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25th European Seismological Commission working group volcano seismology

Workshop on 25 years advancing volcano seismology in a wider volcanological context

26th September | 1st October 2016, Stromboli, Italy

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25th EUROPEAN SEISMOLOGICAL COMMISSION WORKING GROUP VOLCANO SEISMOLOGY

WORKSHOP ON 25 YEARS ADVANCING VOLCANO SEISMOLOGY IN A WIDER VOLCANOLOGICAL CONTEXT

26th SEPTEMBER | 1st OCTOBER 2016, STROMBOLI, ITALY

Editors Thomas Braun, Maria Luisa Carapezza, Alessandro Gattuso

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International Association of Seismology and Physics of the Earth's Interior

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Immagine di frontespizio
Strombolian explosion from SW crater June 2014
(Image credit: photo by Alessandro Gattuso)

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Preface and welcome

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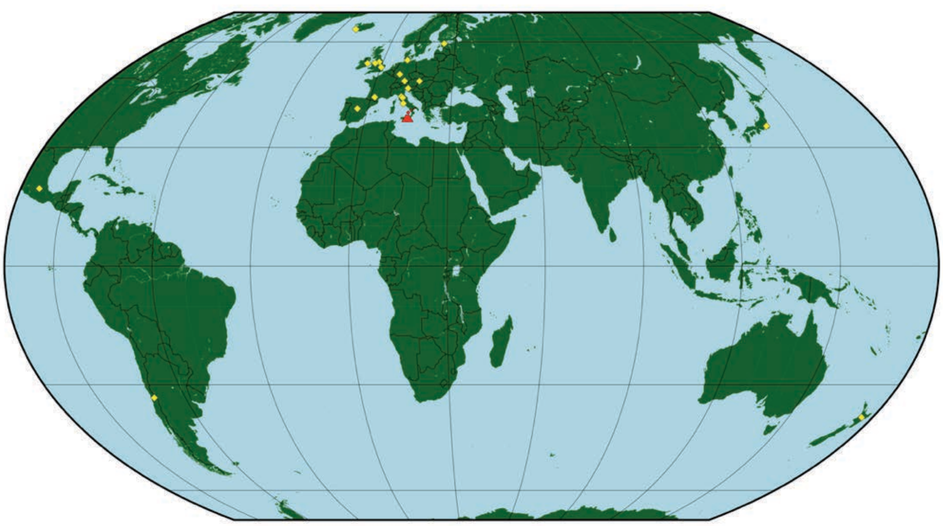
From 26th September to 1st October 2016 the annual meeting of the European Seismological Commission working group "Seismic phenomena associated with volcanic activity" has been held on Stromboli volcano at the Hotel "La Sirenetta". This year's workshop was themed "25 years advancing volcano seismology in a wider volcanological context". After the foundation of the working group at Copenhagen (DK) in 1990, the 2016 conference was the 25th anniversary event, which followed previous workshops [http://earth.leeds.ac.uk/esc_wg/] that took place in:

1991 - St. Roman, Black Forest, DE
1992 - Stromboli, IT
1993 - Lanzarote, Canary Islands, ES
1994 - Nicolosi (Etna), IT
1996 - Ercolano (Vesuvius), IT
1997 - Ambleside, Lake District, UK
1998 - Paratunka, Kamchatka, RU
1999 - Santorini, GR
2000 - Lisbon Sao Miguel (Acores), PT
2001 - Teide, Tenerife (Canary Islands), ES
2002 - Montserrat, West Indies, UK
2003 - Pantelleria, IT
2004 - La Palma, Canary Islands, ES
2005 - St Claude, Guadeloupe, FR
2006 - Olot, Catalunya, ES
2007 - Nesbud, IS
2008 - Leon, NI
2009 - Pico (Azores), PT
2010 - Besse (Massif Central), FR
2011 - Salina, IT
2012 - El Hierro (Canary Islands), ES
2013 - Tomohon, Sulawesi, ID
2014 - Leitrim, IE
2015 - Puerto Lago, EC

Stromboli volcano is one of the most active volcanoes on earth. Since the beginning of time called "lighthouse of the Mediterranean", already the Greek mariners used the Strombolian eruptions for navigation. Uncounted are the number of scientific projects realized at this natural volcanic laboratory during the last decades. Therefore, the island of Stromboli represented the perfect place for receiving 33 researchers from 13 countries.

Provenance of the ESC–workshop participants



Long-period seismic signals and volcanic gas emission at Asama volcano, Japan

M. Takeo

Earthquake Research Institute, University of Tokyo, Japan

Vulcanian eruptions had started on September 1st 2004, lasting until December 2004 at Mt. Asama. After that, several small and minor eruptions occurred in August 2008, from February to May 2009, and in June 2015. We compile long-period seismic data and SO_2 data from October 2003 to June 2015, and consider the state of conduit during the recent eruptions. Several kinds of singular data were recorded near the summit crater; the first category is a very long-period pulse (VLP), followed by large amount of volcanic gas emission from the vent in summit crater. Based on a waveform inversion, we reveal that VLP is excited by a sudden gas emission. The second category is a long-period rebound waveform (LP earthquake). The third category is long-period tremor characterized by pointed tips and saw tooth waveform. Common characteristics of LP earthquake and the tremor suggest a non-linear dynamic of the source. We estimate geometrical and dynamical nonlinear parameters to constrain the dynamics, and propose a mathematical model succeeding in simulating the oscillations resembling with LP earthquake and the nonlinear tremor. Before June 2004, VLP activity was synchronized with the seismicity, but it had gradually decreased toward the eruption in spite of increment of the seismicity. At this turning point, LP earthquakes and nonlinear tremors occurred in cluster. Based on the mathematical model, LP earthquake and the nonlinear tremor could be actualized by a blockage of the conduit, resulting the decline of VLP activity due to shielding of gas emission and the increment of seismicity due to stress accumulation in and around the conduit. SO_2 had been kept in high level from November 2008 to February 2009 in spite of low VLP activity, but this relation had turned over from April to August 2009. The variability of correlation between SO_2 and VLP activity suggests an existence of multi outgassing pathways in the shallow part of the conduit.

Magma budgets and tectonics - Investigating the ongoing deformation field at Montserrat, West Indies

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For over 20 years, Soufriere Hills Volcano, Montserrat has been in a state of volcanic unrest. Intermittent periods of dome building have been punctuated by explosive eruptions and dome collapse events, endangering the lives of the inhabitants of the island. The last episode of active magma extrusion was in February 2010, and the last explosive event (ash venting) in March 2012. Despite a lack of recent eruptive activity, the volcano continues to emit significant volumes of SO_2 and shows an ongoing trend of island inflation.

Through the aid of three-dimensional numerical modelling, using a finite element method, we explore the potential sources of the ongoing island inflation. We consider both magmatic (dykes and chambers) and tectonic (strike-slip and regional extension) sources. We illustrate the effect that different sources (shapes, characters and depths) have on the surface displacement. Whilst a magmatic source suggests the possibility for further eruption, a tectonic source may indicate cessation of volcanic activity. We suggest that whilst the dominant source is magmatic, a tectonic contribution cannot be completely discounted. We also investigate the conflicting scenarios of magma resupply versus second boiling. We compare our model results with preceding Pauses and Phases to better understand the magma budget feeding the eruption. Due to the similarity in the relative displacement between the GPS stations at every episode of the eruption, we suggest the displacement for all Phases and Pauses can be explained by the same basic source. Consequently, we define a suite of models which can explain the eruptive activity since it began in 1995.

Using seismic and tilt measurements to forecast eruptions on silicic volcanoes

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Independent interpretations of seismic swarms and tilt measurement on active silicic volcanoes have been successfully used to assess their eruption potential. Swarms of low-frequency seismic events have been associated with brittle failure or stick-slip motion of magma during ascent and have been used to estimate qualitatively the magma ascent rate which typically accelerates before lava dome collapses. Tilt signals are extremely sensitive indicators for volcano deformation and have been often modelled and interpreted as inflation or deflation of a shallow magma reservoir. Here we show that tilt in many cases does not represent inflation or deflation but is directly linked to magma ascent rate. This talk aims to combine these two independent observations, seismicity and deformation, to design and implement a forecasting tool that can be deployed in volcano observatories on an operational level.

Long-period seismicity at Villarrica Volcano - another example of tectonic LP's?

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It is nowadays widely assumed, that the so-called long-period volcanic events (LP) are caused by volumetric sources. Thus, their source mechanism and nature is considered to be entirely different from that of volcano-tectonic events (VT). This interpretation of LP signals is often based on cases, where seismic stations are situated more than a few hundred meters from the source. Their records show typically spindle-shaped LP-waveforms without clear phase onsets.
However, larger and denser monitoring networks reveal more and more examples that question this: Stations closer to the source exhibit a much shorter signal that may even contain identifiable wave types such as radiated from brittle failure. An explanation of LPs alternative to volumetric source mechanisms might be path effects: LP-events could originate at very shallow depths, but nonetheless have a tectonic source mechanism. The typical shape of the waveforms then results from serious alteration of the signal along its path to the station caused by multiple scattering and reflection in the strongly heterogeneous volcanic medium.
Villarrica Volcano in Chile may be a case where this alternative theory applies. A dense network of ca. 50 stations covering the volcanic edifice was deployed in March 2012. During the two weeks of observation, 81 of the recorded events were identified (visually) as VT-events, whereas more than 300 were categorized as LP-waveforms. Yet these LP signals develop their characteristic waveform only at far stations, while at near-source stations they resemble tectonic earthquakes. The VTs, located by classic travel time techniques, are found ca. 5 km east to southeast of the summit crater in a depth of 3-6 km, underneath the former caldera. The newly located LP events (using beamforming) originate from the same region, slightly closer to the summit. A depth estimate however - from travel time move out of polarization attributes and from slowness comparison - yields a much shallower source depth (< 1 km below surface). Therefore, we think, that at Villarrica, LP events might falsely be classified - and consequently misinterpreted in terms of the volcano's dynamic - when recorded only at far stations. The correct interpretation is however crucial when it comes to monitoring and eruption forecasting.

A geological overview of Stromboli volcano

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The island of Stromboli is located in the Tyrrhenian Sea, in the northernmost part of the Aeolian archipelago. It rises from a depth of 2700 m below sea level (b.s.l.) to an elevation of 924 m a.s.l. It is one of the four active volcanic islands (with Vulcano, Lipari and Panarea) of the Aeolian islands, whose existence is related to the subduction of the African plate under the Eurasian plate. The volcanic activity started around ca. 204 ka ago at Strombolicchio, NE side of the actual volcanic edifice and assumed to be a volcanic neck derived from an old dismantled volcanic centre. The geological subaerial evolution of Stromboli volcano began around 85-75 ka with the formation of Paleostromboli I stratocone with a subaerial and predominantly centrally oriented activity. Paleostromboli II, during 75 – 67 ka ago signalled the renewal of volcanism after a caldera collapse with thick successions of basaltic to andesitic lava flows. During the quiescence period at the end of Paleostromboli II, the SW flank was affected by the SW-dipping flank collapse, which represents the early lateral failure in the history of Stromboli. Paleostromboli III (41-34 ka) was characterized by an alternating effusive and strombolian phases of activity reaching a stratocone elevations of c. 900 m, before truncation by a caldera collapse exposed at heights of 650–700 m. Ranging from 41 to 26 ka (Lower Vancori), major SE-dipping flank collapse occurred (Rina Grande collapse) affecting the eastern flank of Paleostromboli III edifice. Vancori stratocone formation, during 26-13 ka ago, produced a thick successions of lava flows and pyroclastic products that filled the caldera depression and flowed down most of the flanks of Stromboli, also filling the morphological depression of the Rina Grande. Neostromboli eruptive activity, is arranged into three successive sequences of eruptions interrupted by two quiescence stages and erosional unconformities associated with recurrent sector collapses along the north-western flank of Stromboli (13-4 ka). Most of effusive activities were located within the Upper Vancori collapse scar in the area occupied by the presently active craters of Stromboli. Lower Neostromboli and Roisa activities developed during 15-13 ka, followed by the formation of San Vincenzo scoria cone and the hydromagmatic eruption of Semaforo Nuovo. During 13 - 8 ka, Upper Neostromboli activity was characterized by a series of flank eruptions from eccentric vents and NE eruptive fissures located along the lower slopes of both the NE and W flanks of Stromboli. Around 7 ka, Secche di Lazzaro hydromagmatic eruption took place. Recent Stromboli (< 2.4 ka) was dominantly characterized by a central-vent summit activity, with a subordinate fissure-like eccentric eruption along the NE flank (San Bartolo) and the formation of the Sciara del Fuoco and Rina Grande, as a results of two sectorial collapses of volcanic edifice. The present-day activity is assumed to be characterized by persistent and mild explosive activity with intermittent more energetic explosions (major explosions); more rarely (every 5-10 years) paroxysmal explosions forming plumes a few kilometers high can strike the villages of Stromboli and Ginostra with the fallout of pumice and ballistic blocks. Episodic lava effusions within the Sciara del Fuoco depression can interrupt the ordinary regime of the volcano. The last effusive activity, in the Sciara del Fuoco, occurred from August to November 2014 from a vent located at 650 m a.s.l.

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What ambient noise can tell us about magma chambers

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Volcanic activity is directly related to the size and location of magma chambers, which are often poorly constrained. We show few examples of how seismic noise tomography may give relatively precise images of the structure under few volcanoes. We show how the depth and shape of magma reservoirs are different for polygenetic volcanoes and for monogenetic volcanic fields. To solve these questions, large seismic networks are required and different techniques have to be used to image deep magma and volcanic structures.

A first application is on Lazufre super-volcano, in Chile-Argentina border. We determined the geometry and location of the hydrothermal and magmatic reservoirs in the Lazufre volcanic area. This furthers the understanding of the origin of one of the largest worldwide volcanic uplift regions, both in space and amplitude. The exact locations and shapes of the sources generating a double-wide uplift region in the Lazufre found by past deformation data (InSAR and GPS) and generating hydrothermal and magmatic fluids found by geochemical gas analysis have not been well-delimited. In this study, we use seismological data to perform a 3-D high-resolution S-wave velocity model, which allows defining better the locations and shapes of the sources of the deformations and the hydrothermal and magmatic reservoirs. We find three anomalies. Two of them (with S-wave velocity of about 1.2 – 1.8 km/s) are located below the Lastarria volcano. The shallow one (< 1 km below the volcano base) has a funnel-like shape. The deeper one is located between a depth of 3 and 6 km below the volcano base. Both are strongly elliptical in an EW direction and separated by a 2 – 3 km thick zone with V_s of ~1.5 – 2 km/s. As far as these anomalies are located under the hydrothermal activity of Lastarria volcano, they are interpreted as a double hydrothermal (the shallow part) and magmatic source (the deeper part). The latter can feed the former. This double hydrothermal and magmatic source is in agreement with previous geochemical, deformation (GPS and InSAR) and magneto-telluric studies. In particular, it explains the double origin of the gases (hydrothermal and magmatic). The third low-velocity zone (with S-wave velocity of about 2.3 km/s) located at 5 km depth and deeper is centered beneath an area of surface uplift as determined by InSAR data. We compare the seismic tomography and InSAR results to propose that this low-velocity zone is at the top of a large reservoir, hosting hydrothermal fluids and possibly also magma.

A second application is on Colima volcano, Mexico. Colima volcano is one of the most active volcanoes in continental north America. It is located within the Colima graben on the western part of the Colima rift zone. Although extensively studied, the internal structure and deep magmatic system remains unknown. We give new clues to understand how and where magmas are produced and stored at depth. Using ambient seismic noise, we jointly invert for Rayleigh and Love wave dispersion curves for both phase and group velocity, which is applied for the first time in a volcanic environment. The 3D high resolution shear wave velocity model shows a deep, large and well-delineated elliptic-shape magmatic reservoir below the Colima volcano complex at a depth of about 15 km.

An uncomplete summary about seismological research on Stromboli

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Stromboli, the "lighthouse of the Mediterranean", attracts earthquake seismologist since generations. Probably the first "volcano-seismologist" was Giuseppe Mercalli, who observed in 1907 at Stromboli ripples on the surface of a Mercury vessel, some seconds before a strombolian eruption. Since that time, volcano-seismology tries to give a qualitative and quantitative description of the seismic source(s) located at some unknown depth inside the volcanic edifice. Even if many different volcanoes show similar seismic signal characteristics, up to now it was not possible to find a standard seismic source model. Volcanoes with a continuous activity, like Stromboli, represent a perfect natural laboratory to address this question. The presentation tries to give a short historical summary, focused especially on an exciting period (from 1990 on), when broadband and array seismology where applied to volcanoes and tested the first time at Stromboli.

Seismic and infrasonic recordings of explosion-quakes from Stromboli showed that the high-frequency phase propagates with the speed of sound. [Braun and Ripepe, 1993] explained the seismic source as an explosion at the top of the magma column generated by rising gas bubbles. Stations installed near the active crater reveal that infrasonic and seismic recordings of the short-period tremor (>1 Hz) share the same spectral content and show similar energy fluctuations. The short-period volcanic tremor at Stromboli originates from the continuous out-bursting of small gas bubbles in the upper part of the magmatic column [Ripepe et al., 1996]. However, the spectrum of the long-period tremor recorded at Stromboli consists of three main peaks, with periods at 4.8 s, 6 s and 10 s, and amplitudes varying with the regional meteorological situation. Hence, they are not generated by a close volcanic source but rather by ocean microseisms [Braun et al., 1996]. Seismic data from the first broadband array deployed on Stromboli showed surprisingly simple waveforms, indicating an initially contracting source mechanism. The analysis of particle motion and the application of seismic array techniques allowed the location of a seismic source in the shallow part of the volcano [Neuberg et al., 1994]. Eruption parameters and seismic source characteristics of the April 5, 2003 Stromboli eruption have been estimated using different inversion approaches. The paroxysm was triggered by a shallow slow thrust-faulting dislocation event with a moment magnitude of M_w 3.0 and possibly associated with a crack that formed previously by dike extrusion. At least one blow-out phase during the paroxysmal explosion could be identified from seismic signals with an equivalent moment magnitude of M_w 3.7. It can be represented by a vertical linear vector dipole and two weaker horizontal linear dipoles in opposite direction, plus a vertical force [Cesca et al., 2009].

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Geophysical monitoring of "Iddu"

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Open-conduit volcanic systems are typically characterized by unsealed volcanic conduits feeding permanent or quasi-permanent volcanic activity. This persistent activity limits our ability to read changes in the monitored parameters, making the assessment of possible eruptive crises more difficult. Stromboli volcano (Italy) is one of the most famous open-conduit basaltic systems. It is extremely well-known for its persistent Strombolian explosive activity ongoing for centuries [Rosi et al., 2000; 2013] and characterized by rhythmic mild explosions ejecting lapilli, bombs, ash and minor lithic component from the active craters. During periods of ordinary activity, the average magma supply rate from depth is of 0.1-0.5 m^3/s. This steady-state regime is sometimes interrupted by effusive crises, characterized by the opening of new lateral eruptive vents which feed Mm^3-large, weeks to months-lasting lava flows.
We show how an integrated approach to monitoring activities can open a new way to data interpretation. The increasing rate of the explosive transients, tremor amplitude, thermal emissions of ejected tephra, and the change of the very-long-period (VLP) seismic events towards the surface are interpreted as the migration of the magma column in response to an increased magma input rate. During the 2014 flank eruption of Stromboli this magma input preceded the onset of the effusive eruption by several months. When the new lateral effusive vent opened on the Sciara del Fuoco slope, the effusion rate was accompanied by a large ground deflation, a deepening of the VLP seismic source, and the cessation of the summit explosive activity. Such observations suggest the drainage of a superficial magma reservoir confined between the crater terrace and the effusive vent. This model successfully reproduces the measured effusion rate, the observed rate of ground deflation and the deepening of the seismic VLP source, which have remarkable similarities with previous eruptions at Stromboli occurred in 1985, 2003 and 2007. We show how all the effusive eruptions are in fact preceded by a period of high explosive regime in response to an increased magma supply rate transferred to the shallow feeding system. After the effusive onset, effusion rates show a sharp exponential decay lasting <10 days, during which most of the lava volume is usually emplaced and is systematically associated with a rapid deflation of the ground. After that, effusion rates display variable trends and we show how this repeating in time scenario is controlled by the geometry of the shallow magmatic system. Based on the common geophysical evidence we derive a general dynamics to explain the effusive eruptions at Stromboli and on their active role in triggering flank instability and violent paroxysmal explosions. Besides, we demonstrate the capability of the geophysical network to detect superficial magma recharge within an open-conduit system, and to track the magma drainage during the effusive crisis, with a great impact on hazard assessment.

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The fiber optic gyroscope - a portable rotational ground motion sensor for volcanology

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It was already shown that a portable broadband rotational ground motion sensor will have large impact on the interpretation of seismic observations in volcanology. In this contribution, we present results of tests and experiments with a prototype fiber optic gyroscope serving as a pathfinder for the first broadband rotational motion sensor especially designed for the needs of seismology. The instrument is developed by iXBlue, France, in close collaboration with researchers financed by the European Research council project ROMY (Rotational motions - a new observable for seismology). One major application of a direct rotational motion measurement is the correction for dynamic tilt of classical translational sensors (i.e. seismometers). In order to prove this in a field experiment, we installed the sensor close to a seismic broadband station on the same monument and recorded signals from a closely located construction site in Fürstenfeldbruck, Germany. In a further experiment, we collocated the sensor with the center station of a small aperture array (~ 12 m) and performed microzonation and back azimuth estimation for signals originating from the same construction site. For validation, we compared the results from a single station, 6 component measurement (3 components of translation and 3 components of rotation) to better established methods using array measurements.

Eruption source directivity measured from controlled active source explosions

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The impulse response from small man-made eruptions was measured on a distributed array of acoustic sensors in May 2016 at Taupo, New Zealand. The sources comprised active source events produced from small liquid-nitrogen charges within an open-ended water filled barrel. The charges were induced by emersion of liquid-nitrogen filled plastic 'soda' bottles into a warm water-filled barrel. The emersion process induced pressurization and rapid rupture of the sealed bottle. The barrel was oriented manually in vertical and lateral discharge angles of 0^o, 13^o and 26^o from vertical. Each discharge was recorded on 9 BSU infrasound sensors and recorded on Omnirecs CUBE 3 digitizers which recorded at 200 Hz. Data were also observed on GoPro cameras which captured multi-colored balls suspended within the water. Six good discharges were recorded from 12 active source experiments. Generally poor quality results were obtained from a sub-set of discharges from lower strength bottles or from bottles that did not rupture due to cap leakage.

For the six high quality discharges, the waveforms and spectra were analyzed for lateral and vertical eruptions respectively. The vertical eruptions had uniform spectral features regardless of azimuthal direction. The lateral eruption showed systematically higher frequency eruption signals for sensors in the direction of discharge, and lower frequencies for sensors positioned away from the discharge direction. Results are consistent with either a Doppler shift relative to the discharge direction, or alternatively may represent the effects of local proximity of sensors to the discharge barrel. Future experiments are planned which will focus on higher data density and recording a wider range of eruption directivity features. The range of hypotheses will be tested with these data sets and an analysis of the video footage.

Sampling the acoustic wavefield for repeating volcanic eruptions at Yasur Volcano, Tanna Vanuatu, with airborne sensors on tethered weather balloons

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We obtain an unprecedented view of the energy directivity of repeating strombolian volcanic eruptions at Yasur volcano, Vanuatu from acoustic sensors on-board tethered weather balloons. The experiment occurred as part of a wider seismo-acoustic experiment from 27 July - 2 August 2016. Over 500 repeating impulsive volcanic eruptions are recorded on both the airborne array and stationary ground based acoustic sensors. The balloons had helium capacity of 7 m^3 and a payload capacity of > 2 kg. The payload comprised a single Omnirecs CUBE 3 channel sensor (200 Hz sampling) with on-board GPS and a vertical string of BSU type pressure transducers. To maximize the coverage of the eruption focal sphere, we positioned the balloon at 38 tethered loiter positions and computed the back-azimuth and incidence angle for repeating eruptions. The experiment yielded several hundred observations over an azimuthal range of 200° and an incidence angle range of 40°. Simultaneous video observations confirmed the range of eruptive activity and source vent positions. Measurement of the peak amplitude of the balloon sensors normalized by a summit ground sensor, suggest moderate systematic amplitude directivity for the repeating eruptive activity. Future work will examine these directivity features and relate them to possible source (eruption directivity features) and path (scattering) effects.

A pilot study for the seismic monitoring of Fogo volcano, Cape Verde, using array techniques: conceptual details and initial results

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The islands of Cape Verde are thought to originate from a stationary mantle plume underlying an almost stationary tectonic plate. Since settlement of the islands began during the 16th century, Fogo it is the only island of the archipelago with reported volcanic eruptions. The eruptions occur at relatively regular intervals of approximately 20 years, where the most recent eruption took place from November 2014 to February 2015.

Previous studies of earthquakes in relation to magmatic processes beneath Fogo were based on conventional seismic network configurations. However, significant seismicity has been reported to occur offshore to the southwest of the neighboring island of Brava and more recently between the islands of Brava and Fogo. Array seismology can provide detailed information on seismic activity within and surrounding the islands and to lower the detection threshold.

To further test the potential of array techniques for the monitoring of the volcano-related seismic activity surrounding Fogo, we started a pilot study involving the setup of a test array consisting of 10 seismic stations distributed over an aperture of 700 m. The installation of the array took place in October 2015. All stations are equipped with Omnirecs CUBE data-loggers, and either 4.5 Hz geophones (7 stations) or Trillium-Compact broad-band seismometers (3 stations). The stations are powered using conventional car batteries (70 Ah capacity) and are buried completely as a security measure.

The stations are distributed over two circles surrounding a central station. The inner circle with a radius of 175 m is occupied by three stations. Five stations, including the three broad-band stations, are located on the outer circle with a radius of 350 m. One additional station is located between the inner and outer circle. The configuration has been designed to optimize the properties of array transfer function for a reference frequency of 7.5 Hz. To further improve the capabilities for event localization, three additional broad-band stations, distributed across the island of Fogo, were installed in January 2016.

Initial analyses of the data show that seismic activity is dominated by tectonic events around Brava and also tremors and events of unknown origin within the caldera of Fogo volcano. Cars passing by the array represent a frequent and characteristic source of noise during daytime hours. The project focusses on the characterization and localization of the different types of events. We will show results based on conventional localization procedures and on seismic array processing. The pilot project discussed here will soon be complemented by three additional arrays (two on Fogo, one on Brava) to improve seismic event localization and also structural imaging based on scattered seismic phases.

The seismic signature of volcanic rift centers in Iceland

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Iceland is the product of long lived hotspot volcanism in the North Atlantic region, and it is widely believed that this is caused by a hot convective mantle upwelling. The structure of the Icelandic crust, with anomalously elevated thickness, peaking at 37 km beneath central Iceland, is key to this interpretation of an underlying mantle plume.

Here we undertake a study of the crustal structure across the whole island using ambient noise tomography to produce a seismic model of the crustal rift systems at previously unseen resolution. We use continuous broadband records from a high density seismic array deployed by Cambridge University which over the last 10 years has covered the whole of the northern and eastern neo-volcanic zones, with a typical station spacing of 5-10 km. The dataset is augmented by 48 sites from the permanent monitoring network of the Icelandic Meteorological Office (IMO), 30 sites from the HOTSPOT experiment of 1996-98, and further short term deployments to complete coverage of the whole island. Rayleigh waves are extracted from the continuous ambient noise and used to measure group velocity dispersion curves for interstation pairs. Errors in the observations are estimated from the temporal repeatability of the measurement for multiple stacks of the noise correlation function. Group velocity tomographic maps are generated across a range of periods from 5 to 25 seconds. Pseudo-dispersion curves are then extracted from the well constrained cells of the group velocity maps, and are inverted for a shear wave velocity structure.

We find low wave speed anomalies which are extremely well correlated with the active volcanic rift zones of the plate boundary. As much as 0.5 km/s wave speed variation is observed between the slower rifts and the faster non-volcanically active regions. The slow anomalies demarcate each of the neo-volcanic zones, and even delineate a linking branch between the Western Volcanic Zone with the Eastern Volcanic Zone near the Bárðarbunga-Grimsvötn volcanic complex. Within the rifts slower wave speeds are concentrated along the western side of the Vatnajökull ice cap, and the very slowest velocities are centered beneath the Bárðarbunga-Grimsvötn volcanic complex, where the crust is thickest and the center of the mantle plume is believed to lie.

A striking feature of the shear velocity inversions is a clear low velocity zone in the mid crust, which is consistently resolved across the entirety of the model. The layer of slow velocities occurs between 14-20 km depth with a reduction of up to 0.3 km/s. The topography of this zone shallows into the active volcanic rifts, where an elevated geotherm and higher degree of melt extraction is expected.

Relative seismic velocity variations correlate with deformation at Kīlauea volcano

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Passive interferometry using ambient seismic noise is an appealing monitoring tool at volcanoes. The continuous nature of seismic noise provides better temporal resolution than earthquake interferometry and ambient noise may be sensitive to changes at depths that do not deform the volcano surface.

Despite this, to our knowledge, no studies have yet comprehensively compared deformation and velocity at a volcano over a significant length of time. We use a volcanic tremor source (approximately 0.3-1.0 Hz) at Kīlauea volcano as a source for interferometry to measure relative velocity changes with time. The tremor source that dominates the cross correlations is located under the Halema'uma'u caldera at Kīlauea summit. By cross-correlating the vertical component of day-long seismic records between ~200 pairs of stations, we extract coherent and temporally consistent coda wave signals with time lags of up to 70 seconds. Our resulting time series of relative velocity shows a remarkable correlation with the tilt record measured at Kīlauea summit.

Kīlauea summit is continually inflating and deflating as the level of the lava lake rises and falls. During these deflation-inflation (DI) events the tilt increases (inflation), as the velocity increases, on the scale of days to weeks. In contrast, we also detect a longer-term velocity decrease between 2011-2015 as the volcano slowly inflates. We suggest that variations in velocity result from opening and closing cracks and pores due to changes in magma pressurization. The consistent correlation of relative velocity and deformation in this study provides an opportunity to better understand the mechanism causing velocity changes, which currently limits the scope of passive interferometry as a monitoring tool.

Seismicity accompanying the 2014 Bárðarbunga - Holuhraun intrusion and the co- and post-eruptive activity

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An intense swarm of seismicity on 16 August 2014 marked the beginning of intrusion of a large dyke from the subglacial Bárðarbunga volcano, central Iceland. Melt propagated laterally NE from the volcano at the brittle-ductile boundary ~6 km b.s.l. and created over 30,000 earthquakes along a 48 km path. On 31 August, a fissure eruption began at Holuhraun and the seismicity rate within the dyke immediately dropped to a much lower level, suggesting that once a pathway to the surface had formed magma was able to flow freely and largely aseismically. Melt was fed from the subsiding Bárðarbunga volcano to the eruption site at Holuhraun for 6 months. The volcano experienced over 70 earthquakes greater than M5 during the eruption and subsided 65 m in total. We discuss the relationship between bursts of seismicity in the volcano and periods of rapid dyke propagation, and the link between the volcano and the eruption site during the co- and post-eruptive periods. Moment tensor solutions show distinct differences in failure mechanism between earthquakes occurring in the dyke and those occurring in the subsiding caldera. The dominant earthquake source in the dyke is left-lateral strike slip faulting in the advancing tip, orientated sub-parallel to the dyke, whereas in the caldera earthquakes arise from a chaotic trapdoor caldera collapse.

Dyke propagation mechanisms from seismicity accompanying the 2014 Bárðarbunga - Holuhraun dyke intrusion, Iceland

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We present data from our dense seismic network which captured in unprecedented detail the micro-seismicity associated with the 2014 dyke intrusion from the subglacial Bárðarbunga volcano in central Iceland. Over 30,000 earthquakes were recorded and automatically located and yet the seismicity constitutes only 1% of the energy release from emplacement of the dyke. At the propagating tip, and in the inflating region behind, there is a noticeable lack of non-double-couple earthquakes; the dominant earthquake source mechanism is strike-slip failure and the dyke opening appears to be largely aseismic.

The micro-seismicity remains primarily focused at the base of the dyke at 5-7 km depth, near the brittle-ductile boundary, despite magma extending shallower. The lateral migration of the seismicity delineates a complex 48 km propagation, with a concentration of earthquakes in the advancing tip where stresses are greatest, and trailing zones of lesser or no seismicity behind. Rock fracture mechanisms are determined from manually-constructed fault plane solutions, revealing two distinct clusters of strike-slip faulting subparallel to the propagation. At the tip of the advancing dyke, failure occurs with left-lateral motion, releasing accumulated strain deficit in the brittle layer of the rift zone. Behind the tip, both right- and left-lateral strike-slip failure is observed.

Pre-Eruptive Seismic Tremor During a Shallow Dyke Formation

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Eruptions are usually accompanied by a long-lasting, emergent seismic signal – so called tremor. But tremor has also been observed before eruptions. We analyzed the seismic tremor that was recorded with an array during the Bárðarbunga eruption 2014/15. The eruption was preceded by seismicity that migrated 48 km in about 2 weeks from subglacial Bárðarbunga volcano to a glacier-free flood plain called Holuhraun where the eruption ultimately started. This seismicity is interpreted as a propagating dyke and was accompanied by bursts in tremor. These bursts occurred before the eruption started, although subglacial eruptions were suspected due to cauldron formation on the glacier surface. Eruptive tremor started with the opening of the fissure, but was overlain by a strong, 19 h long tremor burst 4 days into the eruption. We located the latter with recordings from a seismic array and seismic network sub-glacially beneath one of the cauldrons. The observed slownesses could be linked to a source depth using numerical full-wavefield simulations. Based on this we conclude that we tracked a shallowing dyke opening in less than 3 km depth leading up to a subglacial eruption.

Tracking deep magma movement preceding the 2014 Bárðarbunga - Holuraun Eruption using microseismicity

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Understanding magmatic plumbing and pressurization within an active volcanic system preceding an eruption is important for future predictions of when and where an eruption might occur. Tracking deep magma movement within the predominantly ductile region of the Earth's crust is challenging as only magma forcing its way through rock at sufficiently high strain rates will induce seismicity and therefore be possible to observe. Earthquakes induced by deep magma movement preceding the 2014 Bárðarbunga - Holuraun eruption are studied, with melt observed to travel up from depths of 15-20 km, pressurizing the volcano before the eruption. These earthquakes are detected using a network of 27 seismometers in SE Iceland, providing sufficient constraint to allow for fault plane solutions associated with the melt movement to be derived. The orientation and any volumetric components of the rock fracture are used to understand how and why the melt travels along the path it takes. This path is of particular interest since it is in close proximity to the path of the dyke during the subsequent fissure eruption. The seismic activity associated with the melt movement is also compared to that after the eruption, possibly induced by the system recharging, in order to understand what role deep melt movement plays in pre-eruptive pressurization.

Long-period earthquakes during the 2014 Bárðarbunga rifting event

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Crustal accretion along the divergent plate boundary in Iceland is governed by rifting episodes and diking. Over a period of two weeks in August-September 2014, magma propagated laterally from the subglacial Bárðarbunga central volcano, Iceland, about 50 km along the divergent plate boundary to the NNE where it erupted continuously for six months. The dyke propagation was associated with more than 30,000 earthquakes at 5-7 km depth, advancing in short bursts at 0.3-4.7 km/h. Following each surge forward, the seismicity behind the dyke tip dropped, implying that the subsequent dyke opening was mostly aseismic. More detailed analyses of the seismic data recorded by a dense network around the Vatnajökull icecap have revealed small magnitude, long-period (LP or B-type) events which in some cases coincide with an increase in continuous tremor. Most of the LP events originate at shallow depths NNE of the edge of the icecap beneath a 1000 m wide and 5 km long graben, which formed and subsided up to 8 m during the initial phase of the Holuhraun eruption. Furthermore, shallow LP events are also observed in the subglacial part of the dyke trajectory, under three distinct cauldrons. The LP events lie within the 0.5-8 Hz band and are too small to be detected by the national network of the Icelandic Meteorological Office (i.e. less than M_L =1.0-1.5). The LP events are most likely associated with surface ruptures caused by magma moving vertically from the laterally propagating dyke.

Magma Transport in Iceland from Deep to Shallow Crust and Eruption

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We have mapped magma transport paths from the deep (20 km) to the shallow (6 km) crust and in two cases to eventual surface eruption under several Icelandic volcanoes (Askja, Bárðarbunga, Eyjafjallajökull, Upptyppingar). We use microearthquakes caused by brittle fracture to map magma on the move and tomographic seismic studies of velocity perturbations beneath volcanoes to map the magma storage regions. High-frequency brittle failure earthquakes with magnitudes of typically 0-2 occur where melt is forcing its way through the country rock, or where previously frozen melt is repeatedly re-broken in conduits and dykes. The Icelandic crust on the rift zones where these earthquakes occur is ductile at depths greater than 7 km beneath the surface, so the occurrence of brittle failure seismicity at depths as great as 20 km is indicative of high strain rates, for which magma movement is the most likely explanation. We suggest that high volatile pressures caused by the exsolution of carbon dioxide in the deep crust is driving the magma movement and seismicity at depths of 15-20 km. Eruptions from shallow crustal storage areas are likewise driven by volatile exsolution, though additional volatiles, and in particular water are also involved in the shallow crust.

The M6.0 earthquake of Aug 24, 2016 in Central Italy

T. Braun[1] and the INGV teams[2]: Sismiko, Emergeo, Quest, Emersito, IES

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On Aug 24, 2016 a M_w 6.0 earthquake struck Central Italy near the town of Amatrice and claimed the lives of 300 people. Two months later, the intensity of the aftershock sequence suddenly increased, when on its northern sector two seismic events of M_w 5.9 and M_w 6.5 indicated the activation of a new fault system. The latter event of Oct 30, 2016 was the strongest in Italy since the M_w 6.9 Irpinia earthquake of Nov 23, 1980, destroying almost all the pre-damaged buildings. The aftershock sequence of more than 40000 localized events extends actually in an area of ca 80 km x 25 km.

Immediately after the event the INGV sent out teams to tackle the emergency in the field:

- Sismiko: installed a mobile seismic network around the ipocentrale area to record the seismic activity
- Emergeo: performed geological field survey, e.g. tracing the rupture at the surface
- Quest: recorded damages on buildings and structures
- Emersito: installed seismic stations in the ipocentral areas to study site effects
- IES: provided information about the seismic emergency

We show preliminary results of the analysis performed by the different groups.

From classifying volcanic tremor to classifying volcanic crystals

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The understanding of the plumbing system and processes below open vent volcanoes crucially depends on the interpretation of chemical and textural information recorded by their crystals. Many open vent volcanoes (e.g. Mayon, Stromboli, Etna, Llaima) show a large variety of phenocryst textures; in particular plagioclase shows a complex textural and chemical record that defies interpretation. Thus, despite the abundance of plagioclase and the easy extraction of textural and chemical data (e.g. electron backscattered images), we are left wondering what it may mean. In volcano seismology, several techniques for automatic discrimination of different patterns have been developed and/or adapted from other fields. In particular, Self Organizing Maps (SOM) have been widely used for classification of volcanic tremor. We therefore started to adapt these techniques to the automatic classification of plagioclase crystals. In parallel, we have started a numerical and natural study of these crystals. A 3D numerical crystal model of varying aspect ratios and with five main chemical zones was produced and cut at random orientations to simulate the typical thin sections. Simulations show that only 2D sections with the largest number of zoning patterns, particular crystallographic orientations, and the largest number of outer faces really reflect the ideal zoning pattern. Thus, a good part of the variety of the textural and chemical features of plagioclase phenocrysts may simply be explained by the effect of random 2D cutting of 3D zoned crystals, and does not necessary imply complex magmatic processes. Different 1D traverses along 2D sections also show complex relations, thus making 1D data comparison within and between crystals challenging. We have started to work on the (mostly automatic) extraction of features from images that maximize invariance within the 1D traverses of a single crystal, as a first step towards the application of pattern recognition methods such as the SOM, in order to extract a more realistic record of magmatic processes from complexly zoned plagioclase crystals. Preliminary results show that automatic clustering algorithms can in fact help to find the most representative crystal profiles/sections. For instance, the 2D sections with 5 zones are correctly separated from the others by the SOM cluster analysis but they do not always belong to the biggest cluster. Smart automatic criteria are therefore still needed to distinguish between the “right” and “bad” clusters to eliminate the effect of random cutting.

Deformation induced topographic effects in interpretation of time-lapse gravity changes

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We revisit the gravitational effects on the temporal (time-lapse) gravity changes induced by the surface deformation (vertical displacements). We focus on two terms, one induced by the displacement of the benchmark (gravity station) in the ambient gravity field, and the other imposed by the attraction of the masses within the topographic deformation shell. The first term, coined often the Free Air Effect (FAE), is the product of the vertical gradient of gravity (VGG) and the vertical displacement of the benchmark. We examine the use of the vertical gradient of normal gravity, typically called the theoretical or normal Free Air Gradient (normal FAG), as a replacement for the true VGG in the FAE, as well as the contribution of the topography to the VGG. We compute a topographic correction to the normal FAG, to offer a better approximation of the VGG, and evaluate its size and shape (spatial behavior) for a volcanic study area selected as the Central Volcanic Complex (CVC) on Tenerife, where this correction reaches 77% of the normal FAG and varies rapidly with terrain. The synthetic predictions of the VGG are verified by in-situ observations. The second term, imposed by the attraction of the vertically displaced topo-masses, referred to here as the Topographic Deformation Effect (TDE) must be computed by numerical evaluation of the Newton volumetric integral. As the effect wanes off quickly with distance, a high-resolution DEM is required for its evaluation. In practice this effect is often approximated by the planar or spherical Bouguer deformation effect (BDE). By a synthetic simulation at the CVC of Tenerife we show the difference between the rigorously evaluated TDE and its approximation by the planar BDE. The complete effect, coined here the Deformation Induced Topographic Effect (DITE) is the sum of FAE and TDE. Next we compare by means of synthetic simulations the DITE with two approximations of DITE typically used in practice: one amounting only to the first term in which the VGG is approximated by normal FAG, the other adopting a Bouguer corrected normal FAG (BCFAG).

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The Ignimbrites of the Azores: a review

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We report the existence of 28 ignimbrites on five islands of the Azores archipelago: São Miguel (17), Terceira (7), Faial (2), Flores (1) and Graciosa (1). The ignimbrites are generally associated with the formation of calderas but at least one, the Candelária ignimbrite on São Miguel island, was produced by a monogenic center. Their volume is generally unknown because the morphology of the Azores islands, mainly elongated WNW-ESE, suggests that much of the ignimbrites deposited out to the ocean. However, the most voluminous do not exceed a few km^3 D.R.E (Flores ignimbrite; Povoação and FogoA ignimbrites on São Miguel island) while the others are considered to be of small to very small volume. Their composition is generally trachytic and 40% have a welded texture. The oldest ones may be some hundreds of thousands of years old (on Flores and Terceira islands), whereas the four most recent are less than 5,000 years (Fogo A and Candelária ignimbrites on São Miguel island; Ribeira do Risco and Cedros ignimbrites on Faial island). On some stratovolcanoes, it is frequently observed that the same paleo-valleys have been occupied by several ignimbrites. This suggests the existence of privileged sectors for the passage of pyroclastic density currents.

Seismic and volcanic activity forecasting: Twenty-five years of progress

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Forecasting is a problem that has been addressed worldwide from different perspectives. Significant advances have been obtained after the introduction of complexity theory [Lorenz, 1963; Mandelbrot, 1977; Turcotte, 1997], and power-law distributions of different parameters. In particular, frequency-magnitude power-law statistics evidences the scale-invariance and self-organization [Newman, 2011] of seismicity, and brittle fracture models show a precursory causal evolution of strain characterized by an accelerating process culminating in a catastrophic failure. These characteristics of organization have allowed the development of forecasting tools. For instance, the Failure Forecast Method (FFM; Voight, [1988]) permits forecasting volcanic activity from the precursory accelerating rate of different strain-related parameters such as RSAM (Real-time Seismic Amplitude Measurement; [Endo and Murray, 1991]), RSEM (Real-time Seismic Energy Measurement; [De la Cruz-Reyna and Reyes-Davila, 2001]), SSAM (Spectral Seismic Amplitude Measurement; [Stephens et al., 1991]), SSEM (Spectral Seismic Energy Measurement; [Tarraga et al., 2008]) and SSW (Similar Seismic Waveforms; [Salvage and Neuberg, 2016]). Forecasting accuracy has been improved with the use of Kalman filtering [Kalman, 1960]. Other types of analysis such as the Base Level Noise Seismic Spectrum-BLNSS [Vila et al., 2006], or the dynamical analysis and Self-Organizing Maps-SOM [Carniel and Di Cecca, 1999; Kohonen, 1982] have proved useful to identify long-term precursory changes and families of events, or even to forecast potentially destructive larger-magnitude volcano-tectonic earthquakes (Mean Recurrence Time-MRT; [Garcia et al., 2016]). Next, we present some examples of these forecasting methods applied to different volcanoes of the world, and how that experience has been used to improve the hardware and software developed for that purpose. In particular, the analysis of changes in the RSAM rates with those tools permitted real-time forecasting of eruptions in Villarrica (Chile) [Ortiz et al., 2003] and Tungurahua (Ecuador) [De la Cruz-Reyna et al., 2010]. Similarly, during the 2004-2005 seismic crisis at Teide (Tenerife Island), the analysis of SSEM series allowed us to forecast local earthquakes [Tarraga et al., 2006]. The observed SSEM fluctuations lead to the development of BLNSS, which proved useful to recognizing and monitoring changes of Teide volcano internal processes [Garcia et al., 2006]. To assess BLNSS capabilities, we analyzed the BLNSS of other active volcanoes such as Soufriere Hills, in Montserrat, West Indies, and Llaima and Villarrica in Chile [Vila et al., 2006]. Generally speaking, the BLNSS provided relevant information about the status of volcanic unrest and its relation with regional and distant major earthquakes. The type of RSEM specifically developed for Colima volcano in Mexico [De la Cruz-Reyna and Reyes-Davila, 2001; Reyes-Davila and De la Cruz-Reyna, 2002], allowed identification of the nature of the stress evolution at the source of strain release. We have also analyzed the time evolution of a number of spectral, dynamical and statistical parameters computed from the continuous streaming of raw seismic data from Villarrica, Teide and Popocatepetl (México) volcanoes. Some results show open close transitions of the conduit systems, and interactions between tectonic events, seismic noise and volcanic activity [Tarraga et al., 2006; Carniel et al., 2007; Tarraga et al., 2012]. The choice of the method to be used depends in each case on a preliminary assessment of the physics controlling the volcanic activity and the type of available data. This requires at times developing new methods to deal with particular situations [see e.g. Salvage and Neuberg, 2016].

The recent volcanic and seismic unrest at El Hierro (Canary Islands; 2011-2015) provided an opportunity to use these real-time tools to follow up the development of such a complex phenomenon since its onset in July 2011, and to assist forecast-based decision-making. Seismic data, including earthquake magnitudes and locations were obtained from the Spanish Geographical Institute (http://www.ign.es/ign/layoutIn/sismoFormularioCatalogo.do) on-line official catalog. To process this information, we first implemented a real-time calculation of the cumulative seismic energy and a stepwise estimate of the Gutenberg-Richter b-value [Gutenberg and Richter, 1944] on intervals showing stability in the rate of occurrence of different earthquake magnitudes. Kalman-filtered data were used to track the SSEM evolution. In the initial stages of the unrest, the b-value provided information about the process of magma migrations causing the unrest, but some difficulties with the stability of the low-cut-off magnitudes made it difficult to keep track of the b-value changes. However, the Kalman-SSEM based forecasting of major earthquakes worked fine until the onset of the submarine eruption (10-10-2011), when the strong tremor caused by the eruption masked all other signals. Nevertheless, the SSEM method still allowed forecasts using distant stations. From the beginning of the seismic analysis, the evolution of the seismic energy conformed to the Yokoyama criterion [Yokoyama, 1988] showing significant increments in the number and magnitude of earthquakes when the cumulative energy exceeded 10^{11} J. Volcano-tectonic activity at El Hierro ended with the eruption, reassuming days later, on 29-10-2011, when a new seismic swarm and significant deformations developed in a way similar to the pre-eruptive unrest, this time with the seismicity reaching a maximum magnitude 4.6. This activity was probably related to a new magma injection process at depth. Afterward, a sequence of similar episodes of seismicity and deformation have been detected, with temporal and spatial evolutions that are consistent with the model of magma injections along paths defined by stress -controlled conical surfaces [De la Cruz-Reyna and Yokoyama, 2011; Garcia et al., 2014a]. Such model allows detection of shallows regions of increased seismic and landslide hazard. The similarities among the different episodes of seismicity motivated the definition of a new family of magma-migration related seismic swarms [Farrell et al., 2009, Garcia et al., 2016]. From the experience obtained during the previous cycles of seismicity, we developed a robust method to forecast the occurrence of the largest-magnitude earthquake in each magma injection process, the MRT, and an associated alert level procedure (VAL) to objectively communicate the hazard [Garcia et al., 2014b; Garcia et al., 2016].

Indeed, the follow-up of a volcanic activity has two lines, one is specifically scientific, while the other is focused on the management of the risk posed by the activity. The latter must generate decision factors in quasi-real time and include criteria and communication procedures to advise authorities and warn the populace with the required earliness. Such timing is determined by the type of necessary preventive actions (e.g. hours in the case of closing of a road in a zone of probable landslides, or days for a possible evacuation). In [Marrero et al., 2010] we present a new tool for simulating and optimizing large-scale evacuation processes: The Variable Scale Evacuation Model (VSEM), which allows simulating an evacuation considering different strategies depending on diverse impact scenarios. The decision to evacuate is one of the critical issues in managing a crisis. In order to make such an important decision, it is essential to estimate the cost in lives for each of the expected impact scenarios. To improve the emergency response planning and facilitate the decision-making process we developed a methodology to estimate the number of potential fatalities, which has been applied to the Central Volcanic Complex of Tenerife and to El Chichon volcano (México) [Marrero et al., 2012; 2013]. Employing the above-mentioned forecasting tools, and with a time window defined by the expected impact scenarios, it was possible to design an automatic watchdog system capable to detect actual data trend changes, and reject spurious signals related to instrumental failure. Thus, only changes related to volcanic activity are translated by the monitoring scientific team into a Volcanic Alert Level (VAL) that is easy to understand and use by scientists, technicians, and decision-makers [Garcia et al., 2014b]. Although this procedure has been tested, its efficacy depends on the political and social contexts in which a crisis develops [Marrero et al., 2015].

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OVAA (Austral Andean Volcanological Observatory): past, present and suggestions for future

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After the eruption of Chaitén volcano in 2008, Chilean government has invested great amounts of money for volcano monitoring. National Geological and Mining Service (Sernageomin) has been the responsible of this development, considering seismic monitoring. The number of seismometers deployed is directly related to volcanic hazard, volcanoes from 40° S to the south have been ranked, giving the highest "risk index" to Chaitén, Michimahuida and Hudson, in addition, volcanoes like Macá, Melimoyu, Corcovado, Huequi, among others are also monitored. Guralp 6T and 40T, Reftek 151-30, Trillium 40 and Trillium 120P seismometers were installed no more than 70 km from each volcano, these volcanoes are located along the Liquiñe Ofqui Fault Zone (LOFZ) which controls geodynamic processes in the region. Plastic vaults were constructed at a maximum depth of 70 cm approximately, in the middle of forests, near fjords or lakes or even in unconsolidated soil. All stations are transmitting data using telemetry and acquisition software Seiscomp (free version) which avoids loss of data during internet breakdowns. Despite seismic noise, Seiscomp can identify a great amount of phase P arrivals from VT events, localized mainly along the LOFZ and beneath craters of active eruptive centers. LP's and VLP's have not been identified yet.

Now, determining the most important procedures to assess volcanic activity is the goal, for instance, we implemented as semi-automatic post processing tools; filtering, spectrograms, focal mechanisms calculations, among others. We have to inspect other methods such as RSAM (used in OVDAS, Sernageomin) and others in order to achieve our goals. Also, receive some feedback about the installation of sensors, density, distance from craters, monitoring of the LOFZ, data acquisition, number of analysts, number of technicians, would be very helpful to us.

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appendix

The INGV Visitor Centre of Stromboli

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Increase of risk perception and awareness in inhabitants and tourists is important to correctly manage volcanic emergencies. The INGV and Italian Civil Protection efforts in improving volcanic risk education include the creation of dedicated Visitor Centres on active volcanoes, such as those operating at Vulcano and Stromboli.
Vulcano and Stromboli are touristic islands, hosting in summer nearly 15,000 people each, with a few hundreds of permanent residents. INGV maintains on each island a sophisticated volcano monitoring system and national and local civil protection authorities prepared emergency plans in case of eruption.
Stromboli is famous world-wide for its persistent mild explosive activity, consisting of frequent explosions (on average one every 10-20') throwing glowing scoriae, blocks and ash to a few hundred metres height. Episodically the volcano produces more violent and hazardous explosions and lava flows descending to the sea.
The INGV Centre at Stromboli was created in 1997, in collaboration with the National Civil Protection Department and the local Municipality of Lipari. Its exhibition has been largely renewed in 2014.

The main aims of the INGV Centre are:

- to inform residents and tourists on the volcanic hazards, the monitoring system and how to behave when climbing the volcano or if a volcanic alert is declared,
- to offer a logistic support to volcanologists involved in monitoring or research activities on the island.

During the summer the Centre is managed, on weekly rotation, by volcanology students of several Italian Universities tutored by a senior researcher of INGV or University. On average there are 8000 visitors in summer. The Centre hosts a wide exhibition room where posters, pictures, PC and videos illustrate (both in Italian and English) the geology and eruptive history of the volcano and some attractive geological structures, its hazards and the surveillance system; the continuous real-time signals from seismic monitoring stations as well as direct images of the active vents of Stromboli from TV cameras are also shown. Depliants are freely provided to visitors.

During 20 years of activity, the INGV Centre increased the risk awareness in local population and visitors and it now represents an important reference points.

Vulcano Island field trip

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Vulcano island, is a composite volcanic edifice located at the southern extremity of the central segment of the Aeolian islands, along the *"Tindari Letojanni (TL) fault"*. It has built through four main eruptive activity developed at Primordial Vulcano, Lentia-Mastro Minico, La Fossa Cone and Vulcanello (Fig. 1), and by two multi-collapse calderas (Piano and La Fossa).

Figure 1. View of La Fossa cone active crater and Vulcanello.

The last eruption of La Fossa cone, the actual active crater which it was built from 6000 years ago (a 391 m high cone with a basal diameter of 1 km), occurred in 1888–1890 and has been documented by Giuseppe Mercalli (Fig. 2).

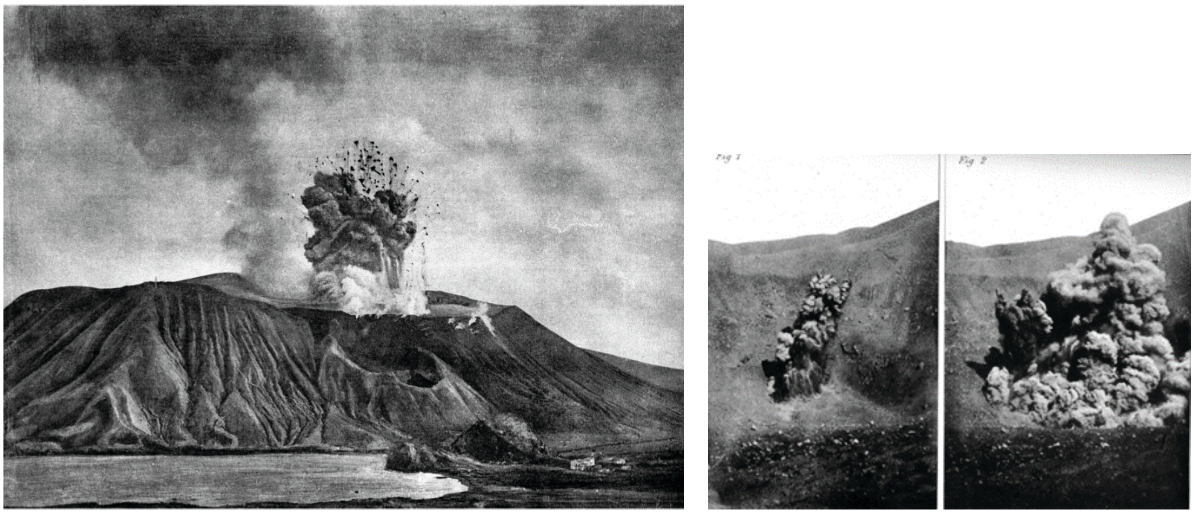

Figure 2. 1888-90 vulcanian eruption of La Fossa cone, documented by Giuseppe Mercalli.

Actually, La Fossa cone is characterized by an intense high temperature fumarolic activity from the NE side of crater rim (Fig. 3) and by a low-temperature one at the foot, at Levante Beach (Fig. 4).

Figure 3. NE rim of La Fossa cone with high Temperature degassing activity.

Since the 1888-90 eruption, La Fossa has been in a quiescent state with episodic occurrences of “crisis” (the last two occurred in 2005 and 2009) characterized by an increasing in temperature and gas output (mainly CO_2%) at crater fumaroles, expansion of the fumarolic field and chemical and isotopic changes ($^3He/^4He$) indicating an increase of magmatic fluids from depth. Characteristic shallow seismicity, below La Fossa cone, accompany these crises.

Figure 4. Low Temperature degassing activity at Levante Beach (mud pool).

During these “crises” periods, the diffuse soil CO_2 flux increases at the crater area but also on the volcano flanks, extending from La Fossa to inhabited zones of Vulcano Porto, Levante Beach and Palizzi. In addition, CO_2 and H_2S air concentrations may exceed the hazardous thresholds in some sites usually frequented by tourists (mud pool or crater area).

Stromboli crater field trip

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The advantage of realizing a volcano-seismological workshop on an active volcano is that the field excursion can be directly started from the congress centre. Almost all the workshop participants joined this opportunity and decided to join the field trip to the crater area of Stromboli along the arduous direct route. The excursion lead by the alpine guide Mario Zaìa (Magmatrek), started from S. Vincenzo in the late afternoon of Sep. 28, 2016 in order to reach the summit area, called "Pizzo sopra la fossa (923 m)", exactly in time for sunset.

Figure 1. Ascent of the workshop participants to the crater area of Stromboli. Note the shadow of the volcanic cone falling on the village of S. Vincenzo (Photo by T. Braun).

Stromboli is one of the most active volcanoes of the world and represents a perfect natural laboratory for studying the volcanic seismicity and for modelling its explosion dynamics. Its continuous and persistent "strombolian activity" with relatively frequent summit explosions (every 15 – 30 min) and the easy access to the active craters makes Stromboli the perfect playground for volcanologist from all over the world.
Every ascent to the crater teaches, however, that the Strombolian reality is not such regular as often described and consists rather in strongly varying volcanic dynamics, including occasionally extended periods of low activity, as even during the 25th anniversary workshop. Since numerous open question remained also after the conclusion of the meeting, Stromboli will be the appropriate place to realize further workshops on volcano-seismology in the future.

Figure 2 and 3. Arrival at “Pizzo sopra la fossa”, 923 m a.s.l. (photos by T. Braun).

Figure 4. Typical ash emission during sunset at Stromboli’s SW-crater (photo by T. Braun).

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