While the two algorithms appear to be equally efficient on volcanoes characterized by a more intense thermal activity (e.g. lava flows), the MIROVA algorithm, turns out to be more efficient in detecting low-intensity (10 MW) thermal anomalies than FIRMS. The MIROVA's greater efficiency for detecting low thermal anomalies translates into a better ability to promptly detect small signs of volcanic unrest otherwise undetected by the FIRMS.

S10 - Poster

The effects of paroxysmal eruptive activity of Mt. Etna in the ionosphere: the TEC-GNSS ionospheric monitoring

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The ionosphere is a region of the upper atmosphere (50-1000 km a.s.l.) characterized by free electrons and ions produced mainly by solar radiations (UV, X) and subordinately by cosmic radiations (Ravanelli, 2021). It's a very sensitive plasma to energy variations, mostly the F2 layer (240-400 km a.s.l.) that is a region of maximum ionization with an electron density of 1000000 e-/cm^3. For this reason, the ionosphere (in particular the F region) can be seen as a field of remote sensing monitoring from which to extrapolate various informations by the natural systems that make up our planet.
About this, solid Earth (e.g. litosphere, internal structure) and fluid Earth (e.g. idrosphere, atmosphere) are two open systems that exchange energy continuously. It means that big dynamic processes (e.g. plate tectonics, genesis of magmas) can release amounts of energy, in the form of earthquakes, volcanic eruptions and correlate phenomena (e.g. tsunami), capable to perturb the terrestrial matter at every aggregation state and up to planetay scale with propagation of gravity-acoustic waves. In this field, the ionospheric volcanology is a targered discipline for the study of the effects that great volcanic eruptions (VEI > 3-4) cause to Total Electron Content (TEC) in the ionosphere (F2 level) through propagation of internal gravity waves (0.1 - 2 mHz) and acoustic waves (2 - 10 mHz). The study of the TEC's variations caused by strong geodynamic events represents a new approach with which to contribute to implementation of the monitoring and research systems in order to mitigate the volcanic and seismic risks.
The method consists to extrapolate the temporal variations of TEC during the volcanic activity period by RINEX and navigational data GNSS registered by RING (Rete Integrata Nazionale GNSS) and local GPS networks. By the way, others outputs can be derived from TEC series such as spectrograms and hodocrones in order to better understand the evolution of the electron activity in ionosphere excited by the volcanic eruption. This study method is applied for some paroxysmal eruptive activities of Mt. Etna occurred in 2021 and 2015 analyzing and comparing the seismoacoustic outputs (volcanic tremor + infrasound) with TEC outputs. The good correlation between seismic and infrasonic data can provide very important informations to identify the time interval of the paroxysmal phases, so the time interval of the GNSS satellite recording for extrapolation of TEC data. The latter have been elaborated with VARION (Variometric Approach for Real-time Ionosphere Observation) algorithm, designed within the Geodesy and Geomatics Division of Sapienza University of Rome in 2015. VARION is based on single time differences of geometry-free combination of GNSS carrier-phase measurements, using a standalone GNSS receiver and standard GNSS broadcast products (orbits and clocks correction) that are available in real time (Ravanelli, 2021).
The study on the Mt. Etna illustrates a basically positive correlation of the TEC amplitude of electronic activity with plume height and infrasonic pressure. One of the goals to be pursued in

the Research is to comprehend the differences between mechanisms (in our case eruptive) capable to generate gravity waves rather acoustic waves, and how such eruptive mechanisms may depend by physical-geometric features of the plumbing system of the volcano and by chemical-physical features of the magma and its amount of gas. The Global Navigation Satellite System (e.g. number of satellites and stations GNSS) is fundamental to have a good satellite coverage with which reconstruct a “ionospheric horizontal plane” where we evaluate the spatial evolution of the TEC anomalies caused by paroxysmal eruptive activities.

Ash fallout during the Cumbre Vieja 2021 eruption: insight from disdrometer measurements and particle microphysical properties

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Measuring the sedimentation of tephra plumes is important to provide eruption source parameters like grain size distribution for the nowcasting of atmospheric dispersion and deposition rate of ash, but also to provide insight into the space-time dynamics of ash plumes and processes controling the sedimentation.

In the frame of the EUROVOLC european program, we measured ash fallout from the 2021 Cumbre Vieja eruption (La Palma Island, Canaria, Spain) using two modified disdrometers from the VOLDORAD instrumental platform of OPGC-SNOV (http://voldorad.opgc.fr/). The goals were to test again each other one Laser Precipitation Monitor (LPM) and one Parsivel2 disdrometer and elaborate dedicated operational measurement protocols, and to study the variations in plume sedimentation in space (distance from crater) and time. The explosive activity comprised lava fountaining and modest tephra plumes from several fissural vents emitting ash and lapilli. Between 12 and 19 October, particle fallout was measured individually (LPM) and every 5 s (Parsivel2). Both instruments were first colocated at a same site about 1 km SW of the eruptive craters, then the LPM was moved at another site to record simultaneously 240 m farther away. In parallel, samples from ground collectors next to the instruments and in various sites were weighted in order to measure variations in the sedimentation rate and to compare with sensors records. The size and morphological parameters of thousands of particles were further characterized using an optical morphograinsizer (Morphologi G3, Malvern) in the range <63 microns to several millimeters and particle densities from various sieved fractions were determined by water pycnometry. These microphysical parameters will contribute to establish a best-fit law for particle terminal fall velocities important for sedimention in models, and to refine retrievals from each sensor.

S10 - Poster

The use of UAS for the aerophotogrammetric survey of lava fields and domes, and the assessment of erupted volumes of magma at Ischia (Italy)

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In the last period of activity at Ischia (13/10 ka - 1302 CE), at least 22 effusive eruptions produced lava flows and domes, mainly exposed in the eastern-northeastern part of the island and in its northwestern corner. A first attempt of volume estimation of the erupted lavas was made some years ago by superimposing on a Digital Elevation Model a mask representative of the extension of the lava bodies to be measured and performing the calculation with respect to a set of theoretical, regular reference base-surfaces.

In order to obtain a better definition of the geometric pattern of the base-surface of some selected lava bodies and make a more constrained estimate of the erupted volumes, a detailed geological survey has been performed.

The geological survey was combined with a detailed geomorphological analysis, based on the study of aerial photographs and an aerial photogrammetric survey, performed with the use of UAS equipped with a visible-range and an IR camera. The results obtained were entered as input data in the calculation of volumes, based on the processing of the images on a georeferenced cartographic base.

Through flights performed with planned missions, it was possible to produce the points cloud and the orthophotograms of the areas of interest. Further elaboration activities made it possible to “classify” the different constituent elements of the points cloud separately, distinguishing the anthropogenic elements from the natural ones. This operation on the points cloud allowed us to manage the numerous elements of the landscape separately, in order to avoid mistakes in the planovolumetric and planoaltimetric evaluations associated with the volcanic landforms that characterize the morphologies of the investigated sectors.

In particular, the volumes of the lava bodies were determined by operating profiles and sections along crossed directions, defined on the basis of the assessment of the underground pattern of the volcanic deposits. A high-resolution digital terrain model of the entire volcanic body was obtained this way.

This result was achieved through the use of a specific software (Pix4D), which, after defining the better constrained basal surface of the lava bodies, returned their volume.

This methodology was verified by importing the same point cloud and the orthophotogram into a cad environment, by making a cartographic overlay of the DTM (5m) and DSM (1m) of the Campania Region and the Metropolitan City of Naples respectively.

The preliminary calculation based on the combination of field geological and geomorphological surveys and aerial photogrammetric analysis, highlighted, in the first instance, a generalized underestimation of the volume of the lava bodies considered, at least for those bodies whose basal geometry differs significantly from that of a horizontal or simply tilted plane. This led to a recalculation of the volumes (still in progress) and leads to the suggestion of applying the tested methodology also to all the lava bodies of the last 13.6-10 ka of volcanic activity at Ischia.

S10 - Poster

Combined UAS measurements for monitoring dangerous volcanic contexts: applications at the Pisciarelli fumarolic field (Campi Flegrei) and Vesuvius crater

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Recent developments and availability of Unmanned Aerial Systems (UASs) in volcanology have contributed to major advances in monitoring active volcanoes and characterizing volcanic landforms and risks. In the past 5 years, hydrothermal activity in the Pisciarelli fumarolic field of the Campi Flegrei caldera (southern Italy) has increased dangerously. This has led local and civil protection authorities to restrict access to volcanological monitoring in the area. In this scenario, sUAS are useful in collecting immediate and real-time data, especially in inaccessible, instable, and/or hazardous, volcanic environments. Main products generated from UAS quadcopter photographs, such as digital terrain data, 3D models, orthophotos and thermal images allowed for the quickly identification of the geomorphologies of the craters at cm-scale resolution and thermal anomalies. Two different drones have been used for mapping, thermal imaging, slope stability studies, and as platforms for sensors to measure outgassing of CO_2, H_2S, CO and CH_4. Analysis derived from the digital imagery captured by the UAS allowed to identify fumaroles, thermal anomalies and volcano-tectonic structures to determine accurate landform changes and in combination with thermal image and atmospheric measurements of hydrothermal gasses to assess hazards in these dangerous volcanic contexts.

S10 - Poster

Morphometric survey of the tunnel lava of Monte Intraleo and of the Snow Cave with laser scanner and drone and application of Virtual and Augmented Reality

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The lava flow caves or lava tunnel are generated during eruptions that emitted very fluid lavas, mainly of basaltic composition and temperatures between 1000 and 1200 ° C. Large quantities of fluid lavas, released during an effusive event create these famous caves, owing to the cooling and consequent consolidation of the external surface of the lava flow. This phenomenon is facilitated by particular morphological conditions, as well as the chemical composition and temperature of the lava and its effusion rate and, last but not least, the considerable hydrostatic pressure. This phenomenon called "roofing" generates a solid rocky wall capable of maintaining, inside the tunnel, a temperature so high as to guarantee the maintenance of the fluid state of the lava and its flow downstream. After the end of the effusive event, if there is an efficient drainage, the lava tube empties and cools, leaving an empty cave as a trace of its passage. Over 200 caves have been registered in the Etna area. The in-depth study of these hypogeal environments has, for several decades, been aimed at their genesis, the observation of chemical and physical phenomena taking place within them, and the monitoring of particular microclimatic conditions and conservation. In order to anchor the studies well to the condition of the sites, it is therefore essential to know their exact consistency. In the last decade, developments in technological innovation have seen the industrialization of new tools for the accurate survey of geometries, based on increasingly high-performance systems that add value to 3D survey techniques and subsequent modelling and rendering. This work will show the qualitative value of an accurate morphometric survey, obtained by processing point clouds acquired using three different instruments, two laser scanners and a drone, in two test sites the Snow Cave and the Mt. Intraleo ones. Considering that lava tubes allow the formation of a considerably extended flow field, their in-depth knowledge is of paramount importance for correct estimation of the lava invasion hazard. Furthermore, the educational and dissemination opportunities provided by this type of product will be presented, exploiting the modern techniques of Virtual Reality and Augmented Reality.

S10 - Poster

Preliminary results of a topographic study at Grotta del Gelo ice cave (Mt. Etna, Italy)

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Grotta del Gelo is a lava tube located on the northern flank of Etna Volcano at 2030 metres a.s.l., (37°48'27.3"N 14°58'19.9"E) and represents the southernmost ice cave in Europe. The presence of perennial ice inside this lava tube, unusual at this latitude and in a volcanic contest, in strong contrast with the desert environment in which it is located, makes it one of the most fascinating place of Etna volcano.

In order to study the morphology of the Grotta del Gelo, various topographic measurement techniques were used. Starting from 2021, repeated surveys have been performed, inside the hypogeum environment, with TLS (terrestrial laser scanner) to reconstruct the three-dimensional morphology and its variation over time. For the registration of the point clouds in a global coordinate system and a continuity of the three-dimensional data in the epigeal environment, aerial photogrammetric surveys and GNSS measurements were carried out.

The measurement campaigns aim to highlight possible detachment of rock blocks from the ceiling and walls in addition to the morphological and volumetric variations of the ice deposit inside the cave. This preliminary study confirmed the decreasing trend of the ice mass. In addition, detachments of rock blocks were highlighted in some sectors of the underground environment in the last year. Further developments are planned in collaboration with specialists in other science fields (environment, glaciology, geophysics).

S10 - Poster

S11 - THE PAROXYSMAL ERUPTIVE SEQUENCES OF MT ETNA BETWEEN 2020 AND 2021

Conveners:

Giuseppe Salerno, Ornella Cocina, Salvatore Gambino, Antonio Paonita

The 2020-22 fire fountain episodes of the SE Crater of Etna: insight from monitoring data and hazard assessment

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Since December 2020, a series of 58 powerful lava fountain episodes have occurred at the South-East Crater (SEC) of Etna volcano until February 2022. The SEC activity was characterized by short and intense episodes of column-forming lava fountains that caused tephra fallout, lava flows and sometimes pyroclastic flows in the summit area of the volcano. The fountain activity led to several km-high eruptive columns, up to 10-12 km a.s.l. in some cases, producing abundant lapilli and ash fallout on the flanks of Etna and ash fallout in eastern Sicily and southern Calabria that caused both the closure of the Catania airport and major problems with air traffic. In addition, the formation of an almost continuous tephra deposit generated considerable damage to the surrounding cultivated areas significantly impacting the economy of the Etna region. During the eruptive crises, routine and new monitoring, surveillance and communication activities were carried out by INGV-Osservatorio Etneo and INGV-Palermo following scheduled protocols developed side by side with civil protection authorities at the national, regional and local levels. In particular, near- and real-time volcanological, geochemical and geophysical data were collected and potential eruptive scenarios developed to gain insights into the on-going phenomena and to forecast their evolutions.

The most intense deflation of the last two decades at Etna volcano (Italy) analyzed by GNSS and tilt data: the 2019-2021 evolution of ground and modelled pressure sources

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On 16 February 2021, an eruptive phase characterized by seventeen paroxysms from the Southeast Crater began at Mt. Etna, producing km-high volcanic plumes and large tephra fallouts, causing hazard to air traffic and impacting inhabited areas. We analyze GNSS (Global Navigation Satellite System) and tilt data from the permanent monitoring networks of Etna volcano starting after the 24 December 2018 eruption to the seventeen lava fountain episodes of February-March 2021, which produced the most intense deflation of the last two decades. We divide the period into five phases, spanning the continued inflation of the edifice, punctuated by short periods of effusive and strombolian activity, and a two-month phase of intensive deflation. We show the evolution of ground deformation and modelled pressure sources. In particular, we observed a progressive deepening over time of the pressure sources until two months before the start of the paroxysms sequence, when we modelled a fast ascending source. We explain these results in light of a recent volcanological model on the nature and behavior of magma ascending through the Etnean feeding system.

S11 - Oral Presentation

Ground tilt changes associated to Mt. Etna lava fountain episodes (2008-2022)

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At Mt. Etna, lava fountains have often occurred during recent decades mostly taking place at the South-East Crater (SEC) causing the formation of dispersal ash plumes and fall-out deposits, which may entail severe aviation hazards and more generally for the population.
Tilt signals allows detecting, monitoring and studying lava fountains; Tilt changes, recorded have a duration comparable with the episodes with low tilt amplitudes generally less than 1.0 microradian.
The first case of tilt signals recorded at more stations occurred during the 10 May 2008 paroxysm and evidenced that clearest changes were visible on radial components showing a general deflation of the edifice during the fountain.
From 2008 to 2022 we analyzed 116 lava fountains estimating the tilt moduli and directions at the stations thus obtaining long time-series of these values.
Our analyses evidenced as tilt changes are generally similar for each episode and we report some estimates about the position of the source generating the tilt signal of the lava fountain episodes.
We focused our attention on 2020-2022 period which was affected by several tens of episodes mainly distinct in two phases:
The first from February 16 to April 1, while the second begins on May 19 and continues until October 23. The first is characterized by lava fountains that are repeated approximately every two days with tilt variations comprise between 0.10 and about 0.70 microradians. The second phase is characterized by more frequent events with smaller tilt variations particularly during the June episodes. We also evidenced that there are some differences between tilt associated to the two phases.
Finally, during the sequences of lava fountains, we measured high tilt values at ECP station (until 4.0 microradians); this fact suggests that ECP is probably affect by an additional, shallower, ground deformation source.

Characterization of strain changes during the 2020-2021 Etna lava fountains

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Lava fountain is a typical and well documented eruptive behaviour at Etna volcano. In the last 30 years, more than 200 lava fountains occurred [Andronico et al., Earth. Sci. Rev., 2021]. In particular, from December 2020 to October 2021, the Etna volcano went through a phase of intense and extraordinary eruptive activity characterized by the occurrence of tens of lava fountains of different duration and intensity [Calvari and Nunnari, Remote Sens., 2022].
At Etna, lava fountains usually last few hours and are accompanied by small deformations of the shallow crust. Such tiny deformations cannot be easily detected with the usual geodetic techniques such as GPS or InSAR, because of their low amplitude and their short time scale. On the other hand, borehole strainmeters have been capable to measure volumetric strain variations of the rock related to the lava fountains, thanks to the very high resolution up to 10-11 [Roeloff and Linde, Volcano Deformation, 2007]. Particularly, the strain signal recorded by the strainmeter placed at Monte Ruvolo (DRUV), on the western flank of the volcano at about 10 km from the summit craters, can provide robust and reliable estimates of the volcano deformation since the sensor is optimally coupled with the rock and it is very sensitive to small strain variations [Bonaccorso et al., J. Geophys. Res. Sol. Earth, 2016].
The analysis of the strain changes provides important information useful to characterize the volcano activity both for research purposes and monitoring. The beginning and the ending of the strain variation provide a precise timing of the onset and the conclusion of the eruptive event [Bonaccorso et al., Geophys. Res. Lett., 2013]. Moreover, the amplitude of the strain changes can be employed to infer both the strain source position and the total erupted volume [Bonaccorso et al., J. Geophys. Res. Sol. Earth, 2016]. By combining the timing and the amplitude, the activity state of the volcano can be inferred [Bonaccorso et al., Front. Earth Sci., 2021].
In this study, we selected the strain signal recorded at the DRUV station and focus the attention on the analysis of the strain changes associated to the lava fountains occurred from December 2020 to October 2021. The goal was to highlight the similarities but also the main differences between the analysed lava fountain events. Before proceeding with the analysis, we efficiently filtered out the main disturbing components of the recorded strain signal [Carleo et al., in print, 2022] to unravel ultra-small volcano-related strain transients [Currenti and Bonaccorso, Sci. Rep., 2019]. We estimated and compared different quantities, such as the duration, the amplitude and the rate of the strain variations in order to better characterize the strain signature of the lava fountain events occurred at Etna in the study period.

S11 - Oral Presentation

Etna 2011-22: what we have learned from a decade of paroxysmal eruptions at the volcano

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During its eruptive history Mt. Etna has given birth to a wide spectrum of eruptions from both the summit craters and the volcano flanks. While the eruptive behavior typically includes mild Strombolian eruptions and lava effusions, there has been a clear growth in the number of high-energy paroxysmal eruptions at the volcano summit during the last four decades. In particular, the last decade has seen a significant increase in eruption frequency together with the development of some of the most energetic paroxysmal sequences recorded at Etna in recent times. These include the three-year-long sequence of lava fountaining during 2011-2013 and the very recent sequence of eruptions that took place between December 2020 and February 2022 at the South East Crater. These two sequences are separated by fairly long period of dominant effusive activity, such as in 2014 and 2017-2020, which were interrupted only by the two short, but powerful paroxysmal series that occurred at Voragine during December 2015 and May 2016.
The latest paroxysmal sequence began on December 13-14, 2020 after nearly two years of continuous, though weak, explosive activity at the summit chiefly at the Voragine and South East Crater. Sixty-two episodes of powerful lava fountains took place in slightly more than one year, with the highest frequency of eruptions falling into two main periods, one during 16 February - 1 April 2021, and one during 19 May - 14 July 2021. The entire 2020-22 sequence was characterized by the rising of huge eruption columns (up to 15 km of height a.s.l.), followed by abundant tephra fallout on the volcano slopes and ash dispersal up to hundreds of kilometers.
In this contribution, we present a comprehensive petrological investigation of tephra from the 2020-2022 sequence of Etna paroxysms, interpreting results in the framework of the post-2011 activity of Mt. Etna in order to provide a realistic illustration of the evolution of the volcano plumbing system. We have combined thermodynamic modeling on whole rock with micro-analytical data on volcanic crystals and glasses to investigate the physical and chemical conditions of magmas involved and the kinetics of magma movement among the different levels of the plumbing systems. Whole rock major element compositions indicate changes in storage conditions and transfer dynamics starting from the 2015-2016 eruptive period, suggesting the emission of more primitive magma during 2020-2022 with respect to the past eruptions. We have inspected the chemical heterogeneities of olivine crystals throughout the whole eruptive period, and correlated the zoning profiles to infer changing conditions of magma accumulation, ascent and recharge driving the eruptions. Fe-Mg diffusion chronometry applied on zoned crystal has been also used as a proxy to estimate the time at which such processes have occurred. One of the main findings of this study is the evidence of activation during the first months of 2022 of some of most basic magmatic environments characterizing the feeding system of Etna, whose olivine crystals having Fo_{86-87} core composition are witnesses. The modeling of the Fe-Mg diffusion of olivine normal and reverse zoning allows us to detect fast migration of this primitive magma across various magmatic environments.

S11 - Oral Presentation

Gas constraints on the source mechanisms of Mt. Etna 2021 paroxysmal lava fountains sequence

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Between December 2020 and April 2021, a spectacular sequence of 21 lava fountaining paroxysms occurred at the Southeast Crater (SEC) of Mt. Etna, while mild Strombolian activity and plume degassing prevailed at the other summit craters. This activity resulted from the influx of a batch of more primitive, volatile-rich magma into the shallow plumbing system of Etna, as shown by geophysical and petrological data. Our survey of Etnean gas emissions actually verifies a pre-paroxysmal period (from late October 2020 to 16 Feb. 2021) of strongly enhanced SO_2 and HCl plume flux (3-5 times the background), due to open-system degassing of ~$38x10^6$ m^3 DRE of the new magma through the central volcano conduits. Instead, the onset of the paroxysmal sequence at SEC coincided with a sharp drop of both SO_2 and HCl fluxes and SO_2/HCl ratio in central crater emissions. The paroxysmal events repeatedly displayed a gradual transition from growing Strombolian jets to powerful (300-800 m high) lava fountains, associated with lava overflows, and dense lapilli and ash fallout from 10 km-high eruptive column. Between each event SEC was silent and the site of weak passive degassing, with a repose interval progressively increasing from <2 to 7 days. Instead, the paroxysmal episodes involved intense SO_2 release of ~11,000 tons per episode according to satellite imaging, and high SO_2/HCl ratio (as measured with OP-FTIR). Using the composition of fountain gas previously measured with FTIR during similar events at SEC in 2000 and 2001, we preliminary infer a total gas release of ~$9x10^3$ Ktons during each paroxysmal event. Comparing such a budget with the amount of degassed and erupted magma for each event provides interesting constraints on the respective role of open-system and syn-eruptive magma degassing during these paroxysmal fountaining events on Etna.

Investigating gas emissions from Mount Etna: a 50-yr retrospective

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Mount Etna has long been recognized to be a major site of persistent gas release into the atmosphere, with its volcanic plume extending visibly for tens to hundreds of km over the Mediterranean Basin. The origins of such a voluminous persistent degassing have early promoted the curiosity of volcanologists and geochemists. Here I'll present a retrospective of scientific investigations of Etna' gas emissions conducted over the past 50 years, since first studies in the late sixties. I'll illustrate the incredible evolution over time in the instrumental tools that were used for these investigations and the remarkable advances achieved in our documentation and understanding of the magma degassing processes, volatile origins and gas emission budget at this highly active volcano. As a matter of fact, since half a century Mount Etna has been one most reliable volcano-laboratory worldwide where new technologies for gas studies could be tested and where multidisciplinary sounding of magma degassing processes has provided outstanding results.

Timely mapping and quantification of the 2020-2021 Etna lava flows through the exploitation of multi-sensors remote-sensing data

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Mt. Etna is a composite basaltic stratovolcano characterised by quasi-persistent activity at its four summit craters and quite frequent events along fissures on its flanks. In the last years, Etna eruptive activity mostly occurred in the summit area and in particular at the South East Crater (SEC). Between December 2020 and October 2021, the SEC produced more than fifty episodes of Strombolian activity and lava fountaining (paroxysms), with up to two events in 24 hours, feeding lava flows towards east, south and southwest. Since the involved area is visited by thousands of tourists, especially in the summertime, we were urged to timely map the lava flows emplaced during each paroxysm. This task has been accomplished through the integration of different remote sensing techniques, based on data availability and weather conditions. Several satellite images (Sentinel-2 MSI, Aster, Ecostress, Skysat, Landsat-8 OLI and TIRS), both in the visible and SWIR bands, allowed us to map the lava flow field at spatial resolutions from 0.7 to 90 meters. Unoccupied Aerial System (UAS) surveys of the lava flows also allowed to acquire visible and thermal images with high-spatial resolution. Finally, thermal images acquired by the permanent network of cameras, managed by the Istituto Nazionale di Geofisica e Vulcanologia, were re-projected into the topography at 5-meter spatial resolution. The analysis of a series of remote sensing data, performed through a Geographic Information Systems (GIS) software, enabled the mapping of the lava flows and the compiling of a geodatabase for collecting their main geometrical parameters (e.g. length, area, average thickness). The joint exploitation of remote sensing datasets acquired through multi-sensors has made it possible, for the first time on Etna, to characterize frequently occurring effusive events in a timely and accurate manner. These data are critical for promptly providing the necessary information for hazard assessment related to lava flow outbursts.

S11 - Oral Presentation

Tracking lava flows during the 2021 Mt. Etna eruptions using Random Forest Machine Learning algorithm

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The advancement of satellite remote sensing techniques offers a great potential for monitoring the effusive activity of any remote volcano. Generally, fixed-based threshold detection algorithms are used to map lava flow fields, even if they do not show good generalization capabilities due to the limitation of setting a priori thresholds. Machine learning techniques can be used to overcome this problem by automatically extracting the best features to generalize the learning phase. Here, a data-driven machine learning approach, based on the random forest (RF) model, is developed by using high spatial resolution Sentinel-2 MultiSpectral Instrument (MSI) images. We developed two models in Google Earth Engine to map lava flows at different volcanoes worldwide. The first one exploits the bands in the infrared portion of the spectrum and their corresponding normalized indices, the second one utilizes bands from the visible to the infrared, exploiting spectral signatures to map also cooled portions of the lava flow. To enhance the generalization power, the two models were trained at different volcanoes, e.g., Cumbre Vieja (Spain) and Geldingadalir (Iceland) volcanoes. As a test case, the 2021 Mt. Etna eruptive activity characterized by a series of paroxysmal events with lava overflows has been considered. Lava flow maps with high performances were obtained thanks to the RF good generalization capabilities. Finally, different performance indices were calculated to compare the results of the fixed-based approaches, the RF with the infrared data and the RF with visible to infrared ones, identifying advantages and disadvantages of each model.

SS11 - Oral Presentation

Hazards from pyroclastic density currents at Etna - revisited

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In the past few decades, there has been a conspicuous increase in explosive volcanism at Mount Etna (Sicily), especially at the summit craters of the volcano. In particular, brief, violent episodes of lava fountaining, tephra emission, and emplacement of fast-moving lava flows, so-called "paroxysms", have become the most common type of activity, which in the past - until the 1960s - has occurred only rarely. With this change in the eruptive behavior of the volcano, pyroclastic density currents (PDCs) have become increasingly frequent. Since my 2009 paper on PDC hazards at Etna [JVGR 180: 148-160, https://doi.org/10.1016/j.jvolgeores.2008.09.021], there have been at least 20 occasions on which PDCs were formed, all during eruptive activity at the Southeast Crater (SEC) in 2011-2014, 2015, 2017, and 2020-2022. There were three different mechanisms of generation of PDCs: (1) sliding of hot, unstable material on the steep flanks of the cone during heavy pyroclastic fallout; (2) collapse of portions of the cone triggered by the push of magma through the cone's flanks; (3) violent interaction of fast-moving lava flows with thick snow/ice on steep slopes. Type (1) and (2) PDCs are generally hot, and at least in one case (10 February 2022) partially carbonized wooden objects; it left a deposit that remained incandescent for a few tens of minutes, and retained heat for several days. Type (3) PDCs are often accompanied by small lahars; their temperatures are generally lower, but in at least one case (18 March 2017) they were incandescent and incinerated vegetation. The longest PDC recorded in this period (11 February 2014) reached a distance of 2.3 km, on the bottom of the Valle del Bove. Since December 2020, PDCs have repeatedly expanded over areas formerly visited by numerous tourists on guided tours. In particular, the partial collapse of the southern flank of the SEC cone on 10 February 2022 led to the formation of a PDC that surmounted one of the 2002-2003 cones about 1 km south of the SEC, and buried a portion of the path where visitors are commonly led to a panoramic viewpoint on the Valle del Bove rim. The rapid growth and steepening of the SEC cone in 2021-2022 have considerably increased the potential instability of its flanks, and future eruptive activity is likely to generate further PDCs, endangering areas up to 2-3 km away from their sources.

S11 - Oral Presentation

Quantification of tephra mass deposited on road network during lava activity in 2021-22 at Mt. Etna

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During explosive eruptions a large amount of tephra is dispersed and deposited around the volcano. Typically, the tephra fallout causes hardship and damages in the densely habited surrounding areas. The quantification of the tephra load accumulated on the ground is of significant interest due to the environmental and socioeconomic impact. Tephra dispersal from an explosive eruption is a function of multiple factors, including mass eruption rate (MER), degree of magma fragmentation, vent geometry, top plume height (HTP), particle size distribution (PSD) and wind velocity and pattern.

In this work we quantify the mass of tephra deposited on the road network on the eastern flank of Mt. Etna, in Italy. We start from a large dataset of short-lasting but intense lava fountain events that occurred at Etna between 2021 and 2022, and that were detected by the X-band radar, located at about 32 km from the Etna summit.

To identify the eruption source parameters, we applied the volcanic ash radar retrieval (VARR) approach to radar data. When the radar data were unavailable, we analyzed images of the SEVIRI satellite and of the visible camera images of the Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo. We focused our attention on lava fountain activity in which the volcanic plume was dispersed towards the east-southeast direction.

To simulate the volcanic ash dispersion, we used two different numerical models: TEPHRA and FALL3D; the model calibration was carried out using data collected during an eruptive event in 2021. Hence, we calculate the ash load in areas of particular interest as e.g., the administrative area of specific municipalities and/or the road network. Such a kind of specialized short-term hazard estimates can be relevant for quick planning and management of the ash mass deposited during volcanic crises.

S11 - Oral Presentation

Tracking volcanic clouds using machine learning techniques: the 2020-2022 Mt. Etna paroxysms

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A long sequence of 66 paroxysmal events took place at the Mt. Etna between late 2020 and early 2022. Paroxysms at Etna volcano were characterized by lava fountaining lasting 1–2 h, reaching the height of 1–3 km above the crater, and generating conspicuous and lengthy ash plumes that can drift hundreds of kilometers from the vents, often accompanied by short-lasting lava overflows from the crater rim. Volcanic clouds produced during these violent paroxysmal eruptions are composed of a mixture of solid ash particles and volcanic gases. These components evolve over time as the cloud disperses in the atmosphere and can have severe adverse impacts on health, environment, critical infrastructures, and economy. In fact, an ash fallout up to ~38 kg/m^2 has a strong impact on the viability, on the stability of roofs, on the air traffic (the Catania airport is about 30 km from Etna), on agriculture, on water contamination, and on the health of the local population. To assess the impacts related to a volcanic cloud, it is important to monitor its dispersion into the atmosphere. Satellite infrared (IR) sensors, such as the Spinning Enhanced Visible and Infrared Imager (SEVIRI), have been shown to be well suitable for volcanic clouds monitoring tasks. Here, a supervised Machine Learning (ML) model has been adopted to detect and characterize the volcanic clouds produced during the paroxysms of 2020-2022 at Etna. The proposed supervised approach is the Support Vector Machine (SVM), which uses as input a combination of Thermal Infrared (TIR) bands and gives as output an image with four classes: pixels rich of ash belonging to the volcanic cloud (pure ash pixel), pixels rich of SO_2 belonging to the volcanic cloud (pure SO_2 pixel), pixels characterized by mixed components belonging to the volcanic cloud (mixed components pixel) and pixels not belonging to the cloud (background pixel). We found that the SVM algorithm, exploiting information provided by SEVIRI data, allowed more reliable and confident detection and tracking of ash clouds emitted from Mt. Etna, despite some operational limitations (e.g., weather cloud coverage). Moreover, the results show that SVM, tailored to SEVIRI data, may provide accurate information about areas mostly affected by volcanic SO_2.

S11 - Oral Presentation

UV camera-based SO_2 flux observations during the Etna's 2021 paroxysmal sequences

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Volcanic SO_2 flux observations are relevant to understanding the mechanisms governing transition from open-vent, quiescent degassing to paroxysmal explosive activity, as repeatedly observed on Mt. Etna since the early 2000s. Here, we report on a SO_2 flux time-series derived from a permanent UV camera system during a ~1 year-long temporal interval encompassing the two most recent paroxysmal sequences of Etna's South-East Crater (SEC) in February/April 2021 and May/October 2021. This fully automated UV camera system, housed in the Montagnola INGV-OE hut, is designed to spatially resolve SO_2 emissions from the southern portion (SEC + Central Craters) of the summit craters' terrace, and is thus complementary to distal bulk plume observations with scanning spectrometers. This gas record is interpreted by integration with independent volcanological, seismic tremor and (ground- and satellite-based) thermal output records. Our results identify a clear acceleration in SO_2 degassing during the two 2021 paroxysmal sequences (time-averaged SO_2 flux ~3500 t/d), relative to non-eruptive (quiescent) periods (time-averaged SO_2 flux ~1750 t/d). This accelerating degassing parallels a notable escalation in seismic tremor amplitude and thermal output, which exhibit a peaky behaviour with prominent peaks associated with individual paroxysmal episodes. From this evidence, we propose that initiation of a paroxysmal sequence is controlled by a factor ~2 increase in the rate of magma transport (and degassing) in the shallow Etna's plumbing system, e.g., at pressures above the S exsolution level (~100 MPa). Our results are therefore corroborative of recent geophysical and geochemical evidence showing Etna's paroxysmal sequences are driven by over-pressure development in a ~3 km deep magma storage zone below the summit region, caused by escalating supply of fresh volatile-rich magma rising from deeper in the pluming system.

S11- Poster

Volcanic tremor and infrasonic data relative to the December 2020 - paroxysmal sequence at the South East Crater of Mount Etna

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During the last decades, Mount Etna has been the site of various paroxysmal sequences. Since 1986 there has been an evident increase in mid-intensity explosive eruptions from its summit craters, with more than 240 paroxysmal episodes. The last sequence occurred between December 2020 and February 2022 at the South East Crater (SEC), and is characterised by 62 episodes of lava fountaining varying in their duration and intensity. The prelude of this exceptional paroxysmal sequence has been characterized by almost two years (2019-2020) of persistent and weak effusive and explosive activity at summit craters (prevalently at the Voragine and South East Crater), then the eruptive behaviour of Mt. Etna shifted drastically to more energetic manifestations.

We consider here the first 21 paroxysmal eruptions, which occurred between 13 December 2020 and 1 April 2021 and were characterised by: i) formation of ash columns, with maximum height up to 15 km (asl); ii) almost ubiquitous formation of rheomorphic lava flows during the most energetic phase of the eruption; iii) occasional small pyroclastic density currents (PDCs) due to partial collapses of the South East Crater. The most important feature of this studied sequence is the marked cyclicity with which individual episodes occurred. With exception of a few events, starting from 16 February (i.e. the first part of the whole 2020-21 sequence) a number of paroxysmal episodes occurred with cyclic frequency.

In this study, we show volcanic tremor and infrasound regarding the first 21 lava fountaining episodes that took place between 13 December 2020 and 1 April 2021, in order to highlight changes in volcanic features occurred during the paroxysmal sequence. Specific goals of this work are aimed at: i) locating the volcanic tremor source and defining its shift over the time; ii) estimating the peak and cumulative amplitudes associated with each lava fountaining episode; iii) characterising the morphology of the volcanic tremor pattern; iv) characterising the infrasonic signals accompanying the eruptions.

S11- Poster

Volcanic tremor investigation through seismic and infrasonic advanced monitoring

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Volcanic eruptions have an important social and economic impact on the life of local populations living near active volcanoes, causing loss of life, damage to infrastructure, and disruption to aviation. Mt. Etna (Italy) is one of the most active multi-vent volcanoes in the world, exhibiting persistent degassing activity, sudden episodes of paroxysmal activity and/or significant lava flows from its summit craters and recurrent flank eruptions. Due to the rapid changes observed in location and style of eruptive activity, monitoring the paroxysmal activity at Mt. Etna remains a challenging task. Seismic tremor has long been considered as an important and reliable precursor of eruptive activity and magma migration at volcanoes. By using traditional seismic networks, tracking of volcanic tremor source over time could represent a further challenge since it requires good azimuthal coverage and high station density. In this case, traditional seismic location methods cannot be performed, due to the non-impulsive nature of seismic tremor, its lack of clear body wave arrivals and the rapid loss of waveform coherence with increasing inter-station distances. On the other hand, by using seismic arrays, which exploit the coherence of the seismic wavefield over short inter-station distances, it is possible to detect tremor sources, and track their evolving location over time. Monitoring active volcanoes through the deployment of infrasound sensors is also becoming increasingly commonplace. The joint seismo-acoustic analyses hold potential to study the magma dynamics into the shallower plumbing system of volcanoes. In this study, we analyzed seismic and acoustic data acquired at Mt. Etna during 2021 summertime, by a small-aperture seismic array and a seismo-acoustic station. During this period, paroxysmal activity affected the southeast sector of the volcano summit, while explosions and degassing activity focussed on the craters in the central and northeast summit area. From analysis of pre- and syn-eruptive seismo-acoustic data, we retrieve systematic variations, preceding consistently the onset of paroxysms, associated with the changes in the style and location of activity across different craters in the summit area of Mt. Etna. The detection of these shifts could allow the development of new strategies, based on more extensive use of seismic arrays, able to provide significant improvement in early warning systems at multi-vent volcanoes. This study is supported by the project SINFONIA, progetto Bando Ricerca Libera 2021- Delibera 214/2021-INGV.

S11- Poster

Effects of topography on the partitioning of elastic energy in atmosphere and solid Earth: 2021 Mt. Etna case study

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Mount Etna is known for its persistent and largely variable eruptive activity from both the summit craters and the flanks of the volcano. Over the past 20 years, Mt. Etna has been frequently affected by paroxysms, which have taken place at the summit craters. In 2021, Mt. Etna has been characterized by a sequence of paroxysms. From 16 February to 23 October, 54 paroxysms took place at the South East Crater (SEC) and gave rise to lava flows rapidly propagating towards East, South, and South-West.

We analyzed volcanic and infrasonic tremor accompanying these 54 paroxysms, which occurred in two distinct periods, and it was possible to identify two cycles: the first cycle began on 16 February and ended on 1 April 2021 and was characterized by 17 paroxysms with intervals from a few hours to 7 days; the second cycle began on 19 May and ended on 23 October 2021. In the second cycle, 37 paroxysms occurred, with intervals ranging from a few hours to almost one month. The analyses of volcanic and infrasonic tremor were performed on the recordings of 7 stations located at Mt. Etna at distances ranging from 1 km up to 8 km from SEC. By integrating the seismo-acoustic data with two detailed digital surface models (obtained during the two eruptive cycles of 2021) and with results of acoustic 3D numerical simulation, we investigate how the local topography and the propagation effects can influence the relative partitioning of elastic energy in the atmosphere and solid Earth.

S11- Poster

Relationship between volcanic tremor and SO_2 emission at Mt. Etna between the 2008 and 2015

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Open-conduit volcanoes are characterized by considerable outgassing and seismo-volcanic signals. In order to better understand the volcanic activity, the volcano monitoring has been widely implemented in recent "decades volcanoes", leading to an increase in the number of sensors with an improvement of their spatial and temporal resolution, which has allowed a better correlation between different parameters. One example is the association between seismic and geochemical parameters and the eruptive activity. Our work focuses on the relationship between the bulk SO_2 fluxes emitted from the summit craters and seismic-volcanic events and the eruptive activity at Mt. Etna in the period between January 2008 and December 2015. Results showed the two parameters correlated with respect of the volcanic activity both for magnitude and temporal scale. By statistically post-processing the geochemical and seismic temporal series, we have obtained an 'index of pressurization'. Temporal inspection of the index indicates its changes in magnitude correlated with the gas flow dynamics able to trigger pressurization-depressurization of the very shallow part of the volcanic conduits. Here we show the first results and correlation with volcanic activity providing an interpretation behind the process.

S11- Poster

Ballistic particles and main eruption conditions during the lava fountains of 21 February 2022 at Mt. Etna

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During the last two years more than sixty lava fountain events occurred at Mount Etna volcano (Southern Italy), which have formed high eruption columns rising up to 15 km above sea level. During those events larger clasts felt around the volcano flanks, sometimes reaching touristic areas. The rather frequent activity poses questions on how we can estimate the hazard associated to fallout of this pyroclastic material, quantifying their impact. In this work we present field data collected after the last lava fountain event occurred on 21 February 2022. This eruption produced a volcanic plume higher than 9 km above sea level with ash dispersion directed primarily toward SE. Several larger clasts felt in the area of Mts. Barbagallo (just southeast of the summit area at around 2900 m a.s.l.), which is one of the most popular touristic areas on Mt. Etna volcano. We collected several samples, performing for all of them laboratory analysis in order to retrieve size, shape and density. We also tested a new method to analyse particles shape directly on the field by using image analysis techniques. Main features of collected samples were hence used to estimate the drag coefficient and to run a free-available calculator of ballistic trajectories for volcanic particles ejected during volcanic eruptions. We therefore estimated the main eruption conditions that occurred during this lava fountain event and compared them with other data obtained by other remote sensing sensors.

S11- Poster

On the physical models and numerical algorithms for the simulation of lava flows and their interaction with topography and structures

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Lava flows are complex phenomena that involve numerous physical processes. Among these, phase transitions and interactions with irregular topographies of volcanic environments can result in complex and non-intuitive behaviors of the flow. Numerical models constitute a precious tool for the prediction of the emplacements, however, taking into account all the processes can be challenging for numerical and computational reasons. Many models and codes have been developed, varying in complexity of the implementation and execution time, and consequently in accuracy and level of description of the flow. We will talk about the features that a model for lava flows should include, giving an overview of the main available models and discussing their applicability. We will focus on the Smoothed Particle Hydrodynamics (SPH) method, as one of the most complete representations of lava flows. SPH is a Lagrangian and particle based mesh-free method, shighly versatile thanks to its ability to deal with complex flow features and its extensible implementation to parallel computing hardware, which improves simulation speed. We will discuss the current applicability of the method, showing examples of validation for lava flows, and we will talk about its potential, by showing some preliminary simulations of lava-environment and structures interactions.

S11- Poster

S12 - THE 2021 UNREST OF VULCANO, AEOLIAN ISLANDS (SICILY): NEW INSIGHT FROM MONITORING DATA AND HAZARD ASSESSMENT

Conveners:
Mauro Coltelli, Stefano Branca, Francesco Italiano, Augusto Neri

The 2021 ongoing volcanic unrest at Vulcano island (Italy): clues from the INGV multidisciplinary surveillance network

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Vulcano, the southernmost island of the Aeolian Archipelago in the Tyrrhenian Sea, has developed a fumarolic activity since its last eruption in 1888-1890. The main fumarolic field is located in the northern part of La Fossa crater, with temperature ranging, in the last decade, from 100°C to about 400°C. Other low temperature fumaroles (100°C) occur in the Baia di Levante, while widespread soil CO_2 flux anomalies are detected in the Vulcano Porto area and on the lower flanks of the cone. During the 80's of last century, an embryonic geochemical and geophysical surveillance network, now managed by the Istituto Nazionale di Geofisica e Vulcanologia, has been deployed on Vulcano island. The network was progressively implemented and, nowadays, it includes the monitoring of seismicity, ground deformation, thermal aquifers, soil degassing, fumarole chemistry and temperature, and plume chemistry. The network detected some episodes of volcanic unrest, occurred in 1987-1990, 1996-1998, 2004-2005. All episodes were characterized by the enhanced concentration of acidic gas species, increase of temperatures, exhaling surface area and steam output from fumarolic vents [Paonita et al., 2013 and references therein]. Marked variations were also observed in temperature, water level, and the chemical and isotopic compositions of thermal waters, as well as in soil CO_2 degassing outside the fumarolic field and on the lower flanks of the La Fossa cone [Capasso et al., 1999; Diliberto et al., 2002]. These episodes were usually accompanied by an increase of seismicity produced by the dynamics of shallow fluids, and ground deformation, mostly related to the massive fluid loss from the hydrothermal system [Gambino and Guglielmino, 2008; Alparone et al., 2010]. Conversely, regional tectonics produces peculiar seismicity and deformative patterns, which can affect the volcano-hydrothermal dynamics at more local scale [e.g. Alparone et al., 2019; Bonforte and Guglielmino, 2008; Mattia et al., 2008; Gambino et al., 2012].
In September 2021, a new unrest phase started and is still running. The gas and steam output from the crater drastically increased, and in few days produced an impressive plume. Geochemical stations, measuring the soil CO_2 degassing close to the fumarolic field, recorded an impressive ramp, with a flux increase by almost one order of magnitude. In September, the magmatic contents in the crater fumaroles was the highest ever measured since the beginning of the record, in 1988. Local seismicity sharply increased and was characterised by the appearance of VLP events (peak frequency 0.2-0.3 Hz), never recorded since the broadband network installation in 2006. Moreover, an increase in the earthquake occurrence rate has been observed from October 2021 in the Lipari-Vulcano area, characterized by very low energy release. Permanent GPS and tiltmeter networks measured almost 3 cm dilation and 2 cm inflation of the La Fossa cone.
Some signs of the impending crisis were already evident in July 2021, when the CO_2 content in the crater fumaroles started to increase, parallel to an increase of soil CO_2 degassing east of the fumarolic field. The fumarole outlet temperatures on the rim and northern inner flank of the crater clearly increased by some tens of Celsius degrees.
In October, the massive degassing activity also affected the lower flanks of the cone, by an increase of CO_2 flux by more than one order of magnitude. Meanwhile, some anomalies in chemo-physical parameters appeared in thermal aquifers in the same areas. Most of the above

parameters increased until end October- early November, when the crisis reached its climax, testifying a massive increase of the output of gas and steam, deduced from the plume measurements of SO_2 flux.

After November, the monitoring system revealed either the persistence of anomalies for some parameters or, on the contrary, the gradual or even drastic decrease for others. At present (June 2022), the entire set of monitoring parameters is slowly decreasing although the geochemical anomalies are still evident and some parameters are far from their background levels.

In this paper, we present a comprehensive report on geochemical and geophysical data acquired in the period between July 2020 and April 2022, which provided a robust interpretative framework of the evolving unrest. We discuss the timing of the changes in the different monitored parameters and the inferences on the processes occurring in the volcano-hydrothermal system.

Variation of CO_2 emissions diffused from the soil during the 2021-2022 crisis of the La Fossa volcano (Vulcano, Aeolian Islands)

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After the eruption of 1888-1890, the La Fossa volcano on the island of Vulcano has been affected by periodic crises, mainly characterized by variations in geochemical parameters. In particular, an increase in temperature, concentration of magmatic gases and flow rate of crater fumaroles was observed.

Diffuse emissions of gas from the soil at the base of the cone also increased. Carbon dioxide (CO_2), the most abundant gas released at Vulcano Porto, has created inconvenience and dangers to the inhabitants in the past.

In September 2021, a new crisis (still ongoing) began, which showed a strong increase in degassing from the crater, as well as anomalies in seismic activity and ground deformations. To assess the danger of diffuse CO_2 emissions from the soil at Vulcano Porto, a detailed survey on the efflux of CO_2 from the soil was carried out in November 2021 (1000 points; area 2.5 km^2). The total CO_2 flux was estimated at 312 tons / day. This value is very high considering that in December 2005, during a previous crisis, a total flow rate of CO_2 of about 100 tons / day was estimated from the same area.

From this investigation, the areas with anomalous release of CO_2 from the soil emerged. In particular, the maximum values were measured in the Camping Sicilia area, in a NW-SE oriented band, radial to the crater of La Fossa, as well as in the two already known locations of Palizzi at the base of the cone and of Faraglione-Mud pool-Levante beach.

Starting from October 2021, monthly surveys were carried out in the three target areas (Palizzi, Camping Sicilia, Spiaggia di Levante) chosen in order to monitor the trend over time of the flow of gas emitted from the ground. From November 2021 to May 2022 in the Camping Sicilia area, CO_2 emissions from the soil decreased by an order of magnitude in accordance with the general slowdown of the crisis. At Spiaggia di Levante, after a decrease in the soil CO_2 flux recorded starting from March 2022 (5.20 tons / day), a new increase in emissions was instead observed at the end of May 2022 (from 6.0 to 13.5 tons / day respectively on 6 and on 26 of May) in particular in the sector of hydrothermal emissions of the Mud Pool.

The results of the soil CO_2 flux surveys conducted in Vulcano have highlighted that the La Fossa crisis affected the entire Vulcano Porto area, creating a high hazard in some sectors, such as at Camping Sicilia, where on November 2021 numerous animals died. In 2022, in the target areas of Palizzi and Camping Sicilia, diffuse degassing remained substantially steady at average but still anomalous values, and well above the background. The area of the Mud Pool-Levante Beach is affected by a new strong rising in the degassing rate, which can lead to dangerous gas emissions for the many tourists and bathers expected in the summer season.

S12 - Oral Presentation

Soil CO_2 flux surveys at Vulcano during 2021

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The volcanic gas emissions at Vulcano, Italy, occur from fumaroles at the crater cone and Levante beach. This fumarolic activity became after the 1888-1890 eruption and has been punctuated by changes in the gas output and gas emission temperature that persisted from several months to a few years. The increase in the gas output is accompanied by the increase in the emission temperature and notable changes in the chemistry of the fumarole gases, in the isotopic composition of some species of the fumarole gases, and changes in the chemical-physical parameters of the thermal groundwaters in the peripheral zones. These are termed "crisis" events. The diffuse degassing at Vulcano Porto accounts for 10% - 50% of the volcanic CO_2 output. The anomalous degassing occurs at the zones of Palizzi and Faraglione. The monitoring of soil CO_2 flux (φCO_2) can help to track the changes in volcanic activity. In 2021, the island of Vulcano experienced a significant increase in fluids emissions, which affected not the crater zone of La Fossa volcano as well as the inhabited area at Vulcano Porto.
The increase of volcanic degassing can have a significant impact on accessibility in some areas of Vulcano and, consequently, on the economy of that island which is based on the tourism industry. While people perceive for themselves the risk that depends on an erupting volcano, the volcanic risk correlated with gas emissions (i.e., the "gas hazard") is still underestimated. The high increase in CO_2 emission in this area caused a strong increase in the gas hazard that was drastically evidenced by the death of some domestic animals in October and by the occurrence of some cases of breathing difficulty for people living nearby.
This study examines diffuse degassing and the gas hazard at Vulcano from September to November 2021. Four surveys of φCO_2, soil CO_2 concentration measurements, and soil gas collection were performed on a sampling grid consisting of 53 fixed points. The φCO_2 was measured by following the "dynamic concentration" method. An IR spectrophotometer has been used to measure the CO_2 concentration (i.e., both dynamic concentration and soil CO_2 concentration). The soil gas samples were analyzed in the laboratory for $^{13}C/^{12}C$ ratio determination in the soil CO_2 ($\delta^{13}C$-CO_2). Isotopic measurements were performed by a laser-based analyzer. The dataset collected onsite and in laboratory enabled partitioning of φCO_2 between volcanic and biogenic origins by an isotopic mass balance model. Partitioning of the soil CO_2 allowed evaluation of volcanic CO_2 by scaling φCO_2 down for the mixing proportions with the biologic CO_2.
Periodic soil gas surveys help in volcanic surveillance and risk management at Vulcano. In September 2021, the lateral variations of the soil CO_2 emissions did not show relevant differences from previous surveys. The distribution of the soil CO_2 flux was comparable with a temporary increase in the soil CO_2 emissions that occurred in 2018. During these surveys, the isotopic measurements revealed that a great portion of volcanic CO_2 was observed in the soil CO_2 discharged by the anomalous degassing zones at Faraglione and Palizzi. The isotopic signature revealed also that the soil CO_2 in the large part of the inhabited zone of the Vulcano was of biogenic origin. In October 2021, several notable changes occurred in the diffuse degassing. First of all, the absolute values of the soil CO2 flux increased notably throughout the inhabited zone of Vulcano Porto. Besides Palizzi and Faraglione, anomalous degassing from volcanic origin occurred at Camping Sicilia and Piano delle Baracche. In the period from

September to October 2021, the volcanic CO_2 replaced the soil respired CO_2 in the large part of the zone of La Fossa caldera at Vulcano. The data of two surveys collected in November 2021 show that the soil CO_2 emissions from volcanic origin further rose radially from the base of the La Fossa cone to the peripheral zone of both Lentia and Saraceno mountains. The integrated analysis of φCO_2 and $\delta^{13}C$-CO_2 allowed the calculation of the CO_2 amount from the magmatic origin that was emitted from September to November 2021. The results of this computation showed a notable increase in the volcanic degassing. During this period, Vulcano emitted ~ $40000 \cdot 10^4$ kg cumulative CO_2. The volcanic CO_2 estimation obtained in this study compared with data retrieved from the literature on the plumbing system of Vulcano suggests that the instability of an underlying magmatic lying at the Moho boundary depth triggered the increase in the volcanic emissions that caused the recent "crisis". The results of this study show that the soil gas surveys provide valuable information for early detection of volcanic degassing changes and allow establishing prompt actions for volcano surveillance and risk mitigation.

The effects of volcanic degassing on the air composition revealed by stable isotope surveys

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Volcanoes are active players for changing the composition of the atmosphere, by injecting volcanic gases into the troposphere for millions of years. When injected at stratospheric highs during a super-eruption, volcanic gases and particles can change the weather patterns and produce short-term climatic fluctuations. Therefore, the impact of a volcano on the environment is not only correlated with the eruptions themselves, but also with gas releases. On the small spatial-temporal scale, the changes in the gas emissions during the transition toward a high level of volcanic activity can generate air toxicity. Carbon dioxide (CO_2) and hydrogen sulfide (H_2S) are the main cause of concern. Mild intoxication by H_2S causes irritation, weakness, and nausea that disappear with exposure to fresh air. However, discomfort is easily perceived by human receptors because H_2S has a pungent odor at a very low concentration in the air (i.e., 1 - 2 ppm vol). In contrast, high CO_2 concentration in the air can't be easily detected by human receptors because it is an odorless major component of the atmosphere (i.e., ~400 ppm vol). This aspect is of particular interest at Vulcano and is common in other volcanoes where gas emissions occur in the nearby of the settled zones.

Previous studies have correlated changes in the air CO_2 concentration with changes in the degassing activity, but a few of them have investigated the isotopic composition of the air CO_2 in a volcanic zone. This study reports on the results of four surveys for stable isotopes in the air CO_2 at Vulcano from August 2020 to November 2021. Volcanic CO_2 has a carbon isotopic signature that is less ^{13}C-depleted than ordinary atmospheric CO_2 and an injection of volcanic gases in the air establishes a sensitive increase of $\delta^{13}C$-CO_2. The oxygen isotopic composition of volcanic CO_2 also differs from that of the CO_2 in the air which is usually unpolluted by a volcanic gas plume. Therefore, both $\delta^{13}C$-CO_2 and $\delta^{18}O$-CO_2 allow us to track the impact of the volcanic degassing on the nearby gas vents.

We carried out the first field survey at Vulcano Porto in August 2020 that aimed to inspect lateral variations of $\delta^{13}C$-CO_2, $\delta^{18}O$-CO_2, and the air CO_2 concentration. That survey provided useful results to fine-tune the method to investigate the lateral variations of the isotopic composition of the air CO_2. Two surveys were performed on 2021, June 16 to evaluate the effect of volcanic degassing under the various experimental conditions (i.e., environmental variables during morning and afternoon, respectively). Since late summer 2021 at Vulcano, the gas emissions showed notable changes in both the amount and composition. These variations are termed "crisis" and have punctuated several times the quiescent fumarolic-solfataric degassing after the last explosive eruption occurred in 1888-1890. Two surveys were performed to evaluate the lateral impact of that increase in volcanic gas emissions during the period October to November 2021.

A mobile laboratory was equipped by using an off-road car hosting a laser-based spectrophotometer which has selective detection for ^{12}COO, ^{13}COO, and $CO^{18}O$ isotopologues allowing calculation of both $\delta^{13}C$-CO_2 and $\delta^{18}O$-CO_2. The instrument records the measurements at 1 Hz, while a GPS onboard provided the positioning of the sampling point. The correspondence between measurement and position has been established by synchronization of the internal clock of the spectrophotometer with the clock of GPS. A specific route has been planned by using the tracks of Vulcano to investigate the isotopic composition of the air CO_2 in

the island that extends from Vulcanello to Discarica and includes Vulcano Porto. Each survey required almost two hours of fieldwork and provided datasets for $\delta^{13}C$-CO_2, $\delta^{18}O$-CO_2, and the air CO_2 concentration Each dataset includes > 5000 measurements for each variable. Data processing occurred by an isotopic mass balance model that allowed the partitioning of air CO_2 between the air and volcanic gases.
The results of these surveys show that the volcanic CO_2 affects the air CO_2 concentration near both the mud pools at Faraglione during periods of ordinary to low levels of gas emissions. The volcanic emissions cause an increase in air CO_2 concentration either during a period of a low wind speed or an increase of volcanic degassing. Specifically, during a period of "crisis", volcanic CO_2 has been detected throughout the village of Vulcano Porto. Furthermore, the CO_2 partitioning shows that volcanic CO_2 achieves a very high concentration near the anomalous degassing zones of Faraglione, Palizzi, Camping Sicilia, and Piano delle Baracche during a period of intense volcanic degassing.
The lateral survey of stable isotopes in the air CO_2 allows the estimation of volcanic CO_2 in the air and reveals the origin of the gas hazard. These results can help to identify the point of interest for mitigating the volcanic risk related to gas emissions at Vulcano.

Three dimensional magnetotelluric modeling of Vulcano Island (Aeolian archipelago, Italy) and its implications for recent volcanic unrest

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The raising, from green to yellow, of the alert level concerning Vulcano has led to an increase in scientific attention and monitoring activities concerning the island. In this context, one of the main research topics to increase the knowledge of this volcanic system is related to the characterization of the volcano-tectonic structures of the island and their relation with the geothermal system. An optimal tool for the study of deep buried structures is represented by the reconstruction of the spatial distribution of electrical resistivity, which is a physical parameter particularly sensitive to factors such as temperature, porosity, permeability, and the presence of fluids.

Magnetotelluric (MT) represents the geophysical method able to determine the electrical resistivity by the simultaneous measurement of the time variations of the electric and magnetic fields induced in the subsoil by different external sources. In volcanic environments, this method is regularly used for the characterization of the shallow geothermal system, both in terms of geometry and fluids characterization, as well as for the study of the main volcano-tectonic discontinuities and the deep sources.

To produce an electrical model of the central-northern sector of Vulcano island, an MT campaign was carried out in October 2021, through the realization of 53 independent surveys. Measurements were carried out with a Stratagem EH4 instrument to acquire signals in the [10-1-105] Hz frequency band.

The obtained resistivity imaging identified the three-dimensional electrical pattern of the investigated sector down to a depth of 2 km b.s.l., highlighting the structures of the La Fossa caldera except for the submerged portion that lies outside the surveyed area. The geometry of the resistivity anomalies, associated with distinct processes and physical conditions in the system, well elucidates the different volcano-tectonic lineaments that have characterized the volcanological evolution of the Vulcano island and provides useful indications for understanding the interaction between lithostratigraphic setting, and fluid circulation, and the recent dynamics recorded on the island.

One of the most significant structures detected by the magnetotelluric survey is a resistive anomaly (hundreds of m), located at La Fossa crater, which continuously deepens to the maximum depths detected (2 km) and represents a conduit-type structure, along which there is a preferential ascent of fluids of magmatic origin. In the crater zone, the top of the resistive body coincides with the position indicated by the modeling of the ground deformation data for the source of the processes currently underway. Also along the same iso-resistive that identifies the top of this structure, in the NE sector, located at a greater depth, the source of the VLP earthquakes has been identified. It would therefore be located in an area characterized by the contrast between the resistive anomaly that identifies the rising magmatic fluid conduit and the shallower conductive anomaly that represents part of the geothermal system of Vulcano.

Furthermore, the resistivity anomalies are mainly aligned in the N-S direction and contain the outgassing structures of the N-NE sector of the crater, La Forgia Vecchia and Faraglione/Spiaggia di Levante, and they probably represent the sector of the island where, in addition to the ascent of magmas from recent activity, the largest quantities of fluids from the deep accumulate/channeling. The model also shows that the higher resistivity bodies emerging at the surface mainly correspond to a series of volcanic buildings, craters, volcanic conduits, and/or eruptive fissures. The deep structures imaged by the model become very significant in light of the interpretation of the possible unrest dynamics at Vulcano, as MT investigations have shown in some active volcanic systems elsewhere in the world.

A deep learning approach to monitor the thermal anomalies associated with the 2000-2022 exhalation activity in Vulcano Island (Italy) using ASTER

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Over the last decades, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) onboard of TERRA satellite has provided a huge amount of thermal measurements available globally to monitor volcanic thermal activity. ASTER has allowed to routinely investigate volcanoes in remote and inaccessible regions, including those with no ground-based monitoring, thanks to its high spatial resolution and thermal bands available. Since the dataset produced is too large to be manually analyzed on a global basis, deep learning algorithms allow to automatically extract volcanic thermal features. We apply a Convolutional Neural Network (CNN), specifically UNET, to catch subtle to intense thermal anomalies exploiting spatial-based volcanic features. We applied this approach, to measure the thermal anomalies associated with the gas emissions taking place at Vulcano Island, Aeolian Archipelago, Italy. The fumarolic activity of both la Fossa crater and Baia di Levante areas are investigated. Time series analysis of the last 20 years over these areas is performed with particular emphasis on the on the thermal changes registered in the period of June 2021–June 2022. The results demonstrate the potential applicability of the proposed approach that has allowed to describe accurately the level and duration of the exhalative crisis that has affected Vulcano Island.

S12 - Oral Presentation

Detection of thermal unrest at La Fossa crater (Vulcano Island, Italy) using VIIRS imaging bands

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We present the preliminary results of the analysis of VIIRS (Visible Infrared Imaging Radiometer) imaging bands (at 375 m spatial resolution) data that reveal how this sensor can measure the heat flux radiated by La Fossa crater (Vulcano Island) with unprecedented frequency and accuracy. The application of the MIROVA (Middle Infrared Observation of Volcanic Activity) algorithm to the VIIRS dataset (2012-2022) allowed to measure the Volcanic Radiative Power (VRP) emitted by the fumarolic areas and to timely detect the phase of major unrest started in September 2021 (still ongoing at the time of this writing). Notably, the 10-years-long timeseries allows detection of a departure from the steady-state thermal emission which preceded and which accompanies the ongoing phase of volcanic unrest. By early October the anomalous VRP had peaked to its maximum then started to gradually decline in the following months. A minor thermal pulse was recorded in May 2022 in correspondance a submarine degassing episode suggesting a possible link between central and distal degassing processes. The analysis of VIIRS data presented here opens new frontiers in the thermal monitoring of quiescent volcanoes, especially those characterized by high-temperature fumarolic activity.

Satellite time series analysis: a statistical approach. The Vulcano Island 2021 crisis

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Satellite images are increasingly used as a tool to support volcanic surveillance. In order to accomplish this activity, sensors collecting images at Thermal InfraRed (TIR) wavelengths have been used. Specifically, in this work, we considered the TIRS sensor, on board the Landsat 8 satellite mission (launched in 2013) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor, onboard to the Terra satellite (launched in 2000). These data, both analyzed at 90 meters of spatial resolution, allow to retrieve the Land Surface Temperature (LST) parameter. The aim of this work is to test algorithms employing these sensors for the detection of changes in volcanic activity.
We focused our attention to the last hydrothermal crisis of Vulcano Island (Sicily, Italy). This crisis showed significant changes in geochemical parameters: increasing in temperature values of fumaroles and in CO_2 and SO_2 fluxes on "La Fossa" cone site. Due to these changes, the alert status of the island, declared by the Italian civil protection department, changed from green to yellow.
The use of both TIRS and ASTER sensors allowed us to analyze up to 308 images acquired in the period from 2000 to 2022; these images were used to obtain 308 LST maps and pile up in a LST time series.
We focused our analysis on a ROI (Region Of Interest) of 10x10 pixels centered on "La Fossa" cone. With a statistical approach, we calculated the standard deviation of each LST map and analyzed its variation in time.
The promising result obtained from this analysis suggests that a simple methodology can generate a reliable information useful to remotely study changes in the surface thermal state of Vulcano Island.

S12 - Oral Presentation

Volcanic-related flank instability at Vulcano island

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Volcanoes are systems typically connected to a wide range of dangerous phenomena, which can occur during both eruptive phases and unrests, and among these slope instability phenomena. Vulcano island, the southernmost island of the Aeolian archipelago (South Mediterranean), was affected during the 1988 volcanic crisis by a tsunamigenic landslide, which ran along the north-eastern flank of la Fossa cone. The recent, still ongoing volcanic crisis, has prompted a research activity aimed to identify the potential unstable areas at La Fossa cone. This work has been based on fieldwork, GIS and satellite analyses, such as INSAR data, high-resolution DEM, slope map, geological cartography and the distribution of high and low temperature fumarolic areas. Several (13) possible source areas for landslides have been identified, most of which with an associated tsunamigenic potential. In addition, a methodology to obtain the potential instable mass volumes in case of landslides has been set up by using GIS resources. The results show that the hazard associated to flank instability of this active volcanic structure is high even for small landslides, due to the location of most of the instable slopes in close proximity of the inhabited areas, often highly exposed to touristic exploitation.

S12 - Oral Presentation

Analysis of seismic signals accompaignying the unrest of Vulcano in 2021

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This thesis deal with seismic data recorded in September-October 2021 period at Vulcano. In particular, count and visual classification of signals recorded by the vertical component of IVCR station (nearest to La Fossa crater) were carried out and, subsequently, the comparison between the results obtained by this visual inspection and the temporal series derived from the automatic analysis of seismic events performed by INGV was performed. Thanks to visual analysis of the seismograms, 9,399 volcanic seismic events were identified, most of which present VLP component. A dataset was compiled gathering various information, such as time, amplitude and frequency component (LP, VLP, HF, TR) of every single event. Also, graphs were created to show the variation in time of the daily number of events, as well as of the cumulative amplitude for the analyzed period. By Matlab software, it was possible to obtain detailed information about the spectral content and source localization (by using radial semblance method) of some of the detected events selected on the basis of frequency, amplitude and signal/noise rate. The data obtained by both visual inspection and automatic analysis allowed a deep study of the seismic events that occurred at Vulcano in the September-October 2021. In particular, three seismic cycles were recognized, the first one from 14/09 to 24/09, the second one much more intense from 27/09 to 12/10, and the last one from 18/10 to 21/10. During these periods, increases of VLP occurrence rate and amplitude took place. Comparisons between the results of this visual inspection analysis and the ones obtained by the INGV automatic detection system were performed dividing the events into two groups: 1 Hz. The automatic system underestimated the number of events by about 7,500 events but it is worth noting that the temporal series follow the same trend. The VLP events, chosen from the dataset, were located at about 1 km NE from La Fossa crater, near Punte Nere zone, at 0.6 - 1.2 km depth. Furthermore, a multidisciplinary comparison with tilt and geochemical data, reported on INGV weekly bulletin, was carried out. The work of analysis and comparison performed in this thesis led to the following conclusions. During the September-October 2021 period, the Vulcano Island was characterized by important geochemical and geophysical anomalies. By the shallow VLP source location, we can suppose that these signals are generated by the increasing interaction between magmatic fluids and the hydrothermal system, giving rise to increase in flux and temperature of gases raising to the along fracture system, generating seismic waves. The analyses performed in this thesis can be the groundwork for next studies that could investigate longer time intervals, and can also help with the monitoring activities and the volcanic hazard assessment of Vulcano Island.

S12- Poster

Subsurface stratigraphy, mineralogy and petrophysics at the Vulcano island (Southern Italy): recovering data for ground deformation and hydrothermal modeling at the unresting volcanic system

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Vulcano (Aeolian Arc, Southern Italy), a well-known active volcanic island whose last eruption was in AD 1888-90 AD, is under an unrest phase since August/September 2021. Ground deformation (uplift) has been recorded on the N-NE sector of La Fossa cone, in association with low-magnitude seismicity, while CO_2 and SO_2 emissions increased and spread over larger areas of La Fossa. Numerical modeling of the ground deformation, hydrothermal circulation and alteration, can aid to understand the unrest dynamics, study the energy transferring through the edifice and constrain the triggering source. Tough, a realistic knowledge of medium parameters in term of stratigraphy, lithology and petrophysics of the subsurface rocks is mandatory for such a modeling.

Here, we present preliminary results of our research funded in the frame of the Pianeta Dinamico-Task V2 project. Based on the existing information from AGIP's drillings and the outcomes from new field studies, we propose a representative stratigraphic succession of volcanic units in the Vulcano subsurface down to ca. 1000 m, i.e. spanning from the shallower convective to the deeper conductive portions. Therefore, recognized rock units were sampled and characterized by combining optical microscopy (OM), electron microscopy plus energy dispersive micro-analysis (SEM-EDS), X-ray diffraction (XRD), X-ray microtomography (Mct) and mercury Injection capillary Pressure (MICP) test. The studied rocks are porphyritic to glassy, display different textures, display shoshonitic, latitic to trachytic and rhyolitic compositions and show a variety of hydrothermal alteration and mineralization. Texture, porosity, permeability, and mineralogy information will be parameterized and can be used as input data for numerical modeling of ground deformation, hydrothermal circulation and alteration, and to investigate the spatial and temporal variation of monitored phenomena as well as to understand the behavior of the hydrothermal system.

S12- Poster

Modelling erosion and floods on the Island of Vulcano (Italy)

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Volcanism modifies boundary conditions of the site hydraulic structure by depositing large volumes of volcaniclastic material, increasing erosion rate and drainage mass (water and sediment) flux. This work focuses on the La Fossa cone on Vulcano Island (Aeolian Archipelago, Italy), where the erosion and transport of volcaniclastic material have been both described as ongoing processes and identified in the geological record. The erosion phenomena that affect La Fossa cone and the floods of the inhabited area of Vulcano Porto do not generate serious problems for human lives, but can lead to inconveniences to the population and economic losses. This is particularly significant for the events occurring in late summer - early autumn, where the presence of tourists on the island is still significant.

This work is aimed at studying the effect of different precipitation intensity scenarios on the erosion affecting the volcanic cone, with the aim of identifying the areas most exposed to erosion. In addition, the effect of precipitation on the hydraulic structure of the island is also studied, with calculation and analysis of flood scenarios. Rainfall scenarios are constructed for different intensities on the base of a hydrological study aimed at processing a dataset of 19 years of hourly total rainfall, provided by the Agrometeorological Information Service of Sicily. Precipitation scenarios are simulated with the 2D inundation model Iber [Bladé et al., 2014]. This model, that simulates the non-steady surface flow, consists of five modules among which the hydrodynamic and the sediment-transport ones were used in the present work. The hydrodynamic module solves the two-dimensional depth-averaged Shallow Water Equations and is applied for the unsteady flow computation. The sediment-transport module, which solves the 2D Exner equation, is used here to compute the bed elevation evolution due to the erosion process.

The methodology proposed for the analysis involves several phases: i) analysis of the land cover and land use of the northern sector of the Island of Vulcano, in order to identify the areas with different coverage, which correspond to different flow/infiltration coefficients, ii) analysis of bibliographic data regarding the material characterization, useful for defining the erosion parameters of the deposits, iii) analysis of rainfall data, deriving from the Salina station, and hydrological study for hyetographs reconstruction and definition of rainfall scenarios, iv) numerical simulations of runoff and erosion scenarios with the software Iber. Moreover, field surveys conducted over the last few years have allowed to constrain model results.

Simulation results reveal that moderate-low to high intensity rainfalls produce the deepening of the canals on the northern flank of La Fossa cone, as well as different floodings in the inhabited area of Vulcano Porto. However, the distribution of water level maxima is controlled by the road network, since it is the main collector of the surface run-off from the cone and the surrounding valleys.

S12- Poster

S13 - FROM MULTI-HAZARD ASSESSMENT TO INTEGRATED RISK IN VOLCANIC AREAS: DATA-ENABLED SCIENCE AND APPLICATIONS WITH NUMERICAL TOOLS AND STATISTICAL METHODS

Conveners:
Raffaele Azzaro, Andrea Bevilacqua, Francesco Neglia, Silvia Massaro, Jacopo Selva

VIGIL: a Python tool for forecasting and probabilistic gas dispersion modelling

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Volcanic gas emission represents a source of hazard to humans and livestock. It is a widespread and frequent concern, since gas emissions can occur both during volcanic unrest, eruptions and in quiescent stages of the volcanic activity. Many gas species (e.g., CO_2, SO_2) can affect human health and even threaten life at concentrations and doses above species-specific thresholds. Volcanic gas emissions can be generally classified as dilute passive degassing and dense gas flow based on the buoyancy at the emission location. The former occurs when the density of the gas plume is lower than the atmospheric density (e.g. fumaroles). The latter takes place when the gas density is higher than the atmosphere and the gas accumulates on the ground and may flow due to the density contrast with the atmosphere to form a gravity current (e.g. limnic explosions).
In order to quantify the hazard related to gas dispersion and/or accumulation, monitoring and numerical modelling are generally employed, often together. Numerical simulations of gas dispersion involve a workflow that can be complex and time consuming, since it starts with the modelling of the wind field, proceeds with the gas dispersion simulation and ends with the post-processing stage. This process should be replicated several times (hundreds to thousands) for probabilistic volcanic hazard applications, in which the uncertainty of the relevant input parameters (e.g. wind field, emission rates, source locations) is explored to obtain probabilistic outputs. Here we present VIGIL (automatic probabilistic VolcanIc Gas dIspersion modeLling), a Python simulation tool capable of handling the gas dispersion simulation workflow and interfaced with two dispersion models: a dilute (DISGAS) and a dense gas (TWODEE-2) dispersion model. The post-processing script offers the option to create Empirical Cumulative Distribution Functions (ECDF) of the gas concentrations combining the outputs of multiple simulations. The ECDF can be interrogated by the user to produce maps of gas concentration at specified exceedance probabilities. Tracking points can also be used to produce time series of gas concentration at selected locations and hazard curves if ECDF is produced. We also present results from different applications showcasing the various capabilities of VIGIL.

S13 - Oral Presentation

Computational fluid dynamics tools to replicate mono- and poly-disperse granular flows: powerful instruments to better understand physic of multiphase flow

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Granular flows consist of discrete macroscopic particles. If they are non-cohesive, their status is determined by the interaction of particle-particle frictional forces, external boundaries and gravity. In particular, the understanding of the transport mechanisms of granular materials is of paramount importance for the characterization of volcanic granular flows and for hazard assessments associated with these flows. In order to investigate dynamics of these kinds of flows, we replicated large-scale experiments with multiphase computational fluid dynamic (CFD) simulations using the Two-Fluid Model approach, with an emphasis on the dynamics regulating the flow-wall interaction and the polydispersity effect on the flow behaviour. The CFD simulations were run using the software MFIX. The present work consists of: 1) investigations on the boundary conditions and the drag force relationships implemented in MFIX by means of sensitivity analysis of simulated mono- and poly-disperse granular mixtures on several flow parameters; 2) applications of MFIX to replicate large-scale experiments on volcanic dry granular flows sliding on an inclined channel; 3) comparisons between experimental and simulated data obtained from simulations of mono-, bi- and three-disperse granular mixtures, analysing the difference in the flow parameters with particular emphasis on the velocity of the granular flow front. The conducted work showed how the choice of the boundary condition and the non-uniformity of solid phases size highly affect the dynamic of the whole flow. Furthermore, simulations of large-scale experiments proved the capability of MFIX code to replicate the physic of real granular flows, showing a good agreement between simulated and experimental velocities of the flow front.

S13 - Oral Presentation

The total probabilistic long-term hazard of tephra fallout from Neapolitan volcanoes, and disaggregation analysis

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When performing probabilistic volcanic hazard assessment (PVHA) posed by tephra fallout, a well accepted assumption is that higher eruptive sizes have a lower probability of occurrence. Therefore, a high intensity eruptive phenomenon is counterbalanced by its low probability of occurrence, while the opposite occurs for less intensive ones.
Quantifying the contribution of a particular eruptive size class to the total hazard increases in complexity in areas that host several volcanoes, as each one of them could be the source of hazardous phenomena. In such areas, understanding which volcano and which eruptive size class contributes the most in exceeding a selected tephra load threshold in a target site is of pivotal importance.
Here, we present a methodology for (i) evaluating the total probabilistic hazard from tephra fallout in the Campanian area (Italy), considering the three active volcanoes, Somma-Vesuvius, Campi Flegrei and Ischia within a radius of less than 50 km from the city of Naples, and (ii) performing the disaggregation analysis to hierarchize the different volcanic sources and eruption sizes considered. In this regard, we consider three eruptive size classes for Vesuvius (Small, Medium-large, Large), three for Campi Flegrei (Small, Medium, Medium-large) and only one for Ischia (Medium). For each eruptive size class, we provide a dataset of ground tephra load by performing 1500 simulations of tephra dispersion through the numerical model Fall3D (v.8; Folch et al., 2020) over a 3-km resolution gridded domain covering the target region. A large variability in eruptive source parameters is taken into account, as well in weather conditions by using a 30-year ECMWF ERA5 reanalysis dataset (from 1991-2020).
The results of these simulations are included in a Bayesian Event Tree (BET, Selva et al.; 2010) and considering the mean annual eruption rates within a given exposure time of 50 years (Selva et al.,in review). As result, for each point of the domain, we obtain mean absolute hazard curves of ground tephra load representing the average annual rate of overcoming a set of selected intensity thresholds in 50 years.
The contribution to the hazard of each volcano and of every eruptive size class is obtained by calculating the ratio between the relative annual rate of threshold overcoming to the sum of all the annual rates. In this way it is possible to evaluate, for any given target location, which volcano or size class gives the greatest contribution to the total hazard.
Using an exposure time of 50 years, our results show that in the majority of target points within the region the Large size class of Vesuvius gives the greatest contribution, especially in the distal areas. For low tephra ground load thresholds (i.e. 0.1 kPa) the smaller size classes have a dominant contribution in the proximal area of the respective volcano, while the importance of

the larger size classes grows with the distance from the source. For higher thresholds (i.e. 3 kPa) we found that the larger size classes give a dominant contribution also in the proximal area.

Geophysical and geological constrains for modelling the source of the 2017 Casamicciola volcano-tectonic earthquake as contribution to the assessment of the Ischia seismic hazard

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Our study aims to show the effectiveness of multidisciplinary analysis, based on integrated geophysical and geological investigations, for constraining the source characteristics of the Casamicciola Terme active and capable fault system at Ischia Island.
We conducted a) a geophysical survey using the impulsive electromagnetic method of the Ground Penetrating Radar (GPR); b) SAR data analysis; c) five UAS surveys aimed to obtain a 3D point clouds and high-resolution orthophotographs of the study area; d) two new stratigraphic boreholes in the hangingwall (Piazza Maio) and footwall (Via della Grande Sentinella) of the Casamicciola Terme Holocene graben. This graben is the causative source for the August 21st, 2017, earthquake: a shallow event of Md 4.0 which caused two fatalities and heavy damage in a restricted area of a few square kilometers. The damaging earthquakes at Ischia Island repeat themselves with similar characteristics over the historical time window (Alessio et al., 1996, Cubellis and Luongo, 1998, 2018, De Natale et al., 2019). Their location is systematically confined to the same area of Casamicciola, just within few square kilometers, where a clear stratigraphic and morphological trace is preserved and is represented by the graben at the base of the northern flank of Mt Epomeo. The epicentral area of all the relevant seismic events in the last three centuries, notably those of the very strong earthquakes in 1796, 1828, 1881, and 1883, is constantly located along this graben, formed as the result of Holocene extensional tectonic deformation. Such a model, first introduced by Rittman, (1930), was later verified and well documented by field geological data of Vezzoli (1988), including the first modern 1:10.000 scale geological map of the Ischia Island, and by the studies of Tibaldi and Vezzoli (1998) and Sbrana et al. (2018).
The primary coseismic deformation at surface, after the 2017 Casamicciola earthquake, allowed to constrain its seismogenic source (Nappi et al., 2017). According to these authors, the 21st August earthquake was caused by a reactivation of the E–W fault systems associated with the uplift of Mt Epomeo northern flank since the Holocene (Vezzoli, 1988; Tibaldi and Vezzoli, 1998). The seismic risk of the Island is one of the largest in Italy, due to the extremely low depth of the fault motion, the presence of dense urbanization on the faults and the vulnerability of edifices. Furthermore, considering that the island represents one of the most famous tourist destinations in the world, such a very high seismic risk cannot be underestimated in the land use planning (De Natale et al., 2019). In order to constrain the geological model of the E-W seismogenic fault hypothesized by Nappi et al. (2018, 2021), based on field mapping of earthquake ruptures immediately after the mainshock and known geological data, we have investigated the piedmont belt of the Northern slope of Mt. Epomeo. The active fault system responsible for the Casamicciola earthquake of August 21, 2017 was mapped following the evidence of coseismic

surface ruptures, in the area from Fango to Piazza Bagni.
We then conducted a geophysical investigation with use the impulsive electromagnetic method of the ultradeep "Loza 2N" Ground Penetrating Radar (GPR) that through low-frequency antennas (10 MHz) (Kopeikin et al., 2012), may perform deep stratigraphic analyzes down to about 100 m.
The survey included three measurement transects oriented N-S, perpendicular to the E-W fault system, and one parallel to it. By our study we have identified the stratigraphic contacts at depth and the presence of synthetic and antithetic fault systems bordering the Casamicciola Terme Holocene Graben. Moreover, we performed two new stratigraphic boreholes in the hangingwall (Piazza Maio) and footwall (Via della Grande Sentinella) of the Holocene graben, which is the surface expression of the Casamicciola Fault System, for constraining the stratigraphic unit involved into displacement. Thanks to orthophotos with a high degree of definition, we reconstructed a more detailed three-dimensional ground model that allowed us to improve the analysis of the volcanotectonic deformation. Finally, through satellite interferometric techniques we assessed the space and time evolution of ground deformation rate and modelled the displacement field.

Slope stability assessment at Stromboli (Italy)

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Volcano slope instability is the result of endogenous and exogenous processes that can produce destructive rock or debris avalanches. These can produce direct impacts, or be part of a cascade process that can include lateral blasts (in the case of lava domes decompression), debris flows, and/or tsunamis. In the last centuries, several episodes of tsunamis generated by volcanic landslides are documented: Oshima-Oshima volcano (Japan) in 1741, Unzen volcano (Japan) in 1792, Mt. Augustine (Alaska, USA) in 1883, Ritter Island (Papua New Guinea) in 1888, and Anak Krakatau in 2018.

Among the volcanoes that are subject to frequent instability phenomena, Stromboli (Italy) has shown landslides of different volumes that can generate landslides-induced tsunamis or avalanches of glowing rocks. The latter are hybrid phenomena between rock avalanches and pyroclastic density currents that have spread over the sea for several hundred meters from the coast-line and occurred at least seven times in the last two decades. For this reason, Stromboli is constantly monitored by a network of multi-parametric sensors, which includes real-time observations of volcanological, geophysical, and geochemical parameters with ground-based or space-borne sensors. Despite this, probabilistic analysis of the hazard and physical models of slope stability are necessary for the correct interpretation of the monitoring data and for the correct definition of the impact scenarios. These are fundamental for identifying the alert levels of the volcano and the transfer of information to civil protection institutions (at local, regional or national level).

Here are presented results of stability analyses conducted in Stromboli, which are fundamental for an appropriate assessment of the landslides impact scenarios. First of all, the stability models conducted with 2D Limit Equilibrium Methods (LEM), were calibrated using the data related to the 30 December 2002 tsunamigenic landslides, considering the existing geomechanical/geotechnical data [e.g. Apuani et al. 2005; Tommasi et al. 2008; Boldini et al. 2009]. Here, in order to describe the stratification of volcaniclastic deposits and lava layers, the use of a rockfill-like material with an adequate failure criterion, such as the combination of Generalized Hoek-Brown criterion [Hoek et al. 2002] with Barton-Kjaernsli criterion [Barton and Bandis, 1991], has been considered.

This approach has been also be generalized to the failures of crater-rims. These phenomena were always associated with high-level of magma within the conduits, as testified by the increased eruptive activity and geophysical parameters. The more frequent/intense eruptive activity produced a greater accumulation of volcaniclastic material, whereas the high level of magma increased magmastatic thrust on the crater-rim. In addition to the geomechanical/geotechnical and morphological characteristics of the crater terrace rim and the magmatic thrust, the effects of the explosions in terms of seismic ground acceleration and disturbance factor (D) of the volcaniclastic material were also considered here. While the ground acceleration compatible with the explosive activity of Stromboli has little influence on the stability of the crater terrace rims, the increase in D increases the proneness for failure.

The approach proposed here, can be generalized and applied to other instability contexts of volcanic edifices. In particular, the use of a rockfill-like material to describe the geomechanical parameters of volcaniclastic deposits, can also be generalized to other volcanoes characterized by persistent or semi-persistent activity.

S13 - Oral Presentation

Pyroclastic avalanches hazard at Mt. Etna volcano

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Pyroclastic avalanches are gravity-driven granular flows at high (above ~10%) particle volume concentration composed by pyroclastic materials, generally characterized by relatively small volumes (less than ~10^6 m^3). In the last 20 years, they were recurrent at Mt. Etna volcano (Italy), particularly during the recent 2020-2022 volcanic activity at summit which was characterized by intense paroxysmal episodes at South East Crater (SEC). Avalanches represent one of the major source of volcanic hazard at summit of Mt. Etna, due to the difficulty to predict their occurrency and their fast (of the order of minutes) development. Indeed, the huge growth of SEC induced by accumulation of proximal pyroclastic deposits posed favorable conditions in triggering partial collapses of the crater, leading to an increase in the frequency of avalanches occurrence in the last two years. They propagated mainly eastward and southward of the SEC, and the major flows, such as that which occurred during the episode of 10 February 2022, covered distances from the crater of up 2 km from the source.
Numerical modeling of pyroclastic avalanches propagation represents a powerful tool for hazard assessment purpose, although the complex and still poorly understood rheology of the polydisperse granular mixture poses several difficulties in simulating their propagation and emplacement. In this regard, we use the open-source code IMEX-SfloW2D to simulate this type of flows. The code uses depth-averaged equations to model the granular flow as incompressible single-phase granular fluid, in which the Voellmy–Salm rheology is implemented. The well-documented pyroclastic avalanche occurred during the 10 February 2022 paroxysmal eruption allowed us to investigate the effects of modification in the topography on flow propagation and to define ranges for the unknown rheological parameters (i.e. dry-friction coefficient μ and viscous-turbulent friction coefficient ξ). These ranges were used, to generate probabilistic maps of emplacements for avalanche volumes ranging from 1×10^6 m^3 to 5×10^6 m^3. This allowed us to provide a preliminary quantification of potential scenarios linked to the propagation of pyroclastic avalanches in order to evaluate the hazard at summit area, where scientists are routinely present to do monitoring activities, and which represents one of the most preferential tourist's destination at Mt. Etna.

S13 - Oral Presentation

Fixing Criteria for Volcanic Unrest Warning

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In volcanic observatories worldwide, geophysical and geochemical data are usually collected remotely, providing continuous information about the state of volcanoes even in unfavorable conditions with respect to visibility and access to the area of eruptive centers. Early stages of unrest can be detected with high reliability; nonetheless, style and, in particular, intensity of eruptions are difficult to predict. Consequently, it turns out important to identify critical moments after which the development of a paroxysmal activity becomes highly probable.
In this perspective, we exploit a machine learning (ML) method for the analysis of seismic data continuously acquired by the permanent seismic network at Etna, Italy. Threshold criteria, which are based on parameters derived from the ML system and the number of stations where changes are detected, have been established with the scope of automatic alert flagging. As mild unrests may continue for weeks and even months, there is the need to adjust the trigger criteria with respect to style and intensity of the impending phenomenon. Our choice of the criteria was guided by so-called “Receive Operation Characteristics” (ROC) curves. These are based on the trade-off between the rate of False Positives and True Positives. With a more sensitive setting one can flag more paroxysms (True Positives); however, this may have the cost to flag an alert, but no paroxysm occurs. Carrying out various tests considering both the signal characteristics and the number of stations where the thresholds were met, we identified robust configurations allowing us to issue an alert of an impending paroxysm, widely avoiding the risk of false warnings. The system we propose here can provide timely and indicative information on possible eruptive scenarios to Civil Protection and other stakeholders. Also, It can be a guide for fixing onset and end-times of paroxysmal phenomena, which are especially helpful when image-based monitoring is hindered, for instance, by meteorological conditions. Finally, if offers the possibility to effectively re-analyze long time spans of data recorded in the past.

S13 - Oral Presentation

Volcano-related hazards at Mt Etna: the new frontiers of the PANACEA project

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Mt Etna is one the most active volcanoes in the world, producing both effusive and explosive eruptions together with a frequent seismic activity, which significantly affect the territory and human society. In order to minimize the impact of these phenomena, a careful assessment of both the individual and multiple hazards is necessary. Here we present the first results of the PANACEA project, which aims to develop a flexible probabilistic framework for the assessment of volcano-related hazards at Mt Etna using the huge quantity of available data (historical, geological, seismic, field-based and remote sensing data) and accurate physical-mathematical models to simulate lava and pyroclastic flows, and tephra fallout. Individual hazard maps are first produced considering the long-term probability of occurrence of the phenomena but they can be easily updated in case of a volcanic unrest to generate short-term scenarios taking advantage of the elaboration of real-time monitoring data. Based on a modular structure (hazards can easily be added or removed) and the ability to rapidly update outputs by revising the inputs without modifying the tool structure, PANACEA will provide a powerful instrument to develop effective and operational strategies to enhance safety and reduce the risk associated with eruptive or seismic crises at Etna.

S13 - Oral Presentation

A multi-risk strategy for Mount Etna: new approaches from the PANACEA project

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Etna volcano (Sicily, Italy) looms over a densely urbanized territory and its volcanic and seismic phenomena severely impact on built-up locations, lifelines and communication systems at different scales. In case of a very active volcano such as Etna, lava flows, earthquakes, tephra fallout and pyroclastic flows can impact simultaneously or could interact, producing cascading effects.

Dealing with multiple hazards is a challenge for effective risk mitigation. This work aims at presenting the approach of the PANACEA project on the treatment of multi-hazards in terms of risk.

The first step of the analysis is the identification of sequences of events occurring at Etna and the possible impact to some infrastructural elements. In this way we hypothesize a set of multi-risk scenarios, by considering as a reference the impact on a given infrastructural element (e.g., damage to house's structure or roofs, disruption of lifelines system or transportation lines), and by reconstructing the series of events potentially driving the impact (e.g., seismic activity, ash fall or ballistics from summit or lateral vents).

To move from hazard to risk, it is necessary to identify the elements exposed and to assess their vulnerability to the different hazards. Data on essential facilities, transportation, lifeline utilities was collected and organized in a GIS. The census data of the Italian Institute of Statistics (year 2011) provide a valuable source of information on building stock and demographic figures, that are updated and spatially detailed. Moreover, the AeDes data ("Post-earthquake damage and safety assessment and short-term countermeasures"), collected after strong earthquakes occurred in 2002 and 2018, are useful in calibrating damage models.

The loss estimation is mainly performed in terms of structural damage, victims, loss of functionality or economic effects on activities, and requires the definition of proper risk indicators, common to all the exposed elements. The model for risk assessment can be outlined by defining the scenarios for the analysis, considering both independent and interacting risks. For example, in the case of roofs, we assess the risk considering (i) the seismic load only (independent), (ii) the ash load only (independent), or their combined effects acting simultaneously or as cascade effects.

As a preliminary step, we elaborate a first urban risk scenario for the residential building stock, considering the territory affected by a fallout of tephra and earthquake shaking. In a more advanced phase of the project, our analyses will be extended to include lava flow hazard and other exposed elements, such as roads and power network. Now we focused on the municipalities of Zafferana Etnea, Santa Venerina and Milo, that are often affected by these kinds of hazards. Indeed, the December 26, 2018 earthquake (Mw 4.9) caused severe damage to the localities of the lower south-eastern flank of the volcano, while few years later abundant

ash fallout affected the same area for weeks, determining continuous disruption to circulation and imposing constant maintenance of building roofs.

We assess the risk considering independent hazards: the probabilistic seismic damage distribution is evaluated for the expected intensity value equal to degree VII EMS, referred to an exposure time of 30 years, equally distributed over the area. Instead, damage to the building roofs due to ash accumulation is calculated by assuming different loads and adopting a distribution of roofs' type calibrated through AeDes data and satellite images.

In the analyse of interaction of different hazards, we consider the effects caused by the accumulation of ash increasing the vulnerability of buildings to the seismic input.

We conceive an adaptive risk model to take advantage of the full range of potential hazards (such as fires, floods, health, regional earthquakes, etc.) that may interact with the prevailing ones. Moreover, a flexible model can adopt different loss estimation methods, implement the area of analysis and procedures so as to make the risk estimation procedure ordinary.

The theme of the multi-risk in a complex and highly active volcano such as Etna is the new frontier to be developed. Although the PANACEA project started just on April 2021, it is proving the actual chance of aggregating research groups working on different themes. Even if Etna is not among the most dangerous volcanoes, the first estimates show that the risk is significant due to the dense urbanization of the area and the interaction of different hazards.

Moment magnitude for weak earthquakes in the Mt. Etna volcano area

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Etna's seismicity is characterised by frequent weak events (local magnitude ML≤ 3) with shallow hypocentral depth (h≤ 5 km), mainly affecting the volcano's eastern flank, where there is morphological evidence of active faults. Although the ML of earthquakes rarely exceeds 4.0, the Etna area is among the areas with the highest seismic potential in Italy, and for the presence of the highly urbanised areas has relevant implications in terms of seismic risk [Azzaro et al. 2015].
Therefore, an accurate estimation of the energy released by weak seismicity is crucial to implement seismic event catalogues and to improve the accuracy of magnitude-return relationships required for an adequate seismic hazard assessment.
In this study, we calibrate a data-driven empirical equation for response spectra as a function of MW following the approach of Moratto et al., [2017], which is based on the method of Atkinson et al., [2014]. This method estimates MW values from response spectra in terms of Spectral Acceleration (SA), since such spectra smooth the irregularities observed in Fourier Amplitude Spectra due to the 5% damping applied in their calculation. The empirical equation is defined for SA computed at 1.0 and 0.3 s.
To fine-tune the relationship for the study, we applied a two-step procedure using ground motion simulations and MW estimates from independent approaches. In the first step, we estimated ground motions with a stochastic method for a Brune point source model using the parameters proposed by Langer et al. [2016], who calculated ground motion scenarios for Etna, distinguishing between two seismotectonic regimes: one with a focal depth of less than 5 km, mainly related to surface deformation processes, and the other related to the regional crustal deformation pattern for earthquakes with a focal depth of more than 5 km.
In the second step, we compiled a dataset of about 400 earthquakes with 1.0 ≤ ML ≤ 4.8 that occurred in the Etna region from 2005 to 2019, and calculated the MW from the long-period plateaus of earthquake source spectra properly corrected for path propagation.
Finally, we also provide an empirical relationship between ML and MW for the Etna region, which, together with relationship SA- MW can be easily implemented in real-time routine analyses and provide a fast method to calculate moment magnitudes.

S13- Poster

Tephra fallout hazard assessment at Fuego volcano (Guatemala)

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Fuego volcano (3763 m a.s.l.; 14°28' N, 90°52' W) is one of the most active volcanoes in the world. It falls within the Guatemalan volcanic chain, where it belongs to the Fuego-Acatenango volcanic complex (age > 200,000 years). It is located about 40 km southwest of the capital Guatemala City (population 2.2 million), 15 km southwest of Antigua (population 25,000), and 20 km northwest of Escuintla (population 75,000+). Hence, Fuego volcano represents a potential hazard for large communities, environment and infrastructure. After a decade of quiescence, in May 1999 it entered a new eruptive cycle that continues until today. Scale of activity is varied, although substantial risks are associated even to eruptions of low-to-moderate intensity, as dramatically demonstrated during the June 3, 2018 event.
Lahars and pyroclastic flows are the most threatening volcano-related phenomena for local population. However, also tephra fallout may cause significant impact, especially in the light of the quasi-persistent activity during the last ~20 years. Nevertheless, there is still a lack of comprehensive hazard maps related to tephra fall at Fuego volcano, where available maps are mainly based on historical higher intensity eruptions (VEI ≥ 3).
We present a probabilistic tephra fallout hazard assessment for Fuego volcano following a scenario-based approach. We developed a set of possible eruptive scenarios based on a critical review of available literature and on the reports from Global Volcanism Program (GVP) and Instituto Nacional de Sismología, Vulcanología, Meteorología and Hidrología (INSIVUMEH). Three eruption scenarios were identified, including: i) low-intensity Strombolian eruptions, ii) Paroxysmal eruptions, and iii) Sub-Plinian eruptions. The modelling was performed through the coupled Plume-MoM/HYSPLIT models, using a 15-years dataset of wind profiles from the NOAA GDAS one-degree archive database.
We show that tephra accumulation significantly varies with eruption intensity and is affected by seasonality (i.e., atmospheric conditions), especially for plume heights > 10 km a.s.l. The smallest eruptions considered (i.e., low-intensity Strombolian) preferentially impact the western sector of Fuego Volcano with light tephra fall regardless of the season. In the case of more vigorous activity, ash preferentially distributes over the western sectors during the rainy season (June–October) and over the northeastern areas during the dry season (November–May), with accumulations exceeding 1–100 kg/m^2. Affected areas comprise main roads including the Pan-American Highway, as well as the capital Guatemala City, the main airport of Guatemala (i.e., La Aurora International Airport), Escuintla, and Villa Nueva cities.
Although the accuracy of the evaluation of areas affected by tephra fall is related to the accuracy in the knowledge of eruptive source parameters, outcomes already seem useful and important for a preliminary, comprehensive evaluation of tephra fall hazard at Fuego.

S13- Poster

Unrest episodes at central volcanoes in 1990-1999: analysis and interpretation

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Active volcanoes can be extremely hazardous, as they can produce unexpected eruptions, impacting the population and the surrounding environment. One of the goals of modern volcanology is to forecast eruptions. In this aim, it is essential to determine the outcome of an unrest, or the pre-eruptive crisis, which can lead to an eruption (eruptive unrest) or not (non-eruptive unrest). The present work is aimed at identifying and studying the common features among eruptive and non-eruptive unrest of central volcanoes. In this thesis, a database was constructed and analyzed, including all the central volcanoes that were characterized by at least one phase of unrest from 1990 to 1999. The data, which mainly include information on the monitoring of an unrest episodes, were analyzed using statistical algorithms for the identification of common behaviors for eruptive and non-eruptive unrest. In particular, statistical tests were carried out a) for the analysis of unrest durations, b) for the analysis of Time Predictability (TPM) and Size Predictability (SPM), c) for recognizing common behaviors in eruptive and non-eruptive unrest (Fisher's discriminating analysis and Binary Decision Tree algorithm). The analyses show that the duration of an unrest is the discriminating feature between eruptive and non-eruptive unrest. In fact, the eruptive unrest in the central volcanoes generally have durations of less than about 0.7 years, while the non-eruptive unrest have longer durations. In addition, TPM and SPM analyses show that central volcanoes have a possible linear relationship between the logarithm of time between two adjacent eruptions and their VEI. It is possible that the VEI of the previous eruption influences the time between the two eruption. The results also show that a longer time interval between two eruptive events can favor a greater recharge of the magmatic system, and therefore influence the size of the eruption. Finally, a preliminary model is proposed. Magma accumulating in shallow magmatic reservoirs and producing a state of unrest, generally no longer leads to an eruption beyond a certain period, estimated at about 0.7 years.

S13- Poster

Pyroclastic current probabilistic invasion maps at the Campi Flegrei (Italy): from field data to numerical modeling

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Pyroclastic currents (PCs) are hot mixtures of gas and pyroclasts that can cause widespread loss of life and structural damage to buildings and infrastructures within tens of kilometres from their source. Hazard assessments, that include the quantification of the aleatory and epistemic uncertainties, are a necessary step toward calculating volcanic risk of PCs in an accurate manner. In this work, we developed a methodology and present the results of the probabilistic volcanic hazard assessment for PCs at Campi Flegrei caldera. In this study, we apply a two-dimensional, transient depth-averaged model to simulate the pyroclastic currents, using the available data about the Astroni eruption (4.8 - 3.8 ka). The data was analysed using Monte Carlo approach: we performed an ensemble of numerical simulations, assuming that model input parameters can vary within a given range, with a prescribed probabilistic distribution. In details, we varied the PC volume, density, and vent location in order to reproduce the natural variability of the deposits and impacts. The results show that the conditional probabilities of PC inundation (given an eruption of a specific size) exhibit spatial distributions controlled by the topography. Results show that, using the Astroni eruptions as scenario and vent locations, almost the entire Campi Flegrei caldera floor is exposed to invasion with a probability of at least 5%, with peaks of 90% in the Astroni area and the Agnano Plain. This approach and the data obtained may contribute to direct future research toward a better computation of uncertainties, thus improving hazard analyses associated with pyroclastic flows.

S13- Poster

New perspectives on the hazard by lava flow invasion at Mount Etna volcano through the spatial and temporal elaboration using a GIS-based approach

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Eruptive dynamics at Mount Etna volcano generally alternate periods of explosive activity to effusive phases producing lava flow emplacement. Although lava flows have marginally affected urbanized areas during the last four decades, a glimpse to the historical record suggests that scenarios of important lava flow invasion cannot be excluded in the future. Reproduction of pre-historical to recent lava flows on geo-volcanological maps is therefore basilar for emphasizing how a volcano worked in the past, and becomes the jumping-off point for any further elaboration aimed at individuating the associated hazards and planning actions of risk mitigation.
In this study we present a multi-parametric GIS database concerning lava flows emplaced during the last 2500 years of activity at Mount Etna. We have planned the spatial and temporal analysis as follows: 1) a total of 12 domains distributed over 3 altitude ranges (0-1500 m asl; 1500-2500 asl; above 2500 asl) for each quarter, arbitrarily sectioned along N-S and E-W directions; 2) timeframes with step of 500 years and focus with step of 100 years during the period 1500-2020 AD. In order to highlight sectors affected by conspicuous or very limited lava flow invasion into the 12 domains, we have defined 5 main thresholds based on the total covered areas by lava flows in each sector. This research allowed us to identify a number of new correlations involving erupted volumes, recharge-discharge ratio for specific periods, eruption duration and how they relate to possible important volcano-tectonic changes that have affected the volcano in the past at different levels of the plumbing system. Furthermore, our elaborations emphasize how short-term inflation and deflation periods, related respectively to magma recharge and the consequent eruption/s, may be viewed as part of long-term cycles of voluminous accumulation and discharge that culminate with catastrophic events potentially affecting the whole Etnean edifice.

S13- Poster

S14 - VOLCANIC RISK MANAGEMENT IN INHABITED AREAS

Conveners:
Antonio Colombi, Chiara Cristiani, Eugenio Privitera

Relative seismic and tsunami risk assessment: the Stromboli Island (UNESCO site, Italy) case study

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Being tectonically and geomorphologically active zones, volcanic areas can be subject to earthquakes, landslides and, in the case of coastal or island volcanoes, tsunamis. In this work, an innovative method of estimating the relative risk of buildings exposed to seismic and tsunami hazards in volcanic islands is applied to Stromboli (UNISCO site, Italy), a well-known stratovolcano [Tibaldi et. al, 2009] affected by moderate seismic events and mass-flow-induced tsunamis. The procedure uses an already consolidated quali-quantitative analysis method for the assessment of building relative risk using indices, i.e. the INSPIRE Index [Gentile et al., 2019] and the RVI [Dall'Osso et al., 2010; 2016], which allow comparing the risk of different buildings, although not providing a reliable absolute estimation of it. This is combined with the historical-geographical analysis of urban and extra-urban settlements using intermediate scales (i.e., 1:10.000, 1:1.5.000, and 1:2.000), taken from the 'territorialist' approach [Magnaghi, 2001; 2010; 2011] to the urban and regional planning and design. The quali-quantitative analysis is based on a new proposed survey-sheet model, useful to collect building information necessary for the relative risk estimation, whereas the historical-geographical investigation is based on the multi-temporal comparison of high resolution aerial and satellite images [Turchi et al., 2022]. The proposal to combine two consolidated methods represents an innovation in estimating relative risk. Considering that Stromboli Island had never been subjected to similar analyses, the results of the relative seismic risk assessment are novel and moreover identify buildings with a fairly-low and spatially-uniform relative risk. The results of the relative tsunami risk assessment are consistent with results of similar past studies, identifying buildings with a higher relative risk index on the northern coast of the island. The complementary use of a building-by-building survey-sheet model with a multi-temporal analysis of settlements allows having a higher detail than previously available for the region, in order to obtain a relative-risk-based prioritisation assessment as accurately as possible. About that, the process to calibrate the survey-sheet model also took into consideration the local characteristics of buildings, deriving from unstructured interviews with some workers in the construction sector (i.e., bricklayers) on the island. At the same time 'territorialist' analysis, allowed to better estimate some attributes of buildings as the construction period which, in turn, is directly related to the building typologies, function, and construction materials and techniques.

If adequately modified, the proposed combination of methods allows for assessing relative risk also considering other geo-environmental hazards and their cascading effects, from a multi-hazard risk assessment perspective.

The 2021 eruption in La Palma Island (Canary Islands, Spain): Volcano monitoring, eruptive processes and crisis management

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The Canarian Archipelago, located along the NW margin of Africa, shows intraplate magmatism attributed to a hot spot mechanism, governed by region geodynamics. The eruptive processes were developed for more than 20 million years and in the last 500 years we had 16 eruptions, all of them being basaltic. Prior to 2021, the last two eruptions in the archipelago took place, in El Hierro Island (submarine eruption of 2011) and La Palma Island (subaerial eruption of 1971). On 11 September 2021, the monitoring network of IGN started to record an intense seismic swarm under the island and Civil Protection was alerted. In the next 5 days, the seismic energy increased and deformation patterns were detected. The day before the eruption, the habitants nearby the possible affected area were informed, and 5 hours before the onset of the eruption, an evacuation was ordered. In the first 48h of the unusual seismic activity a special Civil Protection plan concerning the volcano risk, namely PEVOLCA, was activated by the Canary Government.
On 19 September 2021, an eruption began on the island of La Palma, which lasted 85 days, until 13 December 2021. It began as a fissural one, and in less than 3 months, emitted lavas that covered a surface of >12 km^2, with a bulk thickness of 12 m and generated new lava deltas. The ash layer at a distance of 2 km exceeded 1 m. The eruptive style was mainly effusive, with phases of moderate Strombolian explosions. Lava flows destroyed thousands of edifices, infrastructures, communication networks and extensive areas of farmlands and greenhouses, greatly affecting the local economy. Two evacuations were carried out and no casualties were reported.
The Canarian Government successfully manage the crisis through the Scientific Committee and the Steering Committee of PEVOLCA. This plan is still active (as of 20th June, 2022).

S14 - Oral Presentation

Integrating hazard, exposure, vulnerability and resilience for risk and emergency management in a volcanic context: the ADVISE model

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Risk assessments in volcanic contexts are complicated by the multi-hazard nature of both unrest and eruption phases, which frequently occur over a wide range of spatial and temporal scales. As an attempt to capture the multi-dimensional and dynamic nature of volcanic risk, we developed an integrAteD VolcanIc risk asSEssment (ADVISE) model that focuses on two temporal dimensions that authorities have to address in a volcanic context: short-term emergency management and long-term risk management. The output of risk assessment in the ADVISE model is a function of physical, functional, and systemic damage as well as resilience, where physical, functional and systemic damage are determined combining the available information on hazard, exposed systems and vulnerability. The ADVISE model allows for qualitative, semi-quantitative and quantitative risk assessment depending on the final objective and on the available information. The proposed approach has evolved over a decade of study on the volcanic island of Vulcano (Italy), where recent signs of unrest combined with uncontrolled urban development and significant seasonal variations of exposed population result in highly dynamic volcanic risk. The extension and intensity of most key hazard on Vulcano have been assessed in relation to various activity scenarios showing that multiple urban areas and infrastructure can be impacted both north and south of La Fossa volcano. For the sake of illustration of the ADVISE model, we focus here on the risk assessment of the transport system in relation to the tephra fallout associated with a long-lasting Vulcanian cycle. Results show that risk varies through time during a cycle of Vulcanian explosions with the highest risk being associated with the road network in Piano as well as the road leading to the port of Gelso. The ADVISE models is also combined with additional analysis that can inform emergency management, such as the efficiency assessment of an evacuation. Pre-eruption simulations carried out with a dedicated agent-based simulation tool show that both simultaneous and staged evacuation (simultaneous evacuation of the whole community or sequentially staged evacuation of different areas) are slightly faster during the low touristic season with respect to high season. Nonetheless, the type of evacuation (staged or simultaneous) can optimize the number of people evacuated in time, with the simultaneous evacuation being more efficient at removing people from the island than the staged evacuation, especially in the low touristic season.

S14 - Oral Presentation

Emergency management and risk reduction measures during the Vulcano (Aeolian Islands) unrest 2021-2022

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Vulcano island is the southernmost emerged volcanic edifice of the Aeolian archipelago (Sicily Region). Since the last eruption in 1888-1890, the island has been characterized by fumarolic activity at La Fossa crater and at the Bay of Levante. With a fluctuating population ranging from around 600 residents in winter to monthly peaks of thousands in summer, concentrated mainly in the Porto area at the base of the crater, the risk is high even for small volcanic events.

Since August-September 2021, the National Institute of Geophysics and Volcanology (INGV) and the National Research Centre (CNR-IREA) monitoring systems measured significant variations in some geochemical and geophysical signals.: increase in the concentrations, fluxes and temperatures of volcanic gases emitted by fumaroles from the crater area, extension of the emission areas, and increase in low-energy seismicity were observed. Also, the analysis of the deformations measured by satellite and from the ground also showed an uplift in the summit area of the volcano of about 1 cm. Since the beginning of October, a diffuse degassing activity from the ground has been continuously increasing, and the daily average values measured in the area at the base of the volcanic cone were much higher than those recorded at the beginning of the crisis.

On 1st of October 2021, the Italian Civil Protection Department, supported by the National High Risks Commission, raised the alert level from 'Green - Quiescence' to 'Yellow - Minor Surface Hydrothermal Crisis'. Consequently, some actions were taken such as: i) strengthened volcanic monitoring and surveillance; ii) reinforced the constant information link between the scientific community and the other components and operational structures of the National Civil Protection Service; iii) started updating civil protection planning at the different territorial levels.

Due to the increase in gas emissions from the ground, on 20th of November the Mayor of Lipari has forbidden overnight stays in the area of Vulcano Porto for 30 days. Access to the island was also forbidden to non-residents and the use of self-protection measures was recommended.

The Head of Department's Decree of 6th of December 2021 formalizes a Technical Group for Environmental Monitoring of Volcanic Gases and Air Quality, which consist of representatives from national and regional administration in charge of protecting and safeguarding health, with the aim of providing useful elements for effective monitoring of air quality.

On 7th of December 2021, the National Civil Protection Plan for volcanic risk on the Vulcano island was formalized. The plan, compiled by the Italian Civil Protection Department, defines the mitigation actions that all the stakeholders involved in the emergency management must take.

Because of the high concentrations of volcanic gases on the island, the Council of Ministers, on 29 December 2021declared the "State of emergency" to allow the implementation of the most urgent measures to protect the island's inhabitants.

On 27 January 2022, the Head of the Civil Protection Department issued the ordinance on the first urgent civil protection interventions because of the high concentrations of volcanic gases in the air and appointed the President of the Sicilian Region as delegated Commissioner for the emergency.

Finally, a full-scale exercise was held on the island from 7 to 9 April 2022, with the aim of testing

on site the National Civil Protection Plan for volcanic risk. The exercise, organized by the National and local civil protection authorities, also tested for the first time "It-alert", the public alert system that informs the population in real time by mobile phones about major upcoming or ongoing emergencies or disasters.
In this work we will describe how the unrest in Vulcano was managed by National and local civil protection authorities and what risk reduction measures were adopted, highlighting the interaction between decision makers and scientists.

Continuous monitoring of soil CO_2 flux and air CO_2 concentration at Vulcano during 2021

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Several volcanoes are located either near densely populated cities or in volcanic islands where a combination of beautiful scenery, economic, and touristic activities are attractive for people. In these areas volcanoes establish various risks, including either lava flows or explosions. While people perceive for themselves the risk that depends on an erupting volcano and are sufficiently aware to stay at a safe distance from lava flow, the risk correlated with explosions both impulsive or sustained is not easily perceived. Even more so than that, the volcanic risk correlated with gas emissions (i.e., the "gas hazard") is still underestimated, although several international agencies fixed safety thresholds based on the concentration of specific gaseous component and the time of exposure to it. When a volcano remains quiescent for a long period and then volcanism suddenly resumes, the volcanic degassing can have a significant impact on accessibility to inhabited areas and, consequently, on the economy of the entire regions mostly which economy is based on the tourism industry.
La Fossa Volcano is a suitable case study for gas hazard mitigation because volcanic gas emissions occur in the nearby of the Vulcano Porto village. The current fumarolic-solfataric degassing at Vulcano became after the end of the last vulcanian eruption in 1888-1890. Both sulfur and carbon dioxide emissions expose people to hazard at crater rim, where volcanic degassing occurs from a wide fumarolic field. A similar situation is found at Levante beach, Faraglione, and Palizzi where fumaroles and anomalous zones of soil CO_2 emissions have not changed their position substantially for several years. Since the last eruption, several fluctuations in the volcanic degassing caused increases of the gas emissions at these zones. These transitions in the volcanic degassing are called "crisis" that punctuate the quiescent degassing and show evidences through temperature increase of the fumarolic emissions, the amount of gas emissions, the gas composition, and the isotopic signature of some elements as the carbon, helium, and oxygen.
This study focuses on the soil CO_2 emissions and the impact of diffuse degassing in the air CO_2 concentration during 2021 at Vulcano. The recent increase in volcanic degassing of La Fossa volcano caused increase of the gas hazard, and temporary evacuation of people from the village of Vulcano Porto. Since June 2021 a new permanent network was installed at Vulcano for gas hazard monitoring purposes. The suitable sites for its deployment have based on discrete spatial surveys of the soil CO_2 flux. The monitoring network consists of four stations that measure the soil CO_2 flux (φCO_2), the air CO_2 concentration, and some important environmental variables affecting the gas hazard (i.e., atmospheric pressure, air temperature, wind speed, wind direction, and rain). Three stations are installed in the anomalous degassing zone of Faraglione (i.e., Castello, Rojas, and Porto stations). One station (i.e., Carapezza) is placed outside the anomalous degassing zone and is a suitable benchmark for background soil CO_2 emissions and air CO_2 concentration. The monitoring station has been designed and implemented in the laboratory of the INGV, and is fully customized for acquisition of several geochemical variables. Data transmission occurs by internet connection, and data storage occurs via web services. The monitoring network delivers updated information concerning the diffuse degassing of CO_2 and the correlated gas hazard to the civil defense authorities that can manage the risk based on reliable data. To achieve this goal, some routines (i.e., the Gas Network Analytics software

package) were specifically developed and allow the automated data processing.
Since late summer 2021, the renewed volcanic degassing that occurred at Vulcano, and caused people evacuation from some areas of Vulcano Porto village, provided a valuable test for that gas hazard monitoring network. The integrated monitoring of the soil CO_2 flux and air CO_2 concentration revealed that changes in the diffuse degassing affected the air CO_2 concentration at Vulcano.
The results of the first year of observation show that effective actions to mitigate the gas hazard include the continuous monitoring of both φCO_2 and air CO_2 concentration. The early detection of notable changes in the volcanic degassing by the continuous monitoring network allows establishing prompt actions to mitigate the gas hazard at Faraglione. In the future, the automated data processing of the geochemical parameters could represent a valuable tool to realize gas hazard warning system at Vulcano.

Response of the civil protection office of the town of Pozzuoli to the unrest of the Campi Flegrei caldera

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Since 1970, the Campi Flegrei caldera experienced three unrest episodes: in 1970-71, in 1982-84 and from 2005 to the present. The unrests mainly involved the center of the structure and consisted in relevant in ground uplift accompanied by shallow seismic activity. During the current episode, in addition to the ground deformation and seismicity, there was also a considerable increase in hydrothermal and gaseous emissions (in particular CO_2). As a consequence of the increased activity, in December 2012, the volcanic alert level of the caldera was raised from green to yellow by the National Committee of Great Risks and the National Department of Civil Protection (DPC) decreed the activation of the operational phase of attention for volcanic emergency at national level. Subsequently, in 2016, the area of preventive evacuation (red zone) as well as the overall national plan for the relocation of refugees (500,000 people) were both formally established in a decree of the Prime Minister of Italy.
Starting from 2020, the current unrest has seen a significant acceleration of uplift (from about 7 to over 14 cm / year), a rise in the frequency and magnitude of earthquakes (maximum magnitude 3.6) and also an increase of gas emission.
The growing perception of the phenomena by the residents of Pozzuoli, about 80,000 inhabitants,
due to the rise of the harbor docks, frequent occurrence of earthquakes and the high visibility of the new Pisciarelli fumarole, induced the Mayor, to take actions to better assist and inform citizens on what is going on. The actions have primarily consisted in strengthening the municipal civil protection office, establishing a more effective collaboration, at operational level, between the civil protection office and the local police and also promoting a closer coordination and collaboration with the higher-level institutional bodies of civil protection: Regional Office of Civil Protection (URPC) and (DPC).
The main initiatives undertaken have consisted in: i) establishing and formatting a direct information tool (Facebook messages) for rapid communication between the Mayor and the population when significant seismic events occur; ii) approving the new municipal civil protection plan; iii) informing citizens about the municipal emergency planning by two flyers relating to all risks and to the volcanic emergency plan respectively; iv) activating, by the local police and by the local civil protection center, a night service to provide support and assistance to the population after earthquake events; v) undertaking meetings with schools to draw up shared emergency plans in case seismic events struck during school hours; vi) promoting, in collaboration with INGV-OV, the positioning in the main public places, of information structures for a better awareness of the volcanic nature of the area, the meaning of the present uplift in relationship to a possible volcanic reactivation.
As it concerns the risk posed by the augmented hydrothermal activity in the Pisciarelli area, the municipal administration introduced access restrictions and also took actions to assess the landslide hazard of the slope placed upstream of the hydrothermal vent.
Despite the current unrest and the threat posed by a potential volcanic crisis are both creating considerable concern in the population, the operational initiatives put in place at local level, are contributing to make people more aware on the natural risks of their territory and be more

prepared for a possible future negative evolution of the volcanic unrest. In the short-term the first goal will be is to acquire an augmented capacity to deal with seismic emergencies meanwhile the possibility of an eruptive scenario in the mid-term (years to decades to come) imposes the necessity to improve the preparedness to efficiently manage the evacuation. More in general the preparedness to an volcanic crisis must include the punt in place of all actions and mitigation measures useful to increase people protection and also to minimize the impact on public and private structures and the economy by the expected volcanic phenomena

Buildings vulnerability under effect of bradyseism phenomena: Campi Flegrei case study

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The Campi Flegrei area (Campania Region, Italy) is among the zones of greatest volcanic risk in the world. Currently, on the basis of some variations in the volcanic system activities, the state of alert in the Campi Flegrei area is that of "attention" (marked by the color "yellow" in the National Civil Protection Plan at Campi Flegrei). Among the phenomena recorded by the monitoring systems, ground uplift and subsidence characterize the area. They constitute the so called "bradyseism" (from the Greek, "slow movement"), due to magmatic-hydrothermal processes [Lima et al., 2021; De Vivo and Lima, 2006]. Since Greek-Roman time, many bradyseism episodes occurred in Campi Flegrei area, but only once, in 1538 CE, after a ground uplift of ~7 m, was there a recorded eruption (Monte Nuovo). The last two dramatic bradyseism phases occurred in 1969–1972 and 1982–1984, where Pozzuoli town were affected by a sudden lifting of the soil which brought the latter to an overall higher level of about 3.5m and caused numerous earthquakes (M≤4.2), with severe damage to buildings. During 1984, the seismicity was very intense, with 33 events with M≤3 and six events with M≤3.8. Subsequently, the Campi Flegrei caldera was characterized by general subsidence for about twenty years until 2005, the year in which a period of lifting that is currently underway began. The areal distribution of the recent uplift sees the maximum value in the area of the Port of Pozzuoli, with radial decrease towards the edges of the caldera.

The need to better understand Campi Flegrei volcanic activity is fundamental to protect the population from hazards linked to explosive volcanic eruptions and to understand the role of seismicity as a possible precursor of a potential future eruption. In this perspective, as part of the activities of PLINIVS Centre (Centre of Competence of Italian Civil Protection Department for volcanic risk), the authors have developed a procedure, implemented in a web application, capable of relating the monitoring of the motion of the soil with the behavior of buildings, in order to evaluate near real time the level of progressive damage to the ordinary Phlegraean buildings due to bradyseism.

The procedure provides scenario analysis based on the product of hazard, exposure and vulnerability. The "Hazard" is provided in terms of tilt and lift, through a periodic automatic transfer in the web application, where three different monitored information are connected: the interferometric network of CNR-IREA (National Research Council of Italy - Institute for Electromagnetic Sensing of the Environment), the geodetic network of INGV-OV (National Institute of Geophysics and Volcanology- Vesuvian Observatory) and a sample of sentinel buildings, representing the main building types of the area, suitably chosen in the area subject to deformation and monitored with accelerometers and inclinometers.

The "Exposure" is assessed through the distribution on the territory of the bradyseismic vulnerability classes of buildings (A, B, C for decreasing vulnerability). They are estimated on the basis of statistical procedures adapted from the seismic field [Zuccaro and Cacace, 2015; Cacace et al., 2018], on the basis of information obtained through data collection campaigns on the territory, building on building (about 8,200 buildings in Pozzuoli town) and data on buildings provided by the ISTAT 2011 census.

The "Vulnerability" of the building has been developed on an empirical basis, from the analysis

of the data of the damage to the Puteolan building following the bradyseismic crisis of the period 1983-1984 provided by the Municipality of Pozzuoli. Vulnerability curves for each vulnerability class (A, B, C) in function of tilt and lift are assessed.
The procedure has been automated in a web application, available to the Civil Protection Department. It is able to return at local scale, the number of buildings with assigned damage level (from D0: no damage to D5: total collapse) in a square cell with a side of 250 m (minimum unit of analysis), in function of lift and tilt inputs
The procedure has been developed on the basis of the scientific and technological updating of the methodology devised in the PETIT-OSA research project, Advanced Telecommunications and Information Technology Platforms for the Offer of Services to the Environmental Sector (PON 2000-2006) and thanks to funding from the Civil Protection Department (VIRA 2019-2022, "Assessments of Vulnerability, Impact and Risk induced by Campania volcanoes on the urban environment").

Approaches at regional and National levels to prevent and mitigate the risk of gas hazards in the inhabited areas of Rome, Ciampino and Fiumicino municipalities (Lazio Region)

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Volcanic risk prevention and mitigation in inhabited areas allows a correct and effective management of any potential emergency arising from a volcanic event.

In a complex civil protection system as the Italian, which is defined from the regulatory point of view in a "concurrent" manner between the National and Regional emergency management bodies [art. 117 Italian Constitution], the clarity of the functions, of the tasks, but above all the responsibilities of the actions both in the prevention and in the emergency phases are fundamental (essential).

The hazard related to the emissions of dangerous gases (CO_2, CH_4, Rn) from the soil affects many territories on all continents. The studies carried out have shown how important and useful it is to carry out continuous gas monitoring released from the subsoil in both living and working environments [Varrenti et al., 2016].

We will try to highlight, through a specific case study, the differences between operational and normative actions among the civil protection at National and Regional level.

The National level, on one hand, must always be ready to respond to emergencies with acts that firstly understand the problem and analyse the associated risks, facilitating and supporting regional and local civil protection Authorities.

The Regional level, on the other hand, must assume responsibility for specific acts and operations locally in order to ensure both the governance of the territory, but also the operational support to the local authorities of the areas affected by a long-term emergency event.

So, in a correct institutional synergy, functions of one level do not overwhelm those of the other. Furthermore, each one within their own specific responsibility and competences, and with the fundamental help of the scientific community, they arrive at solutions to be presented at the local level.

Unfortunately, at the moment there isn't any National Directive that regulates the matter relating to the anomalous degassing in inhabited zones active volcanic areas, so that often the problem is dealt with by the territory administrator only at the onset of the event.

The specific case studies concern Lazio Region and in particular (i) gas emissions around Colli Albani area (Municipalities of Rome, Marino and Ciampino) in which about 80,000 people live and (ii) a second area in Isola Sacra nearby the International airport of Rome Fiumicino.

Both areas have long been known to be the site of significant gas emissions from the soils. These areas have been affected, even in recent times, by sudden leaks of gas from the soils, sometimes in conjunction with seismic events, or in relation to excavations carried out for the construction of wells or anthropogenic activities [Carapezza et al., 2012; 2013 and 2014].

It is important to highlight how the scientific and technical-administrative approaches downstream of the studies between the Colli Albani area and Isola Sacra area were different.

The studies that the National civil protection department has conducted with the Scientific Community have produced actions and activities of information and communication for the population and for the Administrations involved [DPC et al., 2006].

The studies that the Lazio Region commissioned to the scientific community have allowed, with mandatory technical-administrative regional acts [Lazio Region Law no. A00271 / 2012, Lazio Region Law n. G10182 / 2016], to delimit areas in which, due to strong CO_2 emissions, it is not possible to issue any urban-environmental binding opinion without preventive measures or monitoring [Presidential Decree no. 380/2001].
The real purpose of this presentation is to understand if, after a few years from the issuing of the regional decrees, the synergy between the two levels of civil protection has determined or can determine positive results for the management of risk mitigation in active volcanic areas.

† This work is dedicated to the memory of Antonio Gerardi, a colleague Geologist who died suddenly during the drafting of this abstract, and who carried out a fundamental technical-scientific work in the development of the regional acts cited in the text.

S15 - THE MANIFOLD INTERACTION BETWEEN HUMANS AND VOLCANOES: INTERDISCIPLINARY STUDIES AROUND VOLCANOLOGY

Conveners:
Stefano Branca, Mauro Antonio Di Vito, Franco Foresta Martin, Daniele Musumeci, Orazio Palio

$^{87}Sr/^{86}Sr$ isotopic ratios of archaeological obsidians from Ustica Island (Italy) confirm prehistoric imports from Lipari and Pantelleria

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The volcanic island of Ustica, located in the southern Tyrrhenian Sea, about 65 km to the north of Palermo, is the small emerging part of a large volcanic seamount, more than 2000 meters deep. The exposed volcanic rocks are mostly Na-alkaline basalts with minor trachytes, produced in the age interval 750 -130 ka during effusive and explosive eruptions, the last of which built the Falconiera Tuff Cone in the eastern sector of the island.

Ustica lacks obsidian deposits; therefore the obsidian fragments recovered on the island were imported in prehistoric times.

In recent years, the cultural institution “Laboratorio Museo di Scienze della Terra Isola di Ustica” has promoted extensive research on archaeological obsidians. The geochemical fingerprints of hundreds of obsidian samples were obtained using many analytical methods: EMPA, LA-CP-MS, XRF, pXRF, SEM-EDS, FT-IR and paleomagnetic. These studies attest that from the Neolithic to the Bronze Age, Ustica obsidian derived mainly from Lipari (80-85%) to a lesser extent from Pantelleria (15-20%), and only occasionally from Palmarola.

In this work, 29 archaeological obsidians from 4 different archaeological areas of Ustica Island were characterized through chemical and, for the first time, isotopic analyses ($^{87}Sr/^{86}Sr$), in order to unravel the provenance of the raw material.

The preliminary results show that the signature of Lipari has been recognized for 24 obsidian samples which have the highest $^{87}Sr/^{86}Sr$ isotopic ratio (0.7058-0.7059), whilst that of Pantelleria for the other 5 samples with the lowest $^{87}Sr/^{86}Sr$ (0.7042-0.7047). It is thus confirmed the proportion between obsidians from Lipari and Pantelleria highlighted by previous studies.

Obsidian samples were also analyzed by FT-IR and SEM-EDS in order to determine the glass H_2O content, chemistry, and mineralogy, as additional constraints to track their provenance.

From a typological point of view, the obsidian fragments are mostly processing wastes and few blades.

Discriminating elements and data processing procedures to determine the provenance of central mediterranean obsidians: new insights and trials

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The geochemical characterization of obsidian archaeological finds is nowadays feasible with a variety of analyses such as SEM, EMPA, LA-ICP-MS, XRF, pXRF, just to mention the most practiced. But the geochemical fingerprint, in terms of some major, minor, and trace elements that allow identifying the outcrops from which the archaeological finds come, is not always easily identifiable. Meteoric alterations of the volcanic glass accompanied by the loss of some elements and relative enrichment of others; devitrification processes; strong interaction of some analytical methods on elemental composition, can make provenancing studies rather problematic.
For the scholars engaged in obsidian sourcing, it has become a standard procedure to combine the analyses of the major-minor elements with those of the trace elements, to have a complete geochemical characterization of the studied specimens and avoid the uncertainty caused by the variability to which some major elements are subject.
In order to limit the number and costs of the necessary analyses, we have identified a minor element, Chlorine, and a major element, Sodium, which together allow unambiguous discrimination of the four obsidian sources widely used in the Central Mediterranean during Prehistory, namely Lipari, Monte Arci (Sardinia), Pantelleria and Palmarola.
The bivariate distribution of the weight abundances of these two elements presents well-defined clusters corresponding to the various original outcrops, and it is possible to develop a rather simple protocol that allows the identification of obsidian samples with respect to their origin. We also investigated the occurrence of systematic deviations, in particular referring to the abundance of Cl, due to the use of different analytical techniques.

S15 - Oral Presentation

Archaeology in relation with the geomorphology of the territory at the eastern foot of Etna. Connection between human and environment: new about prehistoric and historic settlement logic in the territories of Riposto, Fiumefreddo and Mascali (CT)

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The archaeological analysis in the area between the municipalities of Fiumefreddo, Mascali, Giarre and Riposto (CT) has always been very complex. This research wants to focus attention an area of 50 km^2 wide, that is located between the Ionian coastline, and the eastern foots of Etna. During the history, lava flows devasted often this area, even at very low altitudes. For example, in the 1928 a lava flow destroyed the old settlement of Mascali, consequently erasing numerous archaeological remains present in the area of ancient country. Another very important flow was the one called “Scorciavacca” (1020-1040 AD), which generated a large lava flow in the lower north-east slope of Etna, still visible, which probably touched the northern part of the ancient territory of Mascali. However, we must always considered the relationship between the volcano and the nearby coastline. The coast is characterized by the presence of a swamp, still partially visible in the areas near the Fiumefreddo river, and which in the past must have been even larger.
Maybe, such as already pointed out by other past studies, these two factors have strongly influenced the settlement methods and the viability of the territory. In addition, the intense agricultural activities still carried out throughout the territory have distorted the landscape, thus making the research work for archaeologists very complex. At the end, a few well-documented archaeological areas survived, but they are too few in number to allow the history of the area to be reconstructed, at least from the Greek era up to the Middle Ages.
However, despite the premises, starting from the traces still available, combining them with the study of the geomorphology of the area, it was possible to understand the settlement logic of the different human communities that occupied this area over the centuries. In fact, by combining the information on the archaeological contexts already known with the geomorphological study of the territory, it was possible to insert them on a GIS support. In this way, it was subsequently possible to investigate the relationship between human and landscape in greater depth. It was also observed that most of the archaeological sites were in correspondence with precise geological formations. This has allowed us to advance new hypotheses on the exploitation of the territory, on the settlement and road system logics, with particular reference to the passage from the Roman to the Byzantine period. Trying to offer a new interpretative key, based on an interdisciplinary approach, the authors propose the definition of a geo-archaeological research method, which can also be used in other areas where the same characteristics and criticalities are present.

Clustered volcano-tectonic evolution in the central sector of the Main Ethiopian Rift and implications for early hominins evolution

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Reflecting an intermediate stage of rift evolution, the Central Main Ethiopian Rift (CMER) represents an area of particular relevance for understanding the development of continental rift, from rift initiation toward more mature stages of rifting, and the interplay between tectonic and volcanic activity. Large, explosive, caldera-forming eruptions have punctuated the evolution of the CMER, where the presence of several caldera remains and of large ignimbrite deposits testify for the recurrence of periods of intense volcanism in time. However, the long-term time distribution of volcanic activity is still poorly resolved; only few single major episodes of explosive volcanism have been identified up to now and no relation with the tectonic activity has been provided for the heterogeneous evolution of volcanism. In the present work we use a new detailed stratigraphic and geochronological reconstruction of all the largest deposits outcropping along a 70 km-long sector of the eastern and western margins of the CMER to provide new constraints on the timing, evolution and characteristics of volcanism in this area. The stratigraphic reconstruction and the $^{40}Ar/^{39}Ar$ dating of 55 samples of volcanic rocks collected from the CMER suggest a highly pulsed evolution of volcanism during the last 4 Ma. Important phases of explosive silicic volcanic activity occur at 3.85-3.4, 1.3-1.2, 0.8-0.6 and 0.3-0.16 Ma, and are interspersed with periods of reduced volcanic activity.

These findings indicate a clustered volcano-tectonic activity in the CMER which may have had important influence on environmental changes in the area. The geological evolution of the area evidences a strict association between these clusters and major tectonic episodes of faulting and drastic reorganization of rift valley topography. Clusters of intense ignimbritic volcanism like those typifying the evolution of the CMER, would drastically affect wide areas of the rift, with the emplacement of thick, often welded deposits of tens to hundreds of cubic kilometers over huge areas, and with the dispersion of co-ignimbrite ash over the MER and nearby regions. The environmental impact of this activity should be looked at with particular attention considering that it was concentrated over short time-windows during periods in which hominins were living and evolving. Although preliminary data on volatiles released during these events do not suggest major climatic effects, the pulses of magmatic activity appear to impressively match or slightly precede important phases of hominin speciation, suggesting that the strong impact of very large eruptions occurring in relative short time intervals may have devastated entire sectors of the rift valley, making them uninhabitable for prolonged periods of time and possibly representing a forcing agent to hominid migrations.

S15 - Oral Presentation

"Dei Vulcani o monti ignivomi più noti, e distintamente del Vesuvio..." of Giovanni Targioni Tozzetti (1779)

Paolo Sammuri

Libero Ricercatore

In this work Targioni recalls that his master, the great Florentine naturalist Pier Antonio Micheli, recognized as ancient volcanoes in 1722 the Mount of Radicofani and in 1734 the Mount of S. Fiora (M. Amiata). The recognition was possible by analogy, observing the similarity of the rocks in these localities with certain lavas of Vesuvius, observed by him in 1710. This method of observation and comparison of rocks led to the recognition of volcanic characteristics in various locations in the upper Lazio (Montefiascone, Acquapendente, Viterbo) that were identified as the site of extinct volcanoes. Moreover, the observation of the diversity of the lavas (melted, vitrified, cooked or decomposed) also leads to the evaluation of the different degrees of fire, which is considered very strong and much higher than the fires produced by man. The study of the extension of the ancient deposits also led to hypothesize vents or secondary openings, also ignivomous, in analogy with the descriptions of the most recent eruptions observed of Vesuvius and Etna. There is also the collection and study of samples and the observation with the microscope, for example of Pitigliano pozzolana powders defined as similar to the ash thrown by Vesuvius on Naples in 1767 with the description of rounded crystals and well-defined crystalline shapes. In conclusion we can say that it is a real treatise on volcanology *ante litteram*, which shows us the knowledge, limits and methods of study of volcanoes in the eighteenth century.

Legends and medieval sources in the volcanological studies of Lipari

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For much of the Middle Ages, the island of Lipari was marked by a demographic contraction caused not only by the general circumstances of the period, but also by the resurgence of volcanism, which conditioned the stability of local communities and confined settlements to the non-active sector of the island. References to this activity can be found in some contemporary sources and in the local religious tradition. Paulus Silentiarius (520-580 AD), an imperial official and Byzantine poet, reveals that on the island: "...there is a dark conduit that shines at night and launches with great clamour, with the roar of thunder, sulphurous boulders that illuminate everything" [Bernabò Brea, 1998]. It is also recounted in the ancient breviaries of the Catholic Church of a hermit named Calogero, sent to the island by the Supreme Pontiff around 525 AD, with the aim of converting the inhabitants and warding off the threatening evil spirits that manifested themselves in the form of volcanic phenomena. Within the religious tradition of S. Calogero, strongly felt on the island, a fundamental distinction must be made between the historical aspect underlying such cult and the local legendary narratives that most likely arose in the Late Middle Ages as a consequence of the island's last eruptive cycle in the 13th century [Manni, 2022]. However, a different interpretation was originally given by the authors who had the merit of handing them down in writing over the past centuries. These included the historian Campis (1694), who emphasised the thaumaturgic qualities of the Hermit Saint who extinguished the devastating fires, and the naturalist Dolomieu (1781), who commented: "that the last eruptions on this island are ancient and date back to the 6th century AD. - If the chronicles that speak of this Saint refer to true facts, we can deduce that from the 6th century onwards no further eruption has occurred in Lipari". This consideration was taken up by other scholars in the last decades of the 20th century. Firstly by Keller (1970), who initially hypothesised a period between 500 and 550 AD for the eruptions of Monte Pilato (MP) and Forgia Vecchia (FV), a reconstruction later shared by Pichler (1980). At present, the geological literature does not contemplate any eruptions prior to the MP eruption at the end of the 8th century AD. On the basis of the sources cited, however, the hypothesis remains open that Lipari had its own vent in activity as early as the beginning of the Middle Ages. The eruption of MP that Keller (2002) later dated more precisely to 776 AD, represents a milestone in the reconstruction of Lipari's historical volcanism, and is this time placed by the author in relation to the testimony of a religious man named Gregory in the year 786, who while sailing through Aeolian waters noticed the island in eruption. The passage in his description in which he describes "the dark lava flows liquefied", draws attention to the conspicuous south-eastern slope of MP, where numerous rocky outcrops are exposed that can be attributed to a presumed effusive phase of the volcano, which to date has not been geologically detected. A turning point in the reconstruction of Lipari's recent volcanism came with the use of archaeomagnetism, which revealed a chronological gap of almost 500 years between the aforementioned phase and that of Rocche Rosse, which developed in the northern margin of the pre-existing crater area and from which the homonymous obsidianaceous flow was effused, dated around 1230-40 AD [Tanguy et al., 2002; Arrighi et al., 2006]. It has recently been ascertained that it is part of a broader eruptive context, which began with the eruptions of the FV [Pistolesi et al., 2021]. Two separate sources certify destructive events that occurred on the island in 1264 [Martinelli et al., 2019]. Local beliefs about S. Calogero describe with surprising accuracy the eruptive sequence that affected the entire Lipari-Vulcano complex between the 13th-16th centuries, recently redefined by Malaguti et al. [2020; 2021]. Campis reports that after the fires of Pirrera (FV) were extinguished, the devils responsible were driven back to Vulcano. Similarly, Dolomieu narrates that the island's patron saint drove out the devils that lived in the MP and made them flee to Vulcanello and then to Vulcano, where they never stopped throwing fire and flames. The emergence of Vulcanello around 1000 AD in itself ties the setting, and thus the origin of the narratives themselves. According to the newly proposed interpretation, the local legends of S. Calogero are linked to this latter eruptive cycle, while the hypothesis remains that an eruptive centre was already active at the beginning of the Middle Ages, at the time of the hermit's presumed stay on the island. Some stratigraphic clues (breccias underneath the pumiceous deposits of the nearby MP) identified immediately NE of the FV crater area, would support the hypothesis that it may be this volcano

The role of cartography by Wolfgang Sartorius von Waltershausen (1809-1876) in the frame of the geological investigations of Etna volcano

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The cartography of Sartorius is made up of nine issues published between 1844 and 1861 and collected in the Atlas des Aetna, which in total consists of 13 topographic maps and 13 geological maps at 1: 50,000 scale, numerous perspective views, geological and topographical sections and a short accompanying text. It is a monumental work that as a whole constitutes the first topographical and geological map of the volcano, later integrated by a detailed topographic map of the Valla del Bove, at a scale of 1: 15,000, which together constitute the first cartographic documents ever of this type for Etna volcano. In particular, the geological surveys, carried out from 1836 to 1843 and reproduced in 13 sheets, originally at a scale of 1: 30,000, together constitute the first detailed geological map of a volcano in the world. The set of topographic and geological data will allow the author to estimate, for the first time, the absolute age of the volcano and its volume. The knowledge deriving from the geological cartography of Sartorius will represent the only cartographic data of reference for the location and dating of the historical eruptions of Etna up to the sixties of the twentieth century, also influencing the same attributions in the geological map of the volcano published in 1979 by CNR.

The evolution of Chilean volcanology in the 20th century and the work of Lorenzo Casertano

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Chile is one of the most geologically active countries in the world. About 90 volcanoes in Chile are considered active and more than 400 eruptions have been recorded since the 16th century. Until the 19th and 20th centuries, most of the information on volcanic phenomena came from the accounts of travellers and naturalists, including Charles R. Darwin [Darwin, 1840] and Ignacio Domeyko [Domeyko, 1848]. At the beginning of the 20th century, the German geologist Juan Brüggen (1887-1953) made a notable contribution. Brüggen is renowned for having studied Chilean geology for forty years and for composing the first general treatise in Spanish, Fundamentos de la geologia de Chile [Brüggen, 1950]. However, only a small section is devoted specifically to volcanism. A breakthrough came in 1959 with the arrival of the Italian physicist Lorenzo Casertano (1921-2004), who taught the first courses in Volcanology at the Universidad de Chile (Santiago de Chile). His most important contributions concern volcanological studies in Italy, Chile and Costa Rica [Casertano, 1963]. Thanks to the presence of Casertano and other foreign scholars, the first Chilean volcanologists working in the area began to gain experience and broaden their knowledge in the following decades. Scientists such as Oscar González-Ferrán (1933-2014), Hugo Moreno, José Antonio Naranjo and others would go on to lead volcanological studies towards an increasingly complex approach, in line with international standards, thanks to the monitoring and research performed by SERNAGEOMIN and the Universities [de Silva & Francis, 1991; González-Ferrán, 1994].

S15 - Oral Presentation

A combined approach for understanding volcanic hazard: ancient landscape and fragments of daily life, revealed by the effects of the 79 AD Somma-Vesuvius eruption, inside the archeological sites of Stabiae, Boscoreale, Oplontis, Herculaneum (Campania, Italy)

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The Somma-Vesuvius is a densely populated area, where awareness of volcanic risk is still poor. Since 2017, several geoarcheological study-days were organized at the excavation of Stabiae, Boscoreale, Oplontis, Herculaneum, for improving comprehension of the impact of the 79 AD eruption, through promotion of such valuable archeological sites.

Volcanologists, archaeologists and naturalists met retracing the 79 AD eruption events throughout a multi-voice seminar on the eruptive history of Somma-Vesuvius; its effects on the territory, man, and in particular on the Roman cities affected by this Plinian eruption, were carefully explained in order to better understand the complexity of the activity of Vesuvius, through the traces visible in the archaeological excavations of the buried cities, very different traces depending on the place and its geographical position.

Participants could therefore immerse themselves in the Vesuvian reality in a journey back several thousand years, necessary to reconstruct the complete eruptive history of the volcano, known to us from geological, archaeological, historical and anthropological data, and could participate to a Conference on these themes in an interactive mode, with their doubts and questions, discussing on updated and reliable data such as accredited scientific ones.

This indoor phase was followed by a real archeotrek in the excavations, with stops illustrated at the crucial points, like the volcanological stratigraphic sections that document the thickness and type of products erupted by Vesuvius, as well as inside the domus, shops, thermal buildings and relevant monuments, which admirably give us back fragments of the life of the Roman populations, their daily habits and customs.

These study-days were organized through a global approach integrating archeology, volcanology, historical and geophysical data, to stimulate knowledge and awareness of this active volcano and enhance such unique and precious places on geoarcheological point of view.

S15- Poster

Distribution and impact of historical lahars on densely-inhabited territory after sub-Plinian eruptions of Vesuvius

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Lahars directly related to volcanic eruptions can be triggered during or after the end of an explosive eruption. Around Somma-Vesuvius, there are numerous evidences of interaction between historical lahars and local infrastructures, directly related to two sub-Plinian eruptions of Vesuvius, 472 AD and 1631.
In this work, a collection of all findings of lahar deposits has been carried out, by including historical, stratigraphic and sedimentological features into a database with more than 500 points. In particular, the historical fonts have been of help in locating the general impact of those lahars on several Neapolitan municipalities. Then, an integration among stratigraphic and archaeological analyses has been done, by correlating the various depositional units by means of temporal constraints from archaeology. Such analyses have been done both on primary (fall, flow) and secondary (lahar) deposits, in order to define the timing of the lahars vs. primary processes. Also, a reverse engineering approach has been used to calculate lahar velocity and dynamic pressure from the field deposit features.
Results show that the dispersal areas of the primary pyroclastic products are larger than previously thought, both for the 472 AD and 1631 eruptions; this because the distal fine ash has been detected and included into the database. Also, different feeding basins for lahars formation have been identified, which are located on Somma-Vesuvius and Apennine reliefs. From these sectors, the historical lahars invaded the Campanian Plain and various Apennine valleys, impacting the landscape under velocities of a few m/s, and dynamic pressures of a few kPa with local peaks of tens of kPa.

S15- Poster

Risk assessment from volcanic emissions at Mt. Etna: preliminary results from project HEAVEN

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Volcanic emissions (ash, aerosol, plume gas, soil gas and groundwater) represent one of the most important natural sources of major, minor and trace elements (TE) into the atmosphere, sequentially influencing the other geochemical spheres (hydrosphere, lithosphere and biosphere) and hence human biological systems. Several studies both on volcanic gases [Stoiber & Rose, 1970; Menyailov & Nikitina, 1980; Gemmel, 1987] and on particulate matter in volcanic plumes and ashes [Cadle et al., 1973; Mroz & Zoeller, 1975; Lepel et al., 1978; Buat-Ménard & Arnold, 1978; Calabrese et al., 2011; Calabrese & D'Alessandro, 2015] showed that TE are separated from magma during its degassing and they are transported towards the surface by the rising gas phase as halides, native elements or sulfur compounds. As these elements approach the surface, they condense forming small particles that are then dispersed in the atmosphere by volcanic plumes, carried by volcanic ash, emitted diffusely through soil degassing or dissolved into shallow aquifers/hydrothermal reservoirs. Volcanogenic TE may be absorbed by plants, soils, waters and animals, in variable amounts that mostly depend on metal concentration and exposure. Volcanic ash rapidly mobilizes significant amounts of biologically relevant elements (e.g., fixed-N, P, Si, Fe) into the seawater [Frogner et al. 2001, Duggen et al. 2007, Jones & Gislason 2008, Censi et al. 2010] that are utilized by the phytoplankton for reproduction [Duggen et al. 2007, Hoffmann et al. 2012]. Among the soil gases that can have a strong impact on the biosphere, radon is one of the most harmful. The radiation burden due the radon short-lived progeny has been associated to lung cancer incidence [Baxter et al., 1990, 1999; Rodríguez-Martínez et al., 2018] and lymphocytic leukaemia [Tong et al., 2012; Oancea et al., 2017], after long exposures.
An excessive amount of metals in human bodies could result in cellular oxidative stress, due to both an overproduction of free radicals and an underproduction of cellular antioxidants [Cicero et al., 2017] and it could also influence the immune system, leading to abnormal function of T-lymphocytes and macrophages, harmful production of autoantibodies against neuronal proteins and excessive release of proinflammatory cytokines [Napier et al., 2016].
Mt. Etna is the largest stratovolcano in Europe and one of the most active in the world, emitting TE through many different types of volcanic emissions. Several studies already assessed the higher incidence of Amyotrophic Lateral Sclerosi, Multiple Sclerosis, primary brain tumors (meningiomas and glioblastomas) and tyrhoid cancer in the Mt. Etna region, especially in the people living on its SE flank (the most exposed to volcanic emissions), and their possible

correlation with volcanogenic TE [Nicoletti et al. 2013; Nicoletti et al. 2016; Boumediene et al. 2019; Nicoletti et al. 2020] or even with radiogenic elements such as radon [Schwartz et al., 2016; Gonzalo Lopez-Abente et al., 2018]. Actually, the east flank of Mt. Etna is characterized by higher concentrations of indoor radon in locations close to active faults [Neri et al., 2019].

Project Hazard from EtnA Volcanic EmissioNs (HEAVEN), funded within the larger project Pianeta Dinamico, is aimed at i) collecting all the existing data on TE emissions from Mt. Etna and all the data on diseases that may be correlated with volcanogenic TE in the Etna area; ii) assembling a group of scientists with a multidisciplinary background (Volcanology, Geochemistry, Environmental Chemistry, Environmental Modeling, Neurosciences, Oncology, Immunology, Statistics, Geostatistics) to study and possibly reveal the causal links between volcanic emissions of TE and the different pathologies found in the Etna area, trying to model how volcanogenic TE and radon emitted both during quiescent and during eruptive periods reach living beings and accumulate in their tissues.

Within the activities of project HEAVEN, here we present some preliminary results from the analyses of TE both in natural samples (groundwater, seawater, soil and indoor radon, volcanic ash and particles) from Mt. Etna and in biological samples (urine, serum) of people living in the Etna area, and we discuss them in terms of possible related health hazards.

S15- Poster

Volcanology and archaeology: joint investigations reveal the evolution of a territory far from active volcanoes, but largely affected by their phenomena

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We present the preliminary results of a stratigraphic and volcanological survey conducted in several trenches dug for archaeological investigation in the area of Pontecagnano, near Salerno (Campania, Italy). Fieldwork aimed to the reconstruction of the stratigraphic succession, focusing on the recognition and detailed description of the structural and textural characteristics of tephra horizons which have been, preliminarily, correlated to eruptions originated from Somma-Vesuvius and Campi Flegrei, in a time span between 39 ka bp and AD 79, based on the observed features. Our work has a dual purpose: provide useful information to archaeologists to better constrain the age of archaeological findings (e.g. footprints or pole holes) in an area where volcanology and archaeology are strictly related and new data about the dispersal of Campanian tephras in distal settings. From a geomorphological and geological point of view, the study area is represented by flat coastal plain where marine, alluvial and palustrine sediments accumulated during Quaternary. The composite stratigraphic succession is formed by at least 6 tephra horizons (units) mainly represented by grey to yellowish ashes, ranging in thickness from a few centimeters to tens of centimeters, separated by sandy to clayey, dark brown to greyish, often bioturbated paleosols and/or sedimentary deposits. Some paleosols show signs of anthropization as ploughing traces or pole holes. Tephra horizons are often laterally discontinuous due to erosion and/or reworking and, locally, only very small lenses or traces of such horizons can be hardly recognized embedded into the paleosols.
The oldest unit of the composite stratigraphic succession is made up of grey to brownish ash containing very fine, grey pumice and scoria lapilli grading upward into a brown paleosol. This unit can be correlated to the Campanian Ignimbrite (39 ka), the most powerful caldera- and ignimbrite-forming Plinian eruption sourced from Campi Flegrei. The second unit is a grey to yellowish, fine ash containing very fine, light grey, aphiric, well vesiculated pumice lapilli, grading upward in a brown paleosol containing very fine, grey pumice lapilli. This unit can be correlated to the Neapolitan Yellow Tuff (15 ka), the second largest caldera- and ignimbrite-forming Plinian eruption sourced from Campi Flegrei. The third unit is composed of a light grey to yellowish-orange ash, often humified or reworked, containing very fine, light grey pumice lapilli and ash aggregates. The humified top of this unit is often characterized by ploughing traces and pole holes. In addition, footprints have been found on top of this unit. It can be correlated to the Agnano-Monte Spina eruption (4.5 ka) sourced from Campi Flegrei. Locally, up to 4 reworked volcaniclastic horizons, bounded by undulated erosive surfaces and made up of matrix-supported, light to dark grey, ashy deposits containing rounded, grey pumice fragments, rest on

top of this tephra horizon. The absence of a paleosol or signs of alteration between them suggest that the volcaniclastic horizons were emplaced as syn-eruptive, hyperconcentrated flows that contributed to preserve the footprints due to a rapid burial. The fourth and fifth units are represented by light grey ash layers containing grey fine pumice lapilli and subordinated very fine scoria lapilli separated by a brown to greyish paleosol. These units are deeply bioturbated and are often found as partly reworked lenses. Both units can be attributed to the so-called AP eruptions, a sequence of 6 eruptive events sourced from Somma-Vesuvius in the time span between the Avellino Plinian eruption (3.9 ka) and the AD 79 Plinian eruption, also known as Pompeii eruption. Particularly, these units may be attributed to AP2 and AP3 occurred, respectively, 3.5 and 2.8 ka bp. The sixth and uppermost pyroclastic unit is attributed to the AD 79 Plinian eruption and is mainly found as reworked material composed of massive to laminated, matrix-supported deposits containing well rounded, light grey, slightly porphyric, pumice lapilli up to 1 cm in diameter. Just in one trench, we observed the primary deposits of the AD 79 eruption represented by a 14 cm thick fall deposit made up of fine, slightly porphyric, angular pumice lapilli ranging in color from white at the base to grey at the top e minor millimeter-sized lithic lava clasts. This deposit occurs as a primary lens, 62 cm long, grading upward into reworked material.

Multidisciplinar, combined stratigraphical investigations permitted to depict a detailed geological and archaeological evolution of an area inhabited by human communities at least since Eneolithic. The recognition of distal tephra from Campi Flegrei and Vesuvius eruptions permitted to trace isochronous surfaces among the studied sites and proximal ones, and to evaluate the effects of the tephra accumulation in distal areas.

S15- Poster

A historical - methodological review of the studies on the 1932 eruption of the Quizapu volcano, Southern Andes, Chile

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The 1932 plinian eruption of the Quizapu volcano in southern Chile is the largest historical eruption in Chile and the largest of any volcano of the Andes during the 20th century. The Quizapu volcano is a young flank vent of the basalt-to-rhyodacite Holocene stratocone Cerro Azul. It belongs to the Cerro Azul-Descabezado volcanic cluster and is part of a NS volcanic lineament in the Southern Andean Volcanic Zone. Quizapu was mainly constructed by two significant eruptions, in 1846-1847 and 1932, both triggered by magma recharge that extruded similar volumes, 5 km^3, of a volatile-rich dacitic magma. However, they present a remarkable contrast, with a dominant effusive style the 1846-1847 opposed to the plinian activity of the 1932 eruption. The explosive event had a calculated Volcanic Explosivity Index of 5 and comprised a steady plinian phase of 18 hours, producing an exceptionally uniform fallout deposit. Despite its remoteness and only the development of incipient volcanological studies in Chile during the 1930s, this explosive eruption rapidly awakened the interest of the national and international scientific community due to its dispersal and significant impacts in the eastern sector of South America. Although the confusion and uncertainty at the beginning ruled over objective observations, the next five years that followed the eruption resulted in an extremely high number of technical reports and publications from researchers worldwide that notably enriched the Chilean volcanological knowledge. Despite this, only a few investigations were performed during the following decades, and it was not until 1992 that the Quizapu eruptions were studied based on current multidisciplinary volcanological techniques. Additionally, during the last years, several studies were performed mainly focused on the magmatic reservoir conditions responsible of the different eruptive style (effusive vs. explosive) of the two main large events. In this contribution, we present a review from a historical perspective of the 1932 Plinian eruption of the Quizapu volcano, analyzing and contrasting the different applied methodological approaches and their evolution and improvement during the last nearly 100 years for a single eruption of the Quizapu volcano. During this period, scientific investigations typically shifted from pure scientific chronicles and descriptive works focused on the reconstruction of the chronology of the eruption to multidisciplinary and detailed studies aimed at the complete understanding of the eruptive dynamics of the volcanic phenomenon.

S15- Poster

S16 - VOLCANIC HAZARD AND RISK: COMMUNICATION, INFORMATION AND TRAINING DURING QUIESCENCE, UNREST AND ERUPTION TIMES

Conveners:
Rosella Nave, Vincenza Maiolino, Sara Barsotti, Marco Neri, Chiara Cristiani

Emergent tools to promote understanding of natural hazards

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How to improve understanding of natural hazards is a major challenge for the research community. The multiple aspects of the hazard, from earthquakes to volcanic eruptions, landslides and costal erosion, require new methods not only for data acquisition, but also for data processing and consequent management. In this respect, emergent tools, such as augmented and virtual reality, offer great versatility and effectiveness.
Also, gaining insight into natural hazards with these tools can help communication to the general public as well as teaching to the digital native generation, particularly accustomed to these techniques for playing video games.
In this presentation we describe our outreach activity by using augmented reality to help understand hazardous events, increasing preparedness and resilience.

S16 - Oral Presentation

Immersive Virtual Reality: a novel approach for geological exploration in volcanic areas

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Immersive Virtual Reality (VR) represents a crucial technology to survey active volcanic areas otherwise inaccessible, due to difficult logistic conditions. Here we present our innovative approach based on generating 3D models created through drone surveys coupled with Structure-from-Motion (SfM) photogrammetry, which, thanks to their high-resolution and photo-realistic texture, allows to replicate real-world field exploration. Indeed, this technology has greatly contributed to making geological features more accessible to students, researchers and the lay public. The reconstructed virtual geological environments are specifically chosen geosites, spanning from Italy to Iceland, along a series of outstanding geological features.

Through our user-friendly software tailored for geological exploration, any Earth scientist can be able to study these geological sites at a wide range of scales, from small outcrops to large areas, to collect a wide range of quantitative measurements, such as the thickness or attitude of volcanic layers, and to explore key spots choosing between three different modes to navigate the scenery, moving with the thumbsticks on the controllers.

Basing on the positive feedbacks obtained during outreach activities performed at schools and national and international exhibitions over the past years, we believe that our approach, that can support classical field trips, represents a crucial advancement because of its potential to allow researchers and students to virtually travel to key geological areas even in difficult times, such as the COVID-19 pandemic, to increase accessibility of virtual geosites, even for people with motor disabilities, to help students learn geology more interactively, and to potentially reduce travel expenses and carbon emissions.

S16 - Oral Presentation

Promoting interest in geological sites among the public via a field guide and virtual reality of Aci Castello and Aci Trezza (Sicily)

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The villages of Aci Castello and Aci Trezza, on the east coast of Sicily, are home to sites of significant geological interest in the form of the Aci Castello castle rock and the Cyclopean Islands in Aci Trezza. These exposures record the earliest stages of the evolution of volcanism at Mt Etna. Aci Castello and Aci Trezza are frequented by tourists, majority of whom have no understanding of the geological significance of these sites. To improve scientific knowledge and awareness of the public and provide a new activity of interest to tourists, we created a pdf geological field guide for Aci Castello and Aci Trezza. The field guide can be downloaded via the INGV website for viewing on a smartphone (or printed if desired). There are also plans to place QR codes linking to the field guide at the sites. The field guide provides simple, visual explanations of the geological processes recorded by the outcrops at Aci Castello and Aci Trezza, via cartoons shown alongside photographs of features of interest. The field guide is linked, trough QR codes, both to a 3D virtual reality visualization of the outcrops created using images, and video recorded with drones. This virtual reality visualization will also be hosted on the INGV website and provides the option of viewing the geological sites at Aci Castello and Aci Trezza online. This additional resource will allow dissemination of the information contained in the field guide to a much wider audience, beyond visitors to the Sicilian coast, and provides an easily accessible educational tool for use in settings such as classrooms and public lectures.
It is hoped that this product will promote awareness of and interest in Sicilian geology among the lay public and facilitate the creation of similar educational resources for other sites of geological interest around Sicily.

Elica, takes children through reading into the world of science and conscious technology

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To spread scientific knowledge to new generations is a great challenge that, if achieved, will enable the formation of new adults with greater environmental awareness and thus eco-sustainable management skills. The means to achieve this goal are increasingly becoming more both intriguing and technologically advanced, such as Virtual and Augmented Realities. However, the traditional book is still an incredibly versatile tool that can reach people of different ages from grandparents to grandchildren. Books can also facilitate that intimate and recollecting moment that is established between the reader and the listener.
In this perspective and precisely with the intention of bringing the youngest children closer to the world of scientific research and earth sciences, Elica was born.
"Elica!" is the shout that it is usual to emit when starting a plane and warning to pay attention to those in the vicinity of the aircraft. But Elica is also the character of a book, born from the imagination of its author and from the adventures experienced by a drone and narrated by its pilot and instructor. The little drone brought, to the schools the knowledge of one of the research activities carried out by INGV and that most strike the collective imagination of younger. The pressing and evocative story tells of a drone who finds himself operating in the wonderful world of research, with much desire and wish for discovery of the very special, hostile but attracting nature peculiar to volcanic environments. The encounter between the drone, at its first flying experience, and Etna, a magical and legendary place, both personified, leads the child reading this adventure, into a world full of a variety of experiences. Young readers learn, together with Elica, about volcanic regions, the legend of Hephaestus, overcoming uncertainties and fears through the pilot's encouragement, and about the conscious use of new technologies, which are wonderful and useful, but only if properly used. For the past two years, Elica, book sponsored by INGV, fantasy but anchored in a scientific reality and yet close to young readers, has been adopted by some schools. Such experiences have made it possible to evaluate this teaching tool through feedback from teachers and parents, and to observe how the character Elica, succeeds in breaking new positive horizons of knowledge and awareness, developing imagination and creativity in them.

S16 - Oral Presentation

Scientific communication and outreach in the schools: a strategy for the better comprehension of natural risks

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The "Sezione di Catania - Osservatorio Etneo" of INGV constantly organizes scientific dissemination activities, handling meetings with pupils and participating to various scientific outreach events, with the aim of promoting a better diffusion of the scientific culture, expanding the knowledge of natural phenomena and mitigating the related hazards.

A constant and continuous sharing of the scientific knowledge, and efficient messages about natural hazards and related mitigation actions, are particularly important for preparing citizens to correctly assimilate vital information during emergencies. Detailed information and communication, especially if realized via practical experiences, acquire an important cultural value and highlight questions linked to territoriality.

The experience matured until now, along a course made of many meetings with students from primary, secondary and high schools, has evidenced some criticalities but also prompted useful reflections. In particular, the need for a new planning ability focused on a more efficient interaction between pupils and the scientific personnel (technicians, technologists and researchers) and the implementation of working spaces expressly realized for supporting scientific outreach activities.

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 volcano emergency exercise 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 (https://www.unige.ch/sciences/terre/CERG-C/). 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 CERG-C participants and have learned to value their territory even more thanks to the international interest raised by their volcano. In 2019, an EUROVOLC educational focus activity was also carried out at the elementary school of Vulcano that involved the participation of scientists from the University of Geneva (Prof. Costanza Bonadonna, Dr Eduardo Rossi, Dr Lucia Dominguez), the University of Pisa (Prof. Mauro Rosi), INGV (Dr Rosella Nave, Dr Tullio Ricci) and the University of the Azores (Prof. Fatima Viveiros). Representatives of the Italian Civil Protection were also present as observers (Dr Chiara Cristiani, Dr Antonio Ricciardi). The exercise was developed combining the educational volcano emergency exercise carried out since 2011 (in collaboration with Dr Laura Pioli now at the University of Cagliari) with the material produced by the European project RACCE ("Raising Earthquake Awareness and Coping Children's Emotions"; http://racce.nhmc.uoc.gr/it). The main aim of the RACCE project (2011-2014) was to increase awareness of natural hazards and improve knowledge of earthquakes and volcanoes by promoting the education of specific groups of people (teachers, parents, volunteers and civil protection workers) on best practices to address these risks. The objective of the educational activity on Vulcano was to provide the students of the primary school with the opportunity to learn what happens during a volcanic eruption and what preventive actions can be taken, through an exercise that alternated experimental activities and a role-playing game. The combination of the role-playing exercise with the RACCE actions to raise awareness towards the appropriate behaviours to adopt in volcanic areas has largely improved the original role-playing exercise. Certainly, this educational activity could benefit from having more continuity within the scholastic program so that children could be exposed long-term to important concepts of risk reduction and could have more time to develop a full and long-lasting understanding.

An on-line form to promote citizen science: INGV, Osservatorio Vesuviano web form experience

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Citizen Science is a huge context where includes different activities carried out with the main task to make people more connected with researchers and their activities.
In particular dealing with quiescent volcanoes as the Neapolitan ones, it is crucial to make resident more aware and permanently interested to the peculiar natural phenomena occurring in their living area.
To contribute to that aim, in 2015 INGV- Osservatorio Vesuviano created a web platform, designed activate citizen as information sources for anomalous phenomena taking place in the Neapolitan volcanic areas. The observed and/or felt events can be reported by filling in the dedicated web form: "Do you want to report an earthquake rumble or a natural event in the Neapolitan volcanic area". (Ci vuoi segnalare un Terremoto, un boato o un evento naturale in genere nell'area vulcanica napoletana?)
By now we have collected thousands of data, especially concomitantly with earthquakes occurring, and we managed the data through a dedicated GIS Database, that allow us to map the areas where the reported phenomena were observed and / or felt.
The received information are useful for both conveying fast communication on on-going phenomena to the monitoring team, and to keep an higher connection between the researchers and resident community.
Therefore, the result of web-form application has upgraded the actual relationships citizen-scientist, promoting a two-way communication that can contribute to improve volcanic hazard awareness, and possibly limiting fake news broad casting.
Moreover this citizen sciences activity have contributing to develop of the online tool dedicated to collect and disseminate citizens' data regarding European volcanoes. This tool is available at https://eurovolc.bgs.ac.uk developed by the Eurovolc project WP12.2.

S16 - Oral Presentation

Visualizing design thinking for volcanic risk communication

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The mutual understanding between communities, stakeholders, and experts is central to successfully communicating volcanic risk. However, this process does not always involve the voice of people at risk or considering fundamental aspects of their lives (e.g., a social, cultural, and political background). Moreover, considering equality, diversity, and inclusion is key for building trustful and democratic dialogues. In this respect, design thinking is a people-centered technique that has been used for decades in research focused on solving societal problems. According to the literature, the three approaches used in design thinking are focused on addressing it as a cognitive style, a general theory of design, and a resource for organizations. Based on a more critical perspective, a practice approach consists of understanding design as a relational process in which stakeholders are co-designers and designers are other kinds of stakeholders. Other perspectives visualize design thinking as an awareness that seeks to "move away" from some set of circumstances in the present thought to be undesirable, for instance, the current disaster risk facing a community. Recent revisions point to linking designers, end-users, and stakeholders, incorporating creative and analytic approaches to provide more intuitive design outcomes able to meet the real needs of people. Despite design thinking being used to guide both disaster-risk reduction and long-term rebuilding after a disaster, disaster management and communication widely lacks such type of design knowledge. To test the viability of using design thinking as a tool for volcanic risk communication, we updated the technique to three essential steps: 1) Understanding and learning about the local context, by identifying people's needs and priorities; 2) The design and test phase which includes ideating a communication strategy and its improvement through community feedback, and; 3) communicating risk and hazard knowledge as a complement to the local knowledge, with a sensitive application according to people's realities and vulnerabilities.

Between May 2021 and April 2022, we used an ethnographic approach to understand the perceptions and needs on volcanic risk communication of people living in the influence area of Lonquimay volcano (southern Andes of Chile). During this study, the beginning of seismic unrest also led to a rise in the volcanic alert level to yellow, thus allowing the involvement of experts and local authorities in this process.

Preliminary findings allow us to recognize that local ecological knowledge plays an important role in designing a communication strategy, shaping the message and the feedback. Furthermore, we found that people have uncertainties that may externalize at the beginning of the communication strategy design, especially during changing volcanic activity. It is also fundamental not only to bring science closer to the community but bring the volcano closer to the priorities for livelihood protection at all the levels of decision-making. By adopting this approach it has been possible to unravel meanings and perceptions within the local cultural framework of a rural community regarding volcanic hazards.

S16 - Oral Presentation

Communicating volcanic hazard during the 2021 Fagradalsfjall eruption in Iceland: from science to operations

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Based on the data from the Icelandic Tourist Board (2022) about 356 thousand people went to visit the Fagradalsfjall eruption site during the period 24 March 2021-7 January 2022. During the first month of the eruption the number of visitors per day reached 6000 and was comprised of mainly local tourists. The Fagradalsfjall eruption therefore provides an excellent case study of a popular "touristic" eruption, which both individuals and tour companies came to visit. The former for experiencing the forces of nature, the latter for obvious economic interests.

Touristic eruptions require adequate monitoring and response, designed to support mitigation actions and decision-making procedures. Throughout the eruption, the goal was to provide a safe access route to the site, via regular and frequent (initially daily) meetings between the IMO's surveillance room and its managers, selected scientists, the Civil Protection representatives, the police and rangers from the environmental institute that patrol the area on a daily basis. The latest observations, forecasts, and hazard assessment were communicated and discussed. Those attending the meeting had the chance to look at the scientific data and to consider the implications for their actions in the field, like rerouting the walking paths, diverting people to more secure areas, and closing the area when needed because of very bad weather or expected very high concentration of gas at ground level.

Here, we will describe how the communication channels between scientists and civil protection authorities worked, which type of hazard products were generated and shared, and how the information was spread to the general public for guaranteeing a safe access to the eruption site.

S16 - Oral Presentation

Web mapping and visualization services for planetary analogues

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Planetary web mapping services have, historically, been developed by adopting Earth-based standards and best practices [e.g. 1,2]. The basic functionalities and appearance of planetary and terrestrial data access services are relatively similar. However, dataset-specific analytical aspects vary, as well as their coordinate reference systems and cartographic standards. The EXPLORE project's primary goal is to develop and grant access to a suite of scientific data applications (SDAs) to facilitate the exploitation of data from planetary space & astrophysics missions on the fly without the need to download and process the data on local machines. L-Explo and L-Hex are two state-of-the-art Lunar web mapping services (SDAs) that provide access to a selection of higher-level data from existing Lunar orbital and in-situ missions. EXPLORE web services are available at https://explore-platform.eu.

We hereby present the applicability of these SDAs to planetary analogue data and locations, starting with a specific reference case to Mount Etna. Its summit environment, in fact, presents strong analogies in terms of morphology, rock types, and formation processes to Lunar and Martian volcanic environments. With the available 2.5D and 3D data, ranging from satellite imagery to digital outcrop models, both research-focused visualization and analysis, education, and training can be accomplished on EXPLORE platform. While such specific use cases might need different tools, several commonalities exist, not only in the web mapping services architecture but also in the user interaction, e.g., through the use of web mapping narrative [4].

We developed the Lunar SDAs backend-frontend architecture based on an industry-standard open-source framework that provides a 2/3D planet-scale environment. This grants a fluid workflow and access to both SDAs while providing additional visualization capabilities, such as split-screen and pedestrian-centered visualizations. We can connect additional services such as WebMapServices (WMS) to the same Lunar SDAs frontend to expand data access, comparison, and visualization.

Custom pipelines have been developed to process hyperspectral and high-resolution data and are shared across the lunar SDAs. Such pipelines include band composition, spectral profile plots, and more. Further advanced processing capabilities based on Machine Learning are under development [5]. We experimented with the cross-use of Explore SDA with planetary analogue data [e.g. 6], with potential relevance for analogue activities [e.g. 7]. Etna will be the first use case thanks to the wide availability of multi-resolution data. By slightly changing the configuration of the SDAs architecture, and by ingesting Earth data, we found that there is almost a straightforward compatibility of our solution without the necessity of a complete rework. Thus, major changes are only necessary in order to grant plain compatibility between Earth hyperspectral data and our custom APIs.

Connecting our solution with historical data archives can take advantage of time-based visualization, thus improving the comprehension of the evolution of the area through time and landscape evolution. Integration with real-time monitoring services may also increase the citizens' awareness of natural resources and hazards.

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Formulation of a prototype multi-choice online questionnaire as survey for volcanic crisis exercises

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Volcanic crisis exercises are generally run to test crisis response capabilities, communication protocols, and decision-making by the staff of responding agencies (e.g., volcano observatories and/or Civil Protection authorities), or communities in a hypothetical scenario of volcanic unrest with inherent uncertainty. Generally, volcanic crisis exercises simulate a rapid build-up of different parameters and observations (e.g., seismic activity, ground deformation, temperature anomalies, changes in volcanic gas emissions and chemistry) which could culminate in a variety of outcomes including different types of eruption. Exercises may be "tabletop" involving a smaller number of participants, and not interacting in long-distance like in reality, or "full-scale" simulations having more players involved (e.g. public and media) and in which every player plays from the workplace as in reality.

In this framework, we distilled the experience gained by participants of the EUROVOLC project in volcanic-crisis exercises, and created a prototype version of checklist that may be of help to those designing and organizing such an exercise in the future. During the last decades, the use of questionnaires and other social science research methodologies has been increased to acquire information on participant social characteristics, to evaluate the people's knowledge of volcanic hazards and their perception of risk, and how such perception could be related with people's preparedness and response to emergency measures planned for different volcanic areas. We show that interdisciplinary approaches can generate useful and usable outputs for volcanic risk reduction. We first distributed an open-question questionnaire (OQQ) survey within the EUROVOLC-project community; based on that, we developed a user-friendly multi-choice online questionnaire (OMCF) that we also submitted outside the project to different volcanological communities (e.g., LAVA- EVE joint workshop, gathering scientists and civil protection agents with experience in effusive eruption crisis; the volcano listserv community; ALVO association; scientists from different institutions). From the answers to the OMCF, we extracted a prototype checklist outlining the most important steps when organizing an exercise.

In this contribution, we give details of the submitted questionnaires along with a description of the benefits of such approach. In particular, the lessons learnt from this study concern the need to increase training activities, to improve external (between players and general public/media) communication tools, equipment and protocols and to better define decision-makers needs.

Our preliminary results confirm that this type of survey is a very useful tool for gathering information on participants experience and knowledge, and to understand which data and information may be useful when designing exercises for scientists, emergency managers and others involved in a volcanic crisis.

S16- Poster

Virtual Reality Game for Earth Science: “A journey inside the volcano”

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Effective mitigation of risks from catastrophic geophysics hazards requires knowledge and understanding of natural processes. Scientific divulgation deals with the communication of knowledge previously produced in scientific contexts to a non-expert massive audience. One of the difficulties science divulgators need to overcome is to explain specific concepts, even complex, in a simple, understandable and possibly enjoying approach, maintaining scientific correctness, and enhancing skills, knowledge and competences in the interlocutor.
Considering that, nowadays, digital technologies play a large role in young people’s lives and games are directly connected to the life of adolescents, we realized an educational videogame to communicate geophysics and Earth sciences, particularly devoted to school students; an educational computer game, serious game, where electronic medium with all the characteristic of a gaming environment convey formative outcomes. The starting point is that technologies are systems of open possibilities that can be effectively integrated with innovative methods of education necessary to promote more effective, efficient, attractive and durable learning. In fact, the ardour and enthusiasm that digital games evoke in teenagers has brought many researchers, school leaders and teachers to the question “how video games” can be used to engage young people and support their learning.
A first stage of the project of Virtual Reality, “Journey inside the volcano”, were presented at several scientific divulgative events in 2019 and 2020, such as the ESA Living Planet Symposium, The National Geographic Festival delle Scienze, the September 29th INGV Open Day, involving more that a thousand users and receiving appreciation from the public. We present the serious game and the relate appreciation analysis based on guestbook comments compiled by participants at the end of the experience. The comments reveal a great level of appreciation, involvements and emotions, as well as margins of improvement. The results foster us to improve the volcano project and to develop other geophysical topics.

S16- Poster

Vulcano 2022 exercise: A focus on risk and emergency communication activities for the population

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In April 2022 a national exercise on Vulcano Island (Messina, Italy), called "Vulcano 2022", has been carried out by the National Civil Protection Department (NCPD), the Regional Civil Protection Department of Sicily Region, Messina prefecture, and Lipari municipality, testing on-site the evacuation procedures in case of potential and imminent volcanic eruption (red alert scenario), according to the "Civil Protection National Plan for the volcanic risk on the Vulcano Island" and the local civil protection planning.
The plan includes a series of measures related to communication activities for the population both ordinarily and in the stages preceding a possible volcanic eruption. Also, the exercise was an opportunity to test information and communication tools, such as:

- IT-ALERT system;
- questionnaires and interviews on the It Alert system and the exercise's progress;
- civil protection signage;
- training sessions with the local population and schools, where a map of the island with a QR code with the rules of conduct to adopt was distributed.

The exercise aimed to test the functionality of the national public warning system, IT-ALERT, activated for the first time in this exercise context, and at the same time to assess its efficiency for communicating warnings. IT-ALERT system is based on cell broadcast technology and provides a one-way, unilinear, and top-down transfer of information from authorities to the public. It consists of a dedicated cell phone message, with a distinctive ringtone, which alerts the population of a selected area about a specific risk, also communicating the protection actions foreseen in the civil protection plan.
To understand if this national public warning system would effectively alert and communicate risk to the population, assuming also from the current literature that unidirectional ways of risk communication may reinforce negative feelings such as fear and powerlessness, both cognitive and affective dimensions have been investigated and deepened, engaging local stakeholders.
In this task, National Civil Protection Department, CIMA Research Foundation and the Regional Civil Protection Department of Sicily Region, carried out some stakeholders engagement activities, as part of communication/information meetings (such as a preliminary meeting with the Vulcano island population and a preliminary workshop with the Vulcano island primary school students), through consultation and discussion activities, (i) the submission of a questionnaire to the local population during the exercise, and (ii) semi-structured interviews with local stakeholders in the days before the exercise.
The whole research is a preliminary attempt to assess IT-ALERT effectiveness. However, from the analysis of the questionnaires and semi-structured interviews results, some insights for a better application of IT-ALERT in this specific context emerged. First, the need for a robust stakeholders' engagement to use this tool at its best.
The Vulcano 2022 exercise was also an opportunity to install civil protection signage on the island to help guide people away from the area at risk and toward the waiting areas provided by

municipal planning. It also represented an important occasion to increase the population's awareness of the risk and summarize the main rules of conduct and self-protection to adopt in case of an alert declaration.

The signage was designed considering national and international regulations, relevant national experiences (e.g., the signage installed on the island of Stromboli), and international studies on volcanic risk signage (e.g., Japan, United States, New Zealand). Signage messages written in Italian are translated into English to allow tourists to easily understand them. The graphics were created in light of the elements that characterize the visual identity of the Civil Protection Department and the national communication campaign on good civil protection practices "I don't take risks."

During the exercise, rules of conduct for residents and tourists on the island were also revised, after the volcanic phenomena that involved the territory since September 2021 (increase in the concentration and temperature of volcanic gases, extension of emission areas). This content is produced by the Civil Protection Department in collaboration with the National Institute of Geophysics and Volcanology and the Regional Civil Protection Department of Sicily Region, as part of the upcoming I don't take risks - Vulcano Island communication campaign.

In conclusion, Exercise Vulcano 2022 was a valuable opportunity to test communication tools to be deployed in the event of a volcanic eruption, particularly the first field trial of the It-alert public warning system and civil defense signage.

Increasing geo-hazards awareness in students: the "Geodynamic Laboratory" project first experience

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Raising the awardness and response capacity of the economic and cultural community to seismic and volcanic risk, in a nation that has a very high level of geological hazard such as Italy, is one of the most ambitious objectives that modern civil society aims to achieve. With this objective the "Geodynamics Laboratory" initiative, promoted by INGV, Sezione di Catania - Osservatorio Etneo, intends to promote and accelerate a process of civil training and interaction between the world of Research, which already deals with vulnerability and hazard, and that of the School, involving it to operate in the delicate sector of the defence of the territory. The main objective will be to disseminate information about the real risk to which the Italian territory is exposed, for which constant surveillance is essential. In addition, it is intended to raise awareness that with geo-dynamic disasters one must coexist, while taking some necessary precautions so that any damages do actually not occur or at least turn out to be limited. The proposed methodology provides a practical, direct and scientific approach to the knowledge of the dynamics of the territory and the resulting risks, the integration of schools in the monitoring activities of local active faults. The ultimate goal will be to capillarize and make young students sensitive to risk awareness, investigation and mitigation techniques in an environment that presents its specific hazard. The excellent pilot experience, carried out in 2014, was conducted in a technical school for surveyors as it specifically treats, on the ground and in an extremely practical way, the territory management, its structure, its infrastructures, knowledge and the estimate of the economic values falling within it, the construction, restoration and restructuring of the buildings, all sensitive topics to be dealt with in the phases of risk prevention and in the event of natural disaster.

S16- Poster

Lessons learned from the 2021 Cumbre Vieja eruption (La Palma, Canary Islands)

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The 2021 Cumbre Vieja eruption represented a remarkable event from both scientific and emergency management points of view. After a few years of weak microseismicity, on Sept. 12th, hypocenters suddenly moved to shallower depth with magnitudes strong enough to be felt by the people living on the island of La Palma. After a few days, ground deformation was detected, alerting about an ongoing magmatic intrusion process. The seismicity increased rapidly during the night of Sunday, Sep. 19th, culminating with an M=4.2 earthquake with a very shallow hypocenter the morning of the same day, and the eruption started in the afternoon at around 14 UTC. The eruption was accompanied by significant sin-eruptive seismicity with many earthquakes with M>=4.0 and lasted 85, terminating on Dec. 13th 2021.
Even with a general Strombolian mechanism, the eruption was remarkable for the significant amount of distal tephra (>20 Mm^3), making this eruption assigned VEI=3. The extensive complex lava field (>200 Mm^3) covered an area of more than 12 km^2 and caused extensive destruction, with 1676 buildings destroyed and 2329 people losing their homes. The eruption also destroyed 270 ha of plantations, hitting the economic centre of the island, being agriculture the primary source of income.
This eruption marked an inflexion point in the management of volcanic emergencies of eruptions with moderate explosivity both from a scientific and a civil protection point of view. During the pre-eruptive stage, the rapid evolution of the precursors evidenced the critical role of clearly defining communication protocols between the scientific community and civil protection. Another important lesson learned was about defining the different alert levels of the emergency plan without possible ambiguities. Among the syn-eruptive hazards are the repeated issues concerning the air quality in the towns surrounding the volcano. This hazard has been well studied from a scientific point of view, but it was also the occasion of defining strategies concerning the communication of this specific hazard.
Furthermore, the post-eruptive stage has been characterized by relevant diffuse CO_2 emission, posing severe issues concerning the managing of this volcanic hazard which, despite being extremely dangerous, is difficult to understand for common people. Specifically, this hazard affected areas not directly affected by the lava flow and the ash fall and which are among the most relevant for the island's tourism industry. This posed an unprecedented pressure on scientists, civil protection and local authorities from the population, which aims at recovering their houses and activities, requiring special attention in communicating this peculiar hazard.
The opening of the eruptive vent very close to inhabited areas classified this eruption as an "urban eruption". This peculiarity forced finding innovative strategies and solutions for the management of the pre- syn- and post-eruptive phases of the emergency, raising different issues concerning the relationship between scientists and civil protection, communication, and hazard management. In conclusion, the Cumbre Vieja eruption has been the best-studied example of an "urban eruption", providing valuable information which hopefully will be helpful to the management of future similar volcanic emergencies.

S16- Poster

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ISSN 1590-2595 http://istituto.ingv.it/it/le-collane-editoriali-ingv/quaderni-di-geofisica.html/

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ISSN 2039-6651 http://istituto.ingv.it/it/le-collane-editoriali-ingv/miscellanea-ingv.html

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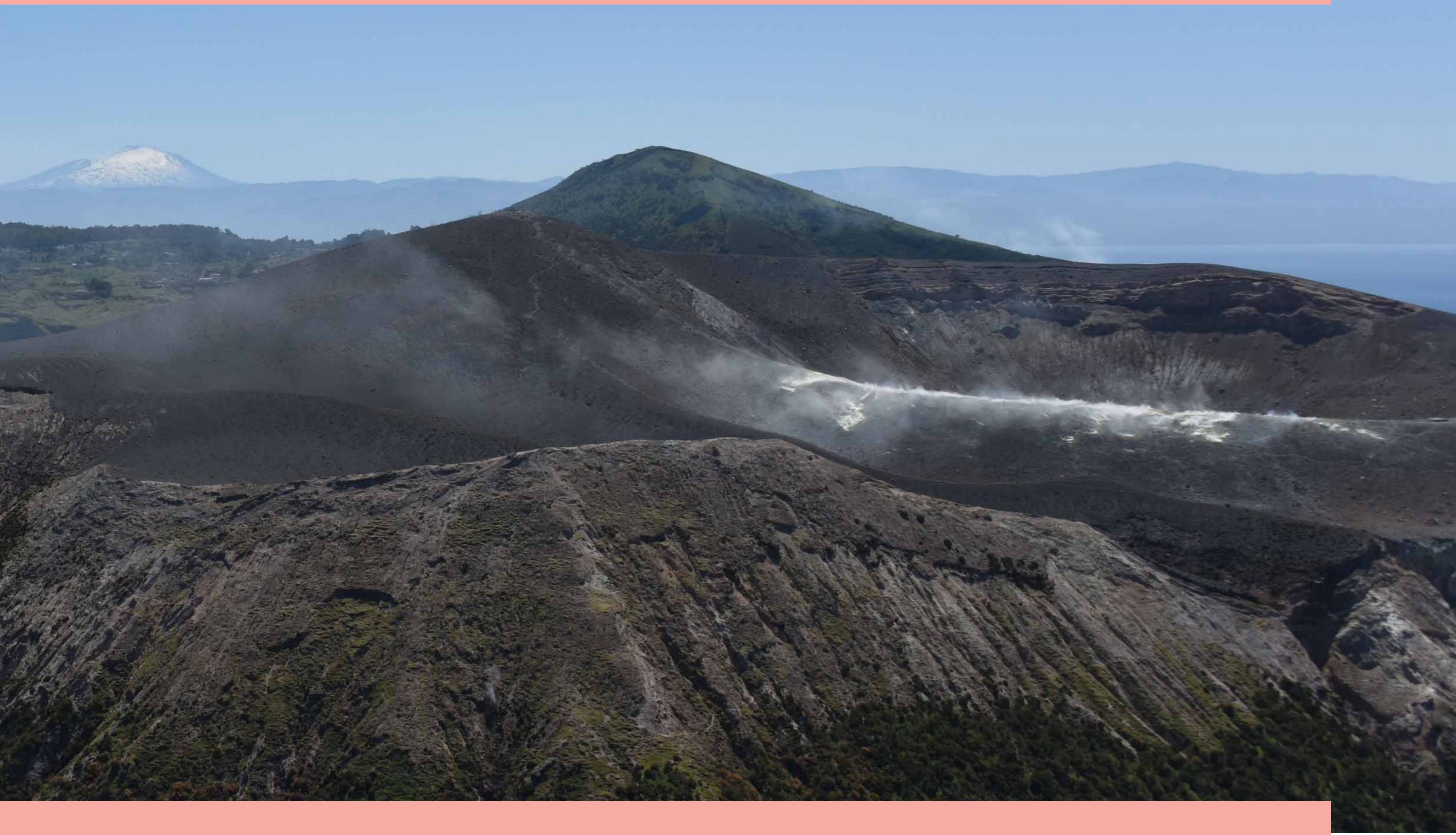

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