Milestones and Developments in Volcano Seismology

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This talk focusses on some of the achievements that came out of the 29 years of history of the ESC working group in the context of other important milestones in volcano seismology. Starting with the reasons why the working group was initiated by Rolf Schick and Bruno Martinelli, the first milestone is listed as the deployment and the results of the first broadband seismic network on Stromboli. However, while nowadays broadband seismic sensors are widely available and deployed, very rarely is their wide frequency range adequately used in data monitoring and interpretation. The identification and modelling of low-frequency events is the next milestone where several groups contributed to potential models of trigger mechanisms and their relevance as a forecasting tool. The next milestone was the attempt of a multi-disciplinary approach providing mutual links between seismology, other geophysical monitoring techniques and also petrology and geology. A further milestone was the deployment of a dense seismic network in Iceland that resulted in an unprecedented data coverage and imaging of a dyke propagation at the Bardarbunga eruption. Finally, the developments of general volcano seismic models are considered in the context of hazard and risk analysis, and linked to the application of automated detection algorithms and machine learning.

Can tilt and low frequency seismicity be used in a combined forecasting tool?

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At Tungurahua volcano, Ecuador, a decrease in tilt and increase in low frequency leading up to a Vulcanian explosion on 1st February, 2014, was successfully used to forecast that an eruption was imminent 3 days in advance. This negative correlation between tilt and seismicity is suggestive of a common driving mechanism. As magma ascends, overpressure pushes the surrounding edifice outwards, whilst shear stress pulls it upwards. Where shear stress exceeds the shear strength of the magma, magma fails in a brittle manner, triggering low frequency seismicity. Shear stress is a function of the ascent velocity and viscosity, so offers a potential link between observed deformation, seismicity, and ascent dynamics. Being able to quantify changes in ascent velocity would be key in forecasting eruption style and scale. By combining flow and deformation modelling using COMSOL Multiphysics, we for the first time present a quantitative model that links magma ascent to deformation. We quantify how both shear stress and pressure vary spatially within a cylindrical conduit, and show that shear stress generally dominates observed changes in tilt close to the conduit. However, to harness both seismicity and tilt in a combined forecasting tool, we require a quantitative understanding of how shear stress partitions between the two. How much shear stress reduction is achieved through a seismic swarm? How fast does the shear strength of the magma recover after failure? And how does frictional heating affect the rheology of magma? Here, we discuss the steps that must be taken to develop an automated combined forecasting tool.

Moment tensor inversions for complex seismic sources in caldera-size ring structures

Rodrigo Contreras-Arratia and Jurgen Neuberg

Ring faults have been studied by several authors, and they have been proposed as the source geometry explaining earthquakes in volcanic environments. For example, a conical ring fault has been used to explain earthquakes in Bardarbunga volcano with dominant Compensated Linear Vector Dipole (CLVD) components in their MT solution. Moreover, a recent numerical study showed a dominant isotropic component for ring faults with vertical dipping (cylinder instead a cone). This study aims to suggest partial ring ruptures as the source mechanism for non double couple seismic events reported by other authors during the Bardarbunga-Holuhraun caldera collapse event (2014-2015). We produced synthetic seismograms using software Specfem3D by superposing point sources with different dipping angles arranged along ring faults. Later, we perform moment tensor inversions (MTI) assuming a point source. We use both; a synthetic network to obtain "real" results with a perfectly distributed seismic network and a simulation of the IMO seismic network in Iceland to compare results and test the quality of the station configuration when we assume ring faults acting. Results show a trade-off between Isotropic and CLVD components as we vary the dip angle, i.e. or 90 degrees dip, solution is dominated by Isotropic component, and for 45 degrees dip it is dominated by a vertical CLVD. During a caldera collapse event, such as Bardarbunga, within a ring fault with a dipping angle different than 90 degrees we obtain negative (for diverging cone) or positive vertical CLVD solutions (for converging cone). Different rake angles result in different orientations for the CLVD solutions which corresponds to the full range of MT solutions obtained in Bardarbunga.

How the seismic network configuration can affect the moment tensor inversions

Dinko Šindija, Jürgen Neuberg

Active volcanoes are often covered with a sparse seismic network. In the case of a volcanic crisis, the number of stations can even be more reduced due to noise saturated data electrical failures, or station being destroyed by volcanic events. Using numerical tests we examined how well different source mechanisms with varying orientations and at different source depths can be resolved using moment tensor inversions. Further, we vary the number of seismic stations, both mimicking an eruption scenario and adding new stations to see how much it affects the resolved moment tensor components. As a case study we use the seismic network configuration at Soufriére Hills volcano, Montserrat. We show that for a reduced number of stations in our seismic network, even though we can resolve the time histories of the surface displacement, the source moment tensor components are not well resolved. Additionally, we show how different slip directions at the same fault can affect the moment tensor component, i.e. making it impossible to resolve moment tensor components for certain source orientation at certain depths. These results show the importance of taking seismic network geometry into account.

ESC/IAVCEI/IASPEI WS “Automatic detection, identification and classification of volcanic signals”
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Recommending best practice for treating deformation induced effects in volcano gravimetry

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Abstract
Some 3D or 4D micro-gravimetric surveys and studies require the knowledge and application of true vertical gradient of gravity (VGG). This demand may be associated with reductions of or corrections to observed gravity or its spatiotemporal changes. In the absence of in-situ measured VGG values, the constant value of the theoretical (normal) free air gradient (FAG) is commonly used. We propose an alternative to this practice which may significantly reduce systematic errors associated with the use of theoretical FAG. The true VGG appears to be better approximated, in areas with prominent and rugged topographic relief, such as alpine or some volcanic regions, by a value based on the modelled contribution of the topographic masses to the gradient. Such prediction can be carried out with a digital elevation/terrain model (DEM/DTM) of sufficient quality: resolution of 5 m or better and vertical accuracy at the order of 10 cm, depending on the roughness of the relief. We quantify also the need of improving the VGG prediction at gravimetric monitoring networks for benchmarks adjacent to man-made structures (walls, buildings, etc.). We also present the possibility to improve the VGG prediction by locally refining the DEM by drone-flown photogrammetry. The predictability of VGGs in regions of rugged relief was verified by in-situ observations in the Central Volcanic Complex of Tenerife (Canary islands) and at Mt. Etna (Italy). We illustrate how strongly and sharply the VGG field deviates spatially from the constant value of FAG. We also analyze the sensitivity of the VGG prediction to the resolution and accuracy of the used DEM. Finally we discuss the applicability and significance of the topo-predicted VGGs in micro-gravimetric studies and the best practice in volcano gravimetry when compiling residual gravity changes to be inverted and interpreted. Various approaches to evaluating the deformation induced effects (DIE) and the deformation induced topographic effect (DITE) are compared and the role and treatment of the effect of inner deformations is discussed.

Keywords: VGG, free-air correction, FAE, gravity survey, microgravimetry, volcano geodesy, time-lapse gravity changes

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Automatic detection/location system for seismic swarms: first results for the unrest of the 2011 Tagoro eruption (El Hierro, Canary Islands)

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Volcanic eruptions are usually preceded by precursory seismic unrests characterized by high density of low magnitude earthquakes. Signal-to-noise ratio (SNR) of most of the earthquakes from those swarms may be low and the seismic phase picking can become a complex task. In the last decades some research groups have been working to implement neural networks or new statistical methods to improve the swarm analysis; being the huge computation time and the high performance hardware the main issue to solve when applying these methodologies.

A semiautomatic earthquake detection and location system has been developed. The two main improvements of this algorithm are: a STA/LTA algorithm was applied to the power spectra of the signal optimizing the computational time to detect and pick the earthquake phases; and a matching-template algorithm (waveform correlation) with well known earthquakes manually caracterized as templates to pick seismic phases. Finally, the location was completed by applying the multiple-master-event algorithm (Master-Cluster) taking advantage of the double differences techniques.

This methodology has been tested with the pre-eruptive seismicity of the 2011 El Hierro eruption resulting in a total number of 38 000 earthquakes detected, almost four times larger than the 10 000 earthquakes of the original seismic catalog from Spanish National Geographic Institute (IGN). Furthermore we could succesfully obtain hypocentral location and magnitude for 24 000 earthquakes. Finally the relocations could be applied to 17 000 events. The magnitude of the earthquakes was also corrected by computing local corrections for all seismic stations using as reference regional earthquakes. The resulting catalog has a more homoegeneous completeness magnitude ($\sim$1.2) and thus, the b-value map of the seismicity was computed. This map shows high b-values (1.7-2.5) in the early northwest seismicty indicating the possible presence of a sill, while the late southern seismicity shows low values (0.8-1).

Automatic seismic network-based monitoring of Tenerife (Canary Islands, Spain)

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Presentation preference: TALK

We apply an automatic network-based method for detecting and locating different kind of seismic signals. Two years of seismic data of the island of Tenerife (Canary Islands, Spain) continuously recorded by the Red Sísmica Canaria (C7), a permanent monitoring network composed of 17 broadband stations operated by the Instituto Volcanológico de Canarias (INVOLCAN), are analyzed. The method is based on the analysis of eigenvalues and eigenvectors of the seismic network covariance matrix, the equivalent in the frequency domain of the cross-correlation matrix. First, the width of the network covariance matrix eigenvalues distribution, that is a proxy of the number of acting sources, is used to detect events. Then, the first eigenvector of the covariance matrix corresponding to each event is used to locate it, using the moveout information of this first eigenvector. The main hypothesis is that, by representing the principal component of the recorded wavefield, this first eigenvector characterizes the dominating event filtering the information related to the seismic noise. Oceanic, tectonic and volcanic seismic sources are efficiently detected and located. This data feature extraction method has the advantage of not requiring a priori knowledge, to be fully automatic and to be able to analyze large amounts of data.

Detecting and Characterizing Repeating Seismicity near Alaska Volcanoes

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Alaska is home to 54 historically active volcanoes, many of which are seismically active. Monitoring these volcanoes is often difficult due to remoteness and harsh weather. Thus, tracking seismicity is very useful for monitoring and forecasting volcanic eruptions. While some open-system volcanoes may erupt with little-to-no precursory seismicity, other Alaska volcanoes produce large amounts of seismicity before, during, and after eruptions. However, it can be challenging to distinguish volcanic seismicity from non-volcanic seismicity and to identify precursory seismicity. Here, we present a few tools and methods that can be used for detecting and characterizing seismicity that can help with successfully forecasting and monitoring eruptions.

The repeating event sequence alarm (RESA) and detector was developed during the 2016-17 Bogoslof eruption to notify observatory personnel of potential explosion precursors. About 20 explosions during the Bogoslof eruption were preceded by accelerating swarms of repetitive earthquakes, motivating the development of the RESA. The RESA uses an STA/LTA detector to find events and then applies a correlation algorithm to compare the detected events with templates produced from those events. When a repeating event sequence reaches a high enough event rate, a notification is sent via email or text. During development, the alarm was also tested retrospectively on data from eruptions at Redoubt in 2009 and Okmok in 2008. Since the Bogoslof eruption ended, the alarm has been used for monitoring repetitive seismicity at other Alaska volcanoes, including Great Sitkin, Makushin, and Okmok. Additionally, the detection algorithm used by the RESA can be applied to past data to create repeating event catalogs for retrospective analysis. The RESA has been used in this way on the aforementioned volcanic activity and also on non-volcanic seismicity that occurs near volcanoes, such as glacier/ice-related signals from near Isanotski and Mount Spurr.

Characterizing the moment rate or inverse moment rate of earthquake swarms may be useful for identifying precursory seismicity. Such analysis may be able to identify an accelerating rate of seismicity that is associated with accelerating creep or an unstable frictional regime that can result in critical mass failure of materials, such as avalanches, landslides, volcanic eruptions, and volcanic crater collapse. We show a few examples of moment rate analysis of seismicity near Alaska volcanoes to demonstrate its potential use in understanding the sources and progression of repetitive seismicity. The inverse moment rate analysis has also been integrated into the RESA to provide more information about detected swarms in near-real-time.

Pattern Recognition in Geophysics and Related Fields. Advantages and Pitfalls

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Continuous data acquisition in Earth Sciences in general, and Geophysics in particular, leads to the accumulation of a huge amount of data piling up in digital archives in short times. Without tools to exploit their content, these archives may turn into "data graves", containing precious information difficult to unearth. Consequently, there is a huge endeavor to get efficient real-time processing and automatic procedures to support decision making for monitoring and surveillance purposes.

The data we deal with are typically multivariate, which entails specific problems in terms of statistical treatment and graphical representation of results. Pattern recognition techniques offer effective strategies to tackle these problems. Pattern recognition is a fundamental element of classification, i. e., the process of assigning objects to a category or – more in general – to a target. Genetic classification is perhaps the oldest approach, in which we consider the origin (or cause) of an object. In Geology, for instance, we distinguish between sedimentary and igneous rocks based on their genesis rather than their mineralogical or geochemical characteristics. Supervised classification can be understood as the inverse process of genetic classification. It uses a priori information inferred from example objects, supposing to know which class they belong to. The object may be a seismic record (or a number of seismic records), and we infer its origin from its characteristics. Unsupervised classification is based on a suitable definition of similarity between patterns rather than on a priori knowledge of their class membership. The task of unsupervised classification can be formulated as finding groups with a minimum degree of heterogeneity, being most distant from each other.

Beside grouping single objects, we may also be interested in their interrelation. This aspect is important not only in pattern recognition, but also in forecast. In Geophysics a sequence of objects may be related to the development of some phenomenon, being it a typhoon, a flood, or a volcanic unrest. This implies that a specific pattern is meaningful not only for the components making up its feature vectors, but also for the context defined by other patterns. This is also a typical problem in speech and text analysis, where the meaning of a word or a number not only depends on single characters or digits, but also on their order.

Thus far, pattern recognition techniques have been applied to numerous fields of Earth Sciences, allowing us to gain practical experience in many real-world problems. Among these, we selected a few examples regarding Mt Etna volcano (Italy), which is often addressed to as a "volcano laboratory" for its persistent activity, favorable logistic conditions allowing the deployment of cutting-edge equipment for multidisciplinary measurements, and with a long tradition of monitoring in the context of surveillance for Civil Protection purposes. Besides, we present applications from other fields of Earth Sciences, such as climate zoning, classification of rocks, seismic source mechanisms. Context-based applications are both used in classification s. str., but also in the framework of forecast, e. g., Tsunami early alert. The variety of applications allows us to discuss the strength of the various methods, but also highlights possible traps and misunderstandings. Often unsatisfying results can be explained by inappropriate formulation of the problem, questionable choice of features, inadequate definition of target and objects. Besides, critical a-posteriori analysis is mandatory in order to avoid overly optimistic interpretations. Methods make us smarter, but they will not be smarter than us, so to speak.

First results of the SEISVOL project: Seismicity of Oldoinyo Lengai volcano, Tanzania

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Oldoinyo Lengai volcano, located in the Natron Basin (Tanzania), is the only active natrocarbonatite volcano world-wide. As such, it presents an important endmember magmatic system, which occurs in a young rift segment (~3 Ma) of the East African Rift System. This volcano typically experiences long-duration episodes of natrocarbonatitic effusions with intermittent short-duration explosive eruptions. These changes may be driven by stress interactions between different magmatic networks beneath Oldoinyo Lengai and neighboring rift volcanoes or caused by a complex differentiation process in which, driven by CO2, natrocarbonatitic magma is exsolved from one magma chamber. To better understand the role of stress interactions and magma plumbing on the eruption dynamics, we have installed a dense seismic network, including a seismic array and four infrasound stations at the end of February 2019 as part of the SEISVOL (Seismic and Infrasound Networks to Study the Volcano Oldoinyo Lengai) project.

Here, we present preliminary results of local seismicity of the first weeks from the seismic network consisting of 22 stations, which span an area of 30 x 30 km and encompass Oldoinyo Lengai volcano, the extinct 1 Ma-old Gelai shield volcano, the active Naibor Soito monogenetic cone field and surrounding fault population. On average, we report up to 30 earthquakes per day within and in the vicinity of our network. The seismicity is clustered along the eastern flank of Gelai volcano, which hosts the majority of events, as well as between Gelai and Oldoinyo Lengai and beneath the latter. Seismicity also occurs beneath Lake Natron to the North and along the border fault to the South of Oldoinyo Lengai. Given the dense station spacing, we are able to lower the detection threshold to -0.7 M_L and detect signals that seem to nucleate directly from the crater of Oldoinyo Lengai. Additionally, we observe periods of recurring, short high-frequency signals, which could possibly be interpreted as seismic tremor.

Analyzing earthquakes and hybrid events on Fogo and Brava, Cape Verde, with multiple arrays

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The Cape Verde archipelago is believed to originate from a mantle plume beneath an almost stationary tectonic plate. Fogo and Brava are located in the south-western part of the archipelago, about 18 km apart from each other and belong to the younger islands of the Cape Verde. Only Fogo experienced historic eruptions at intervals of about 20-25 years, with the last eruption from November 2014 to February 2015.

Here, we aim to investigate the magmatic system of Fogo and to characterize the seismic activity of the region in greater detail. As the majority of the events are located offshore, we employ multi-array techniques to study the seismic activity. Furthermore, as many volcano-related seismic signals lack a clear onset of phases, array methods may be better suited for their localization.

In January 2017 we installed three seismic arrays on the islands - two on Fogo and one on Brava. Each array consisted of 3 broad-band and 7 short-period stations distributed over a circular shaped area with an aperture of approximately 700 m. The arrays were complemented by seven single short-period stations, five on Fogo and two on Brava. The complete network of 37 stations was in operation until January 2018.

To locate earthquakes, we perform the array analysis in the time-domain. While computationally more expensive than traditional f-k analysis, the time-domain approach allows for more flexibility regarding the selection of relevant time windows to calculate the beam energy. Traces are first shifted and then cut to select suitable time windows for the energy stack as function of horizontal slowness.

For a single array, epicentral distances can be estimated from arrival-time differences between S- and P-waves, by assuming a suitable velocity structure. However, with two or more arrays, epicenters can be obtained directly from the intersecting beams. The technique can be applied to earthquakes as well as to volcanic signals lacking a clear onset of P- and S-phases, e.g. hybrid events.

While we observe relatively few earthquakes beneath Fogo (in comparison to Brava), other types of seismic signals, which can be described as hybrid events, occur more often. The signals are characterized by a transition from high to low frequencies in the range between 0.5 and 15 Hz. The events lack clear phases, although they often exhibit a relatively sharp onset. These features provide ideal conditions for the application of the multi-array analysis. First results show that the events originate in the vicinity of the Chã das Caldeiras region, a collapse scar surrounding the present-day Fogo volcano. The localization of the hybrid events will be presented and discussed in detail.

Improvements in the location of events with the Teide array (Tenerife, Canary Islands, Spain)

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Abstract:

During October 2016, a seismic array was deployed in the central part of Tenerife Island (Canary Islands, Spain), close to the Teide-Pico Viejo system. This equipment was set in the context of MultiTeide research project, whose main aim is the multiparametric study of the present level of activity in the central Tenerife volcanic complex. Until now, in addition to the seismic array, MultiTeide has installed, a magnetic network, two self-potential (geoelectrical) continuous measuring stations, two heat-flux sensors and has performed four reiterative field campaigns to measure ground temperature, CO2 diffuse flux and self-potential in selected areas of the upper-Teide hydrothermal field.

The seismic array is located about 6 km SW of Teide´s peak and has an 11-channel, 24-bit data acquisition system sampling each channel at 100 samples per second. The array is composed of 1 three-component and 8 vertical-component seismometers, distributed in a flat area with an aperture of 210 m. All the sensors are of short period. The system has two Centaur digitizers (Nanometrics) of 6 channels each, which makes a total of 12 channels. To ensure the synchronism of the set, a sensor is digitized in both stations simultaneously.

During the operating time of the array there have been more than one thousand earthquakes in Canary Islands. For this study we have focused on the most significant events recorded in the interior of the island of Tenerife and have been analyzed with array techniques like maximum average cross-correlation method. From the analyzed events, we have selected those where the P and the S phase were automatically identified. Adding the parameters azimuth and apparent velocity obtained with these techniques, we have relocated the events in order to compare with the solution given by the National Seismic Network.

Volcano-Independent Seismic Recognition:

can we really do it?

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A continuously growing amount of data is erupted by modern volcano monitoring systems, which should be processed rapidly and efficiently in order to evaluate the status of the volcano and timely recognize a possible unrest. Seismic activity is always a key parameter: before most eruptions, up to thousands of discrete events can be recorded in a few days or hours, without mentioning continuous seismic noise / tremor. Their detection in a continuous data stream and later classification into event types of the same physical source, a.k.a. 'classes', requires therefore a "labelling" that is strongly linked to an "interpretation". This process, if done manually, becomes often too time-consuming to be carried out in real-time in case of a crisis.

Machine Learning and automatic recognition techniques are very promising for analyzing large streams of data in real-time, and can be applied for the recognition of seismic events. Several research groups have proposed applications and have developed prototypes for this purpose. It is now time to put this experience in practice and jump to real-world, real-eruptions, real-time applications. For this, the collaboration between researchers and observatories becomes essential.

We will discuss the problems related to the integration of automatic recognition tools in routine monitoring systems and highlight the need for sharing reliable and large databases of seismic events recorded at different volcanoes.

The EU-funded project VULCAN.ears (Volcano-seismic Unsupervised Labelling and ClAssificatioN Embedded in A Real-time Scenario) goes into this direction, aiming at: a) 'U'nsupervised Volcano-Seismic Recognition (VSR) operation: portable, 'on the fly' volcano-independent VSR; b) 'U'niversal integration into any monitoring/acquisition framework; c) 'U'sability of provided tools and ease of use of the whole environment.

During the recent months, we participated in the last Cities on Volcanoes meeting, we organized a workshop in Costa Rica to present the project in a "hands-on" way to the staff of the volcano observatories of Latin America, and we participated in the last Latin American Volcano Association of Seismologists (LAVAS) meeting in Colombia with the same purpose. The expectations are big. What do we still need to fulfill them?

Tracking Subsurface Melt Movement through the Crust in Iceland using Seismology

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We have recorded and precisely located tens of thousands of microearthquakes in the mid and lower crust of Iceland caused by melt movement. Using dense seismometer arrays and the new QuakeMigrate software with with automated detection and location of small events, followed by cross-correlation for subsample arrival times followed by relative relocations, we are able to map hypocentres to relative precisions of a few tens of metres.

Videos of the spatial and temporal evolution of hypocentres along the 48 km long Bárðarbunga -Holuhraun dyke intrusion during 2014−15 show the complexity of the dyke propagation pathway and dynamics (segmented, jerky). We will display these and doubtless they will cause good discussions about dyke propagation. The spatio-temporal characteristics of the induced seismicity can be linked directly to propagation of the tip and opening of the dyke. Subsequently, after eruption has started, shows a relationship with magma pressure changes (i.e. dyke inflation / deflation). Seismicity occurs only near the base of the dyke, where dyke-imposed stresses are sufficient to induce failure of pre-existing weaknesses in the crust. Emplacement oblique to the spreading ridge resulted in predominantly left-lateral shear motion along and adjacent to the dyke in the best recorded northernmost dyke segment. Moment tensor solutions show double-couple failure with consistent fault plane strikes c. 10 degrees different from the paths delineated by the hypocentres, indicating that they are controlled by the local fabric of the host rock.

In another dyke near Upptyppingar, c. 50 km northeast of the Holuhraun eruption site we have mapped complete reversals of the polarity of fault plane solutions within the space of just a few minutes in exactly the same place to within the resolution of our locations (i.e. to within tens of metres). We interpret these as caused by failure induced on opposite sides of the intruding dyke.

We also map hypocentres throughout the crust from c. 25 km depth to near-surface near three active volcanoes in Iceland: Askja, Bárðarbunga and Eyjafjallajökull. We interpret this seismicity as caused by carbon dioxide release from melt increasing the local pressure and causing high strain rates at otherwise geologically ductile depths in the crust. The hypocentres mark a series of sills accumulating melt at varying depths within the mid and lower crust.

Resources:
We plan at the workshop to display the new automatic location software (QuakeMigrate) and release it on github, along with test datasets. Many of the results, hypocentre locations and videos shown here are available from the following papers and their Supplementary Information:

White, R. S., Drew, J., Martens, H. R., Key, A. J., Soosalu, H. & Jakobsdóttir, S. S. (2011). Dynamics of dyke intrusion in the mid-crust of Iceland, *Earth and Planetary Science Letters,* **304**, 300–312, doi: 10.1016/j.epsl.2011.02.038Hudson, T. S., White, R. S., Greenfield, T., Ágústsdóttir, T., Brisbourne, A. & Green, R. G. (2017). Deep crustal melt plumbing of Bárðarbunga volcano, Iceland, *Geophysical Research Letters*, **44**, 8785–8794, doi: 10.1002/2017GL074749

Woods, J., Donaldson, C., White, R. S., Brandsdóttir, B., Caudron, C., Hudson, T. S. & Ágústsdóttir, T. (2018). Long-period seismicity reveals magma pathways above a propagating dyke during the 2014–15 Bárðarbunga rifting episode, Iceland, *Earth and Planetary Science Letters*, **490**, 216–219, doi: 10.1016/j.epsl.2018.03.020

White, R. S., Edmonds, M., Maclennan, J., Greenfield, T. & Ágústsdóttir, T. (2018). Melt movement through the Icelandic crust, *Proceedings of the Royal Society, Series A,* **377***,* 20180010, doi: 10.1098/rsta.2018.0010

Woods, J., Winder, T., White, R. S. & Brandsdóttir, B. (2019). Evolution of a lateral dike intrusion revealed by relatively relocated dike-induced earthquakes: the 2014−15 Bárðarbunga-Holuhraun rifting event, Iceland, *Earth and Planetary Science Letters,* **506,** 53−63, doi:10.1016/j.epsl.2018.10.032

Ágústsdóttir, T., Winder, T., Woods, J., White, R. S., Greenfield, T. & Brandsdóttir, B. (2019). Caldera collapse and dike-induced faulting recorded by intense microseismicity during the 2014-15 Bárðarbunga-Holuhraun rifting event, central Iceland, *Journal of Geophysical Research, Solid Earth,* **124***,* JGRB53519, doi: 10.1029/2018JB016010

On the origin of the 2016-2019 seismic swarms in Tenerife

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The island of Tenerife is a complex volcanic system with the coexistence of monogenetic volcanic fields and a stratovolcano with a shallow magmatic chamber. Since 2016, the Instituto Geografico Nacional (IGN) has improved the seismic network of Tenerife from 6 to 20 stations and now, we are able to locate 80% of the seismicity detected. In the last years a rate of 1000-1200 earthquakes per year are located bellow the island and surroundings including not only volcano-tectonic earthquakes but also hybrids events. Moreover, this background seismicity has been occasionally shocked by intense swarms of very low magnitude earthquakes in particular regions of the volcanic edifice.

There are two main seismogenic regions in the island. The first one is situated 10-15 km below the western part of Las Cañadas Caldera produced two intense swarms of hybrid events with hundreds of earthquakes in few hours, on 2nd October 2016 and on 14th June 2019. In between these two episodes, around 1000 earthquakes were located in this zone 50% of them being hybrid events. The second seismogenic zone is situated 6-9 km below Vilaflor village, 9 km southern from the first region. Activity in this area started on 2017 and the events show VT characteristics with a clear stress pattern derived from first motion polarities. More than 550 earthquakes have been located with a maximum magnitude of 2.6. The relative relocation of the series shows an evolution to the South and to lower depths and we found a b-value of the Gutenberg Richter higher than 1.5 which may indicate the presence of fluids.

The coexistence of these recurrent regions of seismicity with hybrid activity in Las Cañadas Caldera can be interpreted as the presence of a magma injection which is accumulating in the volcanic system just below the volcanic edifice and pressurizing the surroundings. This pressure would have triggered the recurrent VT swarms in Vilaflor area.

Seismic rate evolution in Tenerife during the period 1997-2016

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The magnitude of completeness of the Instituto Geografico Nacional (IGN) seismic catalog in Tenerife has considerably reduced in the last 5 years due to the network densification. The seismic rate since 2017 is about 1000 earthquakes per year (Mc=0.6), however, very little is known about Tenerife's low magnitude seismicity in the previous years.

We have estimated the seismic rate in the island since 1997 by a manual review of CCAN seismic waveform. This permanent station is placed in the center of the island in Las Cañadas Caldera. The high SNR of the site and the available continuous digital data allowed us to pick P and S phases in most of the earthquakes, estimating the epicentral distances and magnitudes of the corresponding events.

We have compared the results with periods of temporal networks deployed in the area (2007-2008 and 2010) and also checked the method with the permanent seismic network of the IGN nowadays in Tenerife which includes 20 stations and a location capability of more than the 80% of detected earthquakes. The results obtained in this work show a background seismicity of 1000-1200 earthquakes per year with most of the events of magnitudes smaller than 1. Most of the earthquakes are Volcano-Tectonic events, however we found some Low Frequency and Hybrid seismicity, both of them with dominant frequency of 2.1Hz and similar epicentral distance to CCAN station.

Lithospheric Scattering and Structure from Teleseismic P Waveforms

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Subsurface heterogeneities with scale lengths on the order of the seismic wavelength scatter the seismic wavefield, transferring energy from the main arrival to the coda and generating traveltime and amplitude fluctuations. Understanding the effect of these heterogeneities on the wavefield is important for the characterization of natural and man-made seismic sources and to improve our knowledge of Earth structure.

Here, we combine an energy flux model with the analysis of the incoherent coda wavefield to a dataset of over 350 teleseismic events recorded at the Pilbara, Alice Springs and Warramunga seismometer arrays in Australia. This combination allows us to determine heterogeneity (correlation length, RMS velocity fluctuations of the heterogeneities and thickness of the scattering layer) that quantify the scale and magnitude of the lithospheric heterogeneities present beneath the arrays. Our new results show similar heterogeneity structure for all three arrays, despite the fact that they are located on different geological provinces with different crustal thickness and tectonic histories.

These results are the first step in the development of a technique aiming to remove the effect of the small-scale, near receiver structure from recorded wavefields, thus enabling us to improve our source characterization and more clearly image the Earth's interior.

Deception Island: a challenging test database for automatic recognition systems

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Deception Island is an active volcano located in the Bransfield Strait, Antarctica, between the South Shetland Islands and the Antarctic Peninsula. It displays different manifestations of volcanism such as young volcanic deposits, recent eruptions (latest in 1967-1970), fumaroles and gas emissions, geothermal areas, and a moderate but highly variable level of seismic activity. Deception Island is the site of two scientific bases (Spanish and Argentinian), and it is among the Antarctic destinations most visited by tourists, which emphasizes the need for volcano surveillance. We have monitored Deception Island using a seismic network and seismic arrays for over 20 years. The automated detection and classification of seismic signals constitutes a powerful tool that simplifies the work of the seismologists in charge of volcano monitoring. However, at Deception Island volcano it constitutes a challenging exercise, for several reasons. First, there are many different processes that can produce seismic signals: regional tectonic earthquakes related to the Bransfield rift extension; local volcano-tectonic earthquakes produced by brittle fractures within the volcanic edifice; long-period events and tremor, generally associated to the shallow hydrothermal system; landslides and other mass movements; icequakes produced by the dynamics of the glaciers partially covering the island; iceberg movements within or around the island; signals induced by ocean-land interactions; etc. Second, these signals are mostly local, and recorded just in a few nearby stations. Moreover, many of them are shallow and display complex waveforms. These limitations prevent the application of precise analyses and leave us with unanswered basic questions such as the source location or mechanism, the separation between source and path effects, etc. Finally, the medium is heterogeneous and highly attenuative, making waveforms evolve along the propagation path, and changing the signal characteristics from one recording site to the next, even at short distances. All these constraints may affect the way in which signal recognition systems deal with the information contained in the seismograms, and more experiments are needed to ensure a high rate of success. With this in mind, we present a seismic dataset recorded by a permanent seismic station (DCP), operating at Deception Island volcano between 2008 and 2015. The data are homogeneous and have been revised by a single operator, providing a database of event types, start times, durations, dominant frequencies, etc. We share these data with all people interested, and encourage their use and the development of specific tools fine-tuned for the detection and classification of seismic signals at Deception Island volcano.

Magma pathway opening before the 2018 eruption at Sierra Negra volcano, Galapagos, revealed by tremor location and local earthquake tomography

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Located 1000 km west of continental Ecuador, Sierra Negra is a shield volcano with a large summit caldera and is one of the most active volcanoes in the Galapagos archipelago. The 2018 eruption started on 26th June and lasted about two months. At about 17:00 UTC on the eruption day, an intense seismic swarm and relatively weak tremor were recorded on a network consisting of 11 broadband seismometers. Three hours later, tremor amplitudes increased and lava flows from multiple fissures were observed on the north and northwestern flanks of the volcano, marking the start of the eruption. To understand subsurface processes before the eruption, we isolate and locate pre-eruptive tremor signals every 20 seconds beginning three hours before the eruption using a seismic amplitude ratio method. Results show that the onset of the tremor locates to the west of the caldera. The lateral location is stable while the depth gradually reduces over the next two hours. Around 19:30 UTC, the tremor reaches the surface, at a location which matches one of the observed eruptive fissures on the west flank. A few minutes later, the tremor location starts moving towards the north of the caldera. At about 19:55 UTC, the source location becomes stationary and coincides with the location of another eruptive fissure. The location is consistent with a low-velocity body imaged by a local-earthquake body-wave tomography. The spatio-temporal evolution of the tremor may reveal the pathway of opening of a dyke and has the potential to be used as a short-term forecast of the eruption site.

Statistical analysis of volcanic earthquakes at Villarrica Volcano (Chile)
Johanna Lehr

Interevent times and amplitude distributions of volcano-tectonic events and explosions are compared using 10 days of data recorded by a temporary network at Villarrica Volcano in March 2012.
Interevent times can be used to derive a stochastic model of the seismic activity without the need to explain the underlying physical process. Such models also allow the comparison of processes on different scales or locations.
The events were identified using STALTA triggers with different window lengths and a machine learning approach based on Hidden Markov Models. The frequency distributions depend significantly on the chosen detection method and its parameters.
In contrast to e.g. Stromboli, explosions at Villarrica show a periodicity in their occurrence which indicates a non-Poissonian process. The distribution of interevent times of volcano-tectonic events resembles that of normal tectonic earthquakes.

Pre-Eruptive Time-Lapse Velocity Changes Prior to the 2018 Eruption of Sierra Negra Volcano, Galapagos Island Observed with Seismic Coda Wave Interferometry on Seismic Multiplets.

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Abstract

Changes in external stress state and fluid content alter the mechanical properties of an elastic medium. Hence, variations in seismic wave velocity and (crack induced) seismic anisotropy can be used as proxies for changes in stress and possible fluid ingression.
In this study, we use the Coda Wave Interferometry (CWI) technique to measure time-lapse changes in seismic velocity prior to the 2018 eruption of Sierra Negra Volcano. Sierra Negra volcano is one of the most active volcanoes on the Galapagos Islands, about 1000 km west of continental Ecuador. On 26th June 2018 at 09:15 UTC, a magnitude 5.3 earthquake occurred near the south-west caldera rim and an intense seismic swarm started around 17:15 UTC. Seismic tremor dominated at about 19:45 UTC, which marked the onset of the eruption. Both prior to and during the eruption period several families of repeating earthquakes have been identified in a very large seismicity sequence. The events are identified using the Fingerprint and Similarity Thresholding (FAST) method (Yoon et al. 2015). High detection sensitivity, computational efficiency, and scalability to massive data volumes are big advantages of the FAST method over competing approaches.
Our aim is to understand whether changes in seismic velocity measured with CWI method provide new insight into the physical processes related to the eruption and if they match the same information seen in time-lapse velocity changes estimated using seismic noise.

Main characteristics of Canary Islands seismicity. A seismic catalogue revision for 1341-2000

Julio Mezcua and Juan Rueda

Instituto Geográfico Nacional

An attenuation study of both tectonic and volcanic events has been carried out from the revised intensity of shocks different behavior. In this way we can extrapolate the intensity values from different locations to the assigned epicenter obtaining the corresponding maximum intensity. Those values are converted to Moment Magnitude from the relationship obtained for those variables considered for the present seismicity.

In relation with the location, we were considering also the historical seismicity and the instrumental one. In the first case, the epicenter is obtained through the barycenter of points with greater intensity while for the instrumental shocks we use the HYPOSAT code with the advantages of use of the maximum information available such as arrival times of first and later phases with back azimuths, preliminary independent origin time and the standards deviations of the data observed with the corresponding weights to the input parameters.

An analysis of the obtained catalogue shows a loss of small earthquakes detection occurred in the 1996-2000 period because a completely new location process was in operation and perhaps a new magnitude formula applied. This discrepancy is pointed out by the analysis of the magnitude signature for the 1990-1996 and 1996-2000 time intervals.

Crustal Flow in Iceland from Radial Anisotropy

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The formation of crust at mid-ocean spreading ridges is one of the fundamental processes of plate tectonics. Iceland, which straddles the mid-Atlantic ridge and is uplifted by a convective plume in the underlying mantle, has an active mature spreading ridge system exposed above sea level. It therefore represents a unique opportunity to study a spreading ridge using land-based methods. Furthermore, the crust in Iceland has an abnormal structure with a varying thickness (up to 40 km in central Iceland) and a noticeable mid-crustal discontinuity at ~20km depth. While this anomalous structure is usually attributed to the ridge-plume interaction, its formation process and varying spatial distribution are highly debated. In this work, we explore the velocity structure and radial anisotropy of the crust and upper mantle in Iceland using phase velocity dispersion curves measurements from ambient noise for both Love and Rayleigh waves. We find that while both Love and Rayleigh phase velocities are lower along the rift zones, the SH and SV structures differ significantly with depth. In the uppermost crust we find mostly negative radial anisotropy (SV > SH), which we attribute to the existence of vertically oriented cracks and dykes which are formed due to the extensional regime of plate spreading. In the lower crust however, we mostly observe positive radial anisotropy (SV < SH). Furthermore, the radial anisotropy in the lower crust displays a weak azimuthal dependence with lower velocities parallel to the plate spreading direction. These observations suggest that the lower crust is built by layers of sills containing anisotropic minerals such as olivine and that it flows horizontally with a component parallel to the spreading direction. Additionally, we discuss our results from the imaging using similar methods of the Askja caldera. While it is known that the quality of surface wave tomography degrades in lower frequencies which are essential for imaging volcanoes, we show promising results in retrieving the local velocity model and anisotropy. The local velocity model is similar to the one resulting from local earthquake tomography. This suggests the ambient noise can partly replace local earthquake tomography where seismicity is too low.

Witches presence during the eruption of El Hierro 2011-2013

R. Ortiz, J.M. Marrero

The temporal distribution of seismicity during the El Hierro 2011-2013 eruption shows that the magnitudes greater than M3 are concentrated in the vicinity of the full Moon. Smaller events have an isotropic distribution. This phenomenon has been previously described in several eruptions and also in some cases of tectonic seismicity. Consequently, it should not surprise us that witches have traditionally associated with the full Moon.

Advances in volcanic tremor as a pre-eruptive monitoring tool

European Seismological Commission – Working Group on seismic phenomena associated with volcanic activity, 2019 annual meeting: Automatic detection, identification and classification of volcanic signals

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Abstract

The EUROVOLC project aims to promote an integrated and harmonised European volcanological community, and one of its main themes focuses on understanding Sub-surface processes. Early identification of magma moving towards the surface is very important for mitigation of volcanic hazards, and joint research activities within the project aim to develop volcano pre-eruptive detection schemes. Volcanic tremor is a sustained seismic signal associated with eruptions and is often linked to movement of magmatic fluids in the subsurface. However, it can occur pre-, syn- and post-eruption and signals with similar spectral content can be generated by several other processes (e.g. flooding, rockfalls). Hence one of the best ways of distinguishing between the processes underlying tremor generation is by its spatial location. As tremor cannot be located using classical seismological methods, its source must be determined using alternatives such as amplitude-based techniques or seismic array analysis.

This work presents the development of a software tool that uses seismic array data and array processing techniques to detect, quantify and locate volcanic tremor signals. A python-based tool is in development that utilizes existing routines from the open-source *obspy* framework to carry out analysis of seismic array data in real-time. The tool performs f-k (frequency-wavenumber) analysis using beamforming to calculate the back azimuth and slowness in overlapping time windows, which can be used to detect and track the location of volcanic tremor sources.

Graphical and/or web-based interfaces are in development to allow adjustment of highly configurable input parameters. These include options for configuring the data source, pre-processing, timing and update options as well as the parameters for the seismic array analysis which must be carefully selected and tuned for the specified array. The tool is currently being tested using the FDSN client to fetch data from the IRIS datacenter, using example real-time data from the SPITS seismic array in Spitsbergen, Svalbard. Use of a seedlink server as a data source has also been successfully implemented, with other data sources to be considered and/or developed depending on need. Once configured, the tool fetches chunks of waveform data in real time and updates its output accordingly. On each update the tool returns plots of the array processing results (slowness and back azimuth values) as well plots of the seismic waveform, envelope and spectrogram. A 'replay' mode using existing (non real-time) data is also being tested. Further development and documentation of this tool are in progress and additional testing using other data sources and volcanic tremor examples will be undertaken to improve its usability for real-time volcano monitoring in an observatory setting.

Eruption Source Parameter Estimation from Infrasound from Local to Regional

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In characterizing an eruption, one of the main parameters is the plume height. However, while there are multiple ways to measure the height of the plume, with which almost all of them can be hampered by adverse weather conditions in the case of ground based visual measurements, cloud cover and time of day in the case of space based measurements, and scarcity of other technologies like LiDAR and RADAR. Infrasound offers an alternative to these methods, as well as the ability to assess the size of an eruption from various distances. Infrasound source parameter calculation has been established at the local range; but with the addition of atmospheric modelling, it can also be carried out at a regional to global range. Using examples from local (< 20km), regional (~ 400 km), and global-range (>1,000 km) infrasound, this project examines the methods available for near real-time estimation of plume height for use in ash dispersion modelling, and the new methods that are currently in development.

Evaluate the influence of Instrumental bias on Self-Organising Maps in recognising precursory signals

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In the last 10 years, seismic swarms linked to phreatic and magmatic eruptions have been recorded using multiple types of instruments. In some cases clear changes were observed in the monitoring data, while in other cases no signs were identified. Whether the discrepancy was due to the type of activity, the type of instrument or to the type of processing remains to be tested. In our study, we start to shed light on those questions by investigating the design of the monitoring system and the type of analysis that is carried out. We have initiated the first step of this three-year project earlier this year, starting with a single analysis on events with multiple seismic sensors located at different distances from the vent. By standardising the type of analysis performed on continuous monitoring data retrieved from respective sensors, we looked for consistent patterns that allow us to quantitatively evaluate the capability of the analysis in detecting the event. The type of analysis that we began with is Self-Organising Maps (SOM), an artificial neural network that implements machine-learning techniques to cluster seismic data based on frequency content. This processing technique allow us to better visualise the subtle changes in the signal characteristics, which is later quantified using Kolmogorov-Smirnov test (KS test). In the events we examined, we found that seismic data from some sensors presented clearer precursory signals (change in frequency content clusters) than the others. It could be associated with their strategic locations such as the distance from the vent; or the type of instrument used, given it is short-period or broadband sensor. In order to perform a quantitative evaluation on the influence of instrumental bias, more events will be considered and examined. The scope of this work could also be extended to other analytical techniques for further investigation on their bias.

Seismic hazard associated with volcanic seismicity: high resolution mapping of the local seismic response at San Cristóbal de La Laguna (Tenerife)

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There is evidence that the vast majority of deaths due to the historical eruptions in Tenerife are directly linked to earthquakes associated to volcanic activity. The geological complexity of the island strongly affects seismic wave propagation at different scales. In particular, at local scale, the presence of low velocity layers is responsible for seismic wave amplification. This effect has been clearly evidenced during the recent 18th Jan. 2019 M=4.4 earthquake, whose hypocenter was located between the islands of Tenerife and Gran Canaria. Therefore, the realization of detailed local seismic response map is required in order to mitigate the existing seismic hazard in the urban areas of Tenerife. Accordingly, we aim at realizing a detailed map of seismic amplification for the town San Cristobal de La Laguna which, lying on a layer of lacustrine deposits, is likely to suffer for amplification of the seismic shaking duration and intensity during future earthquakes. Furthermore, this town has a peculiar architectural heritage which made it to be declared in 1999 a World Heritage Site by UNESCO. This building style makes this heritage especially vulnerable to strong seismic shaking.

For this purpose, a temporal broadband seismic network will be deployed during summer of 2019, obtaining around 300 measures from the urban area of the city. These measures will be picked up in different groups using mini arrays of 4 stations in order to perform the H/V spectral ratio and at the same time to obtain surface wave dispersion curves through the cross-correlation of seismic noise. Finally, a join inversion of both HV and dispersion curve data will be carried out in order to obtain the S-wave velocity profiles for each point. This subsurface structure information will be used to determine all the necessary parameters to assess the local seismic response at each measurement point.

Improving earthquake location using Ambient Noise Tomography: The case of Cumbre Vieja volcano (La Palma, Canary Island)

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Due to the great geological complexity of islands it is necessary to use high resolution 3D velocity models to improve the determination of local earthquake hypocenters. Actually 1D velocity models does not allow a correct determination of the hypocenters in these areas, being unable to correctly take into account strong horizontal velocity contrasts. The most commonly used method to obtain 3D velocity models in volcanic areas is local earthquake tomography. However, in quiescent volcanoes, missing a background seismicity, this technique is clearly useless. The objective of this work is andemonstrate that Ambient Noise Tomography (ANT) is a convenient technique to obtain detailed 3D velocity models in these areas.

We propose a novel non-linear approach to ANT, specifically devoted to imaging areas characterized by strong lateral velocity contrasts. After performing standard data processing to retrieve Green's functions from cross correlations of ambient noise and picking dispersion curves using the FTAN (Frequency Time Analysis) technique, we performed an inversion of the data to retrieve group velocity maps. We developed an innovative technique based in a non-linear inversion approach for obtaining the maps. The method is based on a progressive increase in the resolution, exploiting the multiscale property of discrete wavelet decomposition and in an advanced forward modeling based on shortest path algorithm.

We present some preliminary results on Cumbre Vieja volcano emphasizing their relevance for in enhancing the quality of local seismic earthquake location. For this purpose, we deployed a temporary seismic network in two phases during the summer of 2018. During the first phase that lasted one month, 12 broadband seismic stations were installed in the northern part of Cumbre Vieja. In the second phase, the 12 seismic stations were moved to the central part of the volcanic complex. Five permanent broadband seismic stations of the Red Sísmica Canaria, operated by INVOLCAN for volcanic monitoring, are also used for this study. We apply this method to the seismic swarms recorded beneath the island on Oct. 2017 and Feb. 2018.

The causes of destructive earthquakes in the active volcanic island of Ischia (Southern Italy): volcanic or non-volcanic seismicity?

Stefano Carlino

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The M=4 earthquake which occurred in 2017 on the island of Ischia (located in the Gulf of Naples) and produced heavy damages of its northern sector, focused the attention on the causes generating the seismicity of this active volcanic island. This earthquake occurred after about 130 years of almost seismic silence, although the island was hit by at least three destructive events, the last of which took place in 1883 and produced more than 2300 deaths and the total destruction of the town of Casamicciola. The 2017 earthquake is the first damaging event recorded by a seismic network in the island and this put new important information in the study of the seismicity of Ischia. In this work, it is showed the possible causes which contribute to generate the earthquakes of the island, the main of which is possibly not directly correlated to magmatic processes, and is instead associated to the inversion of a resurgent process (subsidence) which has been active at least since about 5ky ago.

Problems in seismological monitoring of volcanic islands: unbalanced networks

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The seismic monitoring of volcanic islands poses specific issues because of the network geometry which, often, does not allow high quality locations of the off-shore seismicity. In the case of seismic networks distributed on archipelagos, a further problem arises from the highly uneven distribution of the seismic stations, which can bias the hypocenter locations. This can affect both linear and non-linear earthquake location techniques.

As pointed out by Bondar and McLaughlin (2009) the problem arises when the correlation of the arrival time errors among neighboring seismic stations are disregarded. To solve this issue, they proposed an approach based on singular value decomposition applying it to linearized earthquake location at global scale. We extended this approach to probabilistic non-linear earthquake location using different definitions of the likelihood function. We applied this method to both synthetic data in realistic conditions as well as to actual data recorded by Red Sísmica Canaria, operated since 2016 by INVOLCAN, for the location of earthquake in the surroundings of the island of Tenerife (Canary Islands).

Pitfalls and ambiguities in the inversion of volcanic infrasound data: searching for an optimal network configuration

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Recent studies pointed out the importance of taking into account of the multipolar components of sources of infrasonic signals associated to volcanic explosive activity. This leads to more complex approaches when inverting the data and to possible ambiguities in the results. In this work we performed a systematic analysis on synthetic datasets, taking into account various elementary source models and different network configurations. Synthetics have been computed using a 3D time-domain finite-difference approach. With the purpose of improving the solution quality we propose a non-linear approach for the constrained inversion of the data which improves the stability of the estimated source models. For each combination we computed synthetic signals and performed both unconstrained and constrained inversions. For networks configurations with 3 or more sensors we also performed the location of the source.

We quantify the correctness of each result by considering the RMS on both the data and the source-time function, the difference between the synthetic and estimated source models and the difference in source location (when possible). Our results demonstrate that the inversion of infrasonic data is highly dependent on the network configuration and the selected source model. In many cases the best fit solution is far from being the correct one. Based on such results, an example of optimal network configuration has been proposed for Fogo volcano (Cabo Verde), in order to correctly retrieve source parameters from infrasound data recorded during a possible future eruption.

Bringing volcano seismology at school: The Red Sísmica Canaria Escolar (RESECAN) project

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Throughout the planet there are thousands of seismic sensors monitoring seismic activity, managed by different national and international institutions, which can detect and locate, daily, most earthquakes with magnitude greater than 5. At regional and local levels there are denser networks whose purpose is seismic monitoring of a specific region: a fault, an active volcano, etc. In the last three decades, scientific and technological advances have allowed the development of broadband sensors at affordable prices (10-20 k €) for the most of the institutions that operate a seismic network. In parallel, advances in the field of semiconductors through Micro-Electromechanical Systems (MEMS) technology have allowed the development of accelerometers of very reduced dimensions and costs. The seismic data obtained by commercial sensor, type MEMS, can be sampled, synchronized, stored and transmitted through devices such as: RaspberryPi or Arduino. This allows the development of a complete seismic station of very small size and cost with respect to the traditional ones, although the sensitivity and quality of its seismograms are not comparable.

At the international level, there are already different projects, whose objective is the realization, diffusion and management of seismic networks constituted by low cost stations with different purposes. Intituto Volcanológico de Canarias (INVOLCAN) is currently developing the **Red Sísmica Escolar Canaria** (**RESECAN**), to be, at the same time, a tool for: supporting for the didactics of geosciences, promoting of the scientific vocation and strengthening of the resilience of the Canary Islands communities by improving the awareness about the volcanism of Canaries and the associated hazards. The project aims at distributing low-cost stations in various educational institutions of Canary Islands, complementing with didactic material on the subjects of seismology and volcanology. Each school will be able to access the data of its own station as well as of other centers, being able to locate some of the recorded earthquakes. In addition, the RESECAN would be an instrument of intrinsic scientific interest, being able to contribute effectively to the volcanic monitoring of the Canary Islands, strengthening its resilience during future volcanic emergencies.

4D imaging of the seismic energy release at El Hierro volcano

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The estimation of the spatial and temporal variations of the two parameters of the Gutenberg-Richter law (a and b) is of great importance in different seismological applications. However, their estimate is strongly dependent upon the selected spatial and/or temporal scale due to the heterogeneous distribution of the seismicity. This is especially relevant in volcanoes and geothermal areas where dense clusters of earthquakes often overlap the background seismicity.

For this reason, we propose a novel multiscale approach allowing a consistent estimation of the a and b values regardless of the considered spatial and/or temporal scales. Our method, named MUST-B (Multiscale Spatial and Temporal estimation of the B-value), basically consists in computing estimates of the values at multiple temporal and spatial scales, extracting for a give spatio-temporal point a statistical estimator of the value, as well as an indication of the characteristic spatio-temporal scale. This approach includes also a consistent estimation of the completeness magnitude (Mc) and of the uncertainties over a, b and Mc, as well as, estimates of the seismic energy release rates.

We applied this method to the seismic dataset of El Hierro submarine eruption, started on October 2011 and linked with a previous seismic unrest episode that initiated on July 2011. The seismicity showed a very complex spatial distribution, which also changed over time, suffering a migration from the north of the island to the south. Traditional analysis methods commonly used in statistical seismology fail because of the temporal and spatial superposition of different dynamics, characterized by different a and b values. Results show that the high resolution spatio-temporal 4D mapping is of great importance to understand the distribution of the seismic energy release in volcanic islands, which is possibly correlated to a highly variable dynamics of the magmatic system.

Using GIS as a tool for planning deployment and improvement of seismic networks

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In this work we aim at demonstrating the use of Geographic Information Systems (GIS) to analyze physical and human elements of the territory to aid the design of a seismic network. In particular GIS tools allow determining spatial distribution of sites less affected by seismic noise and therefore most suitable for the installation of seismic stations.

In a theoretical framework, cartography alone can be used in order to reject sites where the installation of seismic stations would be not possible. Among the physical factors which can lead to dismiss an area as a possible installation site are: the presence of slopes, ravines or dense vegetation. Meanwhile among the human factors are: roads, villages and towns, wind turbines or high-voltage lines.

This thematic cartography is the starting point to merge the different data using different GIS tools. This allows preliminary mapping of suitable areas for installation. Subsequently, we establish some quantitative criteria to determine the greater or lesser suitability of that space for the installation of a seismic station. These quantities are calculated for each point of a grid and the values corresponding to different criteria are summed up.

From the anthropic point of view, the quantitative criteria must consider the distance from roads as well as their traffic density, for example. From the physical point of view, other criteria which need to be evaluated are the slope and the vegetation density between others. GIS allow taking into account also logistic factors related to the ease of access to a site, considering for instance the minimum distance from a road practicable by car.

Due to the unique conditions of its territory the first application of this technique has been implemented on the island of Lanzarote.

Earthquakes on Volcanoes. Scenarios on Mt Etna

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The volcanic region of Mt. Etna, with an area over ca. 1200 km^2, is the theatre of intense volcanic activity along with strong ground shaking, caused by local volcano-tectonic earthquakes and large, less frequent regional events. The area is located within a wider region characterized by high crustal deformation rates and seismic energy release, making it one of the highest seismic potential areas in Italy. The peculiar characteristics of seismicity poses particular problems for the identification of seismic scenarios and the assessment of seismic hazard. In areas with prevailing tectonic earthquakes general GMPE relations can be set up for the estimation of strong ground motion occurring with a certain probability. Such an approach fails for volcanic areas like Mt Etna.

Seismicity on Mt. Etna is rather peculiar since fairly small but shallow shocks produce severe destructions on a local scale. These earthquakes must treated apart from regional earthquakes, which have reached magnitudes of 7 or even higher. The shallow earthquakes are rather a consequence of the dynamics related to the volcano. Ground deformation rates measured along the flanks of the volcano can reach up to 10 cm p.a, whereas it is reported in the range of mm per year in the surrounding areas.

Even though magnitudes are rather small (up to $ML \approx 5$), the shallow earthquakes produce heavy damage even to reinforced concrete structures in the epicentral area, often along narrow but elongated zones (typically around 5 km in length). The macroseismic intensities reach a degree of up to VIII on the European Macroseismic Scale. In general, the entire eastern flank has been affected in the past by those seismic events. In particular in the eastern area of the volcano, this type of seismic activity determines a considerable level of seismic risk. The risk is exacerbated by the short recurrence time (ca. 24 years) of the main damaging earthquakes.

Besides the peculiarities of ground motion attenuation, arising from the shallow depth of these events, their waveforms and frequency content differs significantly from those recorded in tectonic environments. Those differences also noticed when comparing shallow and deeper earthquakes recorded within the area covered by the volcano. The signals recorded from shallow events are richer in low frequencies, leading to relevant differences in GMPE relations. The reasons for the richer low frequency content of shallow earthquakes can be searched in part in wave propagation effects, in part by differences in seismic scaling laws. From geological information we must consider that foci of shallow earthquakes fall into sedimentary layers, whose elastic moduli are considerably lower than those encountered in a crystalline basement. The specific geological conditions in the area of Mt Etna are an important aspect for the creation of synthetic scenarios of ground motion.

Imaging the deep structure of Tenerife by Seismic Receiver Functions

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The receiver function analysis (RF) is a commonly used and well-established method to investigate the sub-surface as the crustal and upper mantle structures based on three-component seismograms of teleseismic events. The three components of the seismic recordings are rotated into vertical, radial and tangential components respect to know the backazimuth of each event.

The central point of RF analysis consists in removing the source, ray-path and instrument signatures by the deconvolving of the vertical component from the horizontal components. For this purpose we used the iterative deconvolution technique which is less sensitive to the background noise. The receiver function contains the unique signature of sharp seismic discontinuities and information about P-wave and S-wave velocity beneath the seismic station. In particular using the direct P-wave as a known reference arrival time, and the relative arrival times of P-to-S (Ps) conversions as well as PpPs, PsPs and PsSs reflections we were able to constraint the main crustal structures. We applied the H-k and H-k-c stacking techniques to infer about the depth of the Moho, its dipping and the seismic velocities of the crust. Furthermore, we applied an advanced 3D forward modelling based on ray tracing to further constrain the 3D geometry of the crust. We present a first tridimensional map of the crust beneath Tenerife, evidencing its relationship with known geological features and the distribution of volcanic seismicity beneath the island.

Quantitative analysis of volcanic seismic monitoring networks: the performance of the Red Sísmica Canaria (RSC)

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One of the most important aim of volcanic seismic monitoring network is detection, location and characterization of the microseismicity associated to the dynamics of the magmatic and hydrothermal systems. Because of the low event magnitudes, high seismic attenuation and possibly the presence of a strong background noise, determining the performances of a volcanic seismic monitoring network is a crucial task to ensure the reliability of the performed analysis.

The Canarian Seismic Network (Red Sísmica Canaria) began its full operativity in November 2016 and currently consists of 22 seismic stations deployed on the islands of Tenerife, Gran Canaria, La Palma and El Hierro, with both scientific research and volcano monitoring purposes and acquired through the MAKAVOL Project (MAC/3/C161) and VOLRISKMAC (MAC/3.5b/124). It has been officially assigned the code C7 by FDSN. Up to now stations host Trillium Compact sensors and Centaur dataloggers, both produced by Nanometrics Inc. Data are sent in real-time through UMTS connection to an acquisition center located at ITER where they are processed, stored and managed through a SeiscomPro installation. The noise levels are also continuously checked through the use of PQLX software and are generally within the reference Peterson's curves, especially at frequencies higher than 1 Hz, which are of interest for the monitoring local seismicity. Realtime seismograms and hypocenters are shown at the INVOLCAN monitoring center. Most of the current seismicity is located between the islands of Tenerife and Gran Canaria, in correspondence of a regional transcurrent fault system. The remaining seismicity is located mostly in the upper crust, beneath the active volcanic areas.

We evaluated the performances of the network both in terms of theoretical detection threshold and location uncertainty. Results shows that the network of RSC (Red Sísmica Canaria) is currently capable of detecting and locating low magnitude earthquakes (M<1) beneath Tenerife island with uncertainties ranging from few hundred meters to few kilometers. We quantitatively compare the results of theoretical modeling with the observed completeness magnitude.

Seismicity associated to the anti-correlated ground deformation between Mauna Loa and Kilauea

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The ground deformation pattern of two neighbouring volcanoes of Hawaii was studied using different geophysical data. Specifically we were able to catch an interesting anticorrelated behavior of ground deformation in 2003-2012 by ENVISAT satellite, using 3 tracks of ascending and descending orbits with different look angles. To analyze DInSAR data we applied the Independent Component Analysis (ICA) to decompose the time-varying ground deformation pattern of both volcanoes. The results revealed a marked anti-correlated behavior of the ground deformation of the summit areas of Mauna Loa and Kilauea. The GPS data analysis support our claim about the opposite deformation between both volcanoes by the analysis of the areal strain between stations in the surroundings of two main craters.

We compared these findings with available seismic data to verify if there exist a relationship between the location, depth and magnitudes of the earthquakes with areas of analyzed deformation. The principal aim of this work is to find the evidence if there exist the relation between the location of earthquakes and the ground deformation pattern components. Actually we found that seismicity patterns reflect changes in the ground deformation and helps clarifying the dynamics of the Mauna Loa-Kilauea volcanic system and their mutual relationship.

Enhancing the detection of volcano-tectonic microearthquakes through adaptive spectral subtraction

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The detection of microearthquakes is an important task in various seismological applications as volcano seismology, induced seismicity, and mining safety. Together with improvements in the seismic network technologies (e.g. network densification, borehole installations) it can benefit from techniques of digital signals processing, aimed at enhancing signals related to microearthquakes from the background noise by improving the signal/noise ratio. In this work we propose a novel technique based on a non-linear filtering procedure, which has shown to be more efficient, compared to traditional filtering, in enhancing signals related to small microerthquakes embedded in continuous recordings.

The implemented technique consists in a preliminary band-pass filtering of the signal followed by an adaptive spectral subtraction. The spectral subtraction technique is a non-linear filtering which allows taking into account the actual noise spectrum shape. It allows achieving a good filtering even in cases where the signal and noise spectrum overlaps. In order to take into account of the temporal variation in the background noise spectrum, we designed an adaptive technique. We first divide the incoming signals into short temporal windows. Each window is classified as "noise only" or "meaningful signal" (which can be either a microearthquake or any other relevant transient signal) using different features as the signal energy and the zero-crossing rate. Windows classified as "noise only" are continuously accumulated in a dynamic buffer which allows the average noise spectrum to be estimated and updated in an adaptive manner. This technique can be applied on subsequent stages to further improve the signal/noise ratio.

We have developed an application in Python implementing the aforementioned technique for the automatic detection of the microearthquakes. In order to check the efficiency of the results, we compared the results of an STA/LTA based automatic detection on the initial band-pass filtered signal and on the spectral subtracted signals after different stages of filtering. A notable improvement of the quality of the detection process is observed when repeated spectral subtraction stages are applied.

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

Advanced methods on signal recognition applied to seismo-volcanic events from Planchon Peteroa Volcanic Complex (PPVC): Comparison between Deep Neural Network and Hidden Markov Models.

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Key words: *Planchon Peteroa Volcanic Complex, volcano seismic, automatic detection, feature selection*

Advanced techniques on recognition and classification of seismo-volcanic events are considered a transcendental task, not only for their importance in real time monitoring but also for modeling the dynamic of the volcano under study. It is well known that in real time monitoring the amount of data to be analized can turn into an overwhelming job to be manually done by an operator, therefore the use of automatic detection and classification techniques are suitable to overcome such a challenge.

On the other hand, a detailed modelling of the dynamic of a Volcano requires the use of a very complete catalogue with labeled events. There are various algorithms for automatic detection and classification and chosing the proper one implies analyzing pros and cons of each of them.

The aim of this work is to compared two of such algorithms for the case of isolated events. such as Deep Neural Network (DNN) vs. Hidden Markov Models (HMM). A suitable event parametrization can improve the perfomance of these algorithms, in this sense we will explore the feature space in order to select the most significant ones and make a comparative analysis for DNN vs. HMM.

The data used for this analysis corresponds to the Planchon Peteroa Volcanic Complex (PPVC) located in the Transitional Southern Volcanic Zone (TSVZ) between Chile and Argentina.

The aim of this work is not only to provide an analysis in terms of perfomance of each algorithm as well as an insight regarding optimal event parametrization so as to improve the automatic detection and classification of events.

Financial market tools for the multiscale analysis of geophysical time series

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Financial markets specialists often use multiscale analysis on different kind of time series. Many tools have been developed for these tasks. Two of them, widely used, are: candlestick charts and technical indicators. Our approach consists in using both tools to analyze geophysical and geochemical time series, with special reference to seismic data. We first represent signal using candlesticks at user selected time scales. In our case we use four summary quantities of the signal: the amplitude of the first sample, the maximum amplitude within the candle, the minimum amplitude and the amplitude of the last sample used in the candlestick. We show how the graphical candlestick representation alone is able to emphasize representative changes within the time-series.

On the other hand, many technical indicators have been defined to extract further information from such type of charts. Among the most commonly used technical indicators are: Simple Moving Average (SMA), Exponential Moving Average (EMA) and Moving Average Convergence/Divergence (MACD). EMA is a temporal smoothing with an exponential weighting determined by a time scale factor. MACD is the difference between EMA realized at a short scale with another EMA at a larger scale. For instance, a commonly used MACD in financial markets is EMA on 12 days minus EMA on a 26 days time scale. In the case of actual geophysical and geochemical datasets such scales should be selected on the basis of the time scales of interest. We show how MACD behaves as a proxy of the first derivative also in the case of noisy data.

Since the candlestick analysis highly reduces the number of samples, providing only the relevant information about a time-series, it is highly suitable to investigate correlations between very different type of data (e.g. seismicity, gas flow rates, etc...). This feature is particularly useful when comparing time-series having highly different sampling rates. We applied candlestick analysis to various seismological and geochemical datasets, in particular we show example application to recent eruption of El Hierro, highlighting the capability of this method to detect changes in the trend of time-series earlier that other simpler techniques.

An Unsupervised Machine-Learning Approach to Understanding Seismicity at an Alpine Glacier

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Although small-magnitude earthquakes are not as hazardous as their larger counterparts, understanding the sources of "microseismicity" could prove crucial for investigating the timing of, and the physics governing, earthquake initiation in general. Our project uses machine learning to characterize thousands of microseismic events based on their spectral characteristics, which we will then attempt to correlate to physical conditions at their source. We are particularly interested in settings where fluid-mediated seismicity plays an important, such as glaciers, geysers, and volcanoes.

The algorithm we are using, Spectral Unsupervised Feature Extraction (or, SpecUFEx), takes advantage of advances in the field of audio recognition to cluster seismic events based on how they "sound", and has previously been used to sort microseismicity at a California geothermal reservoir into clusters that could be correlated to fluid levels at the reservoir (Holtzman et al., 2018), suggesting that the presence or absence of fluids alters the seismic signals

Our initial project involves applying SpecUFEx to 10,000 microseismic "icequakes" that occurred during a two-month period (June-July 2007) at Gorner Glacier, Switzerland. Previous seismic studies at Gorner Glacier have concluded that crevasse formation is the primary source of the local seismicity, resulting in hundreds to thousands of microseismic icequakes per day (Walter, 2009; Roux et al., 2010). Our preliminary results using SpecUFEx have shown that these icequakes are consistently clustered into groups that can be differentiated by what time throughout the day or night they occur. Given the well-established relationship between the dynamics of Gorner Glacier and variations in meltwater runoff— which also exhibits a strong diurnal trend— it is possible that the glacial hydraulic system may play a key role in determining the spectral content of these icequakes, and therefore how they are clustered via SpecUFEx.

We are currently testing the sensitivity of our clustering results to variations in the machine-learning parameters and will soon begin utilizing auxiliary geophysical data (e.g., temperature, subglacial water pressure) to aid in understanding the source of these newly identified, subtle spectral differences between microseismic events. Conclusions drawn from this study could assist with interpreting the spectral properties of other fluid-driven seismic sources, such as volcanoes and geysers.

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Near Real Time Remote Characterisation of Explosive Eruptions for Mitigation of Impacts and Loss in SE Asia

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I will present a new research project that aims to develop, expand upon and combine existing technologies to improve the detection, characterisation and understanding of potential impacts from explosive volcanic activity in Southeast Asia, and present information in a timely manner for efficient decision-making. It will focus on rapidly quantifying volcanic ash emissions, by harnessing a multi-technology and multi-disciplinary approach, with the aim to mitigate their short, mid and long term impacts. This project focuses on Southeast Asia where remote ground based or space based monitoring could be challenging (Taisne et al., 2019).
Singapore, like many other smart-cities around the globe, is not immune from volcanic threats. While there are no volcanoes located within Singapore, Southeast Asia is one of the most volcanically active regions in the world and is home to 70% of the global volcanic threat. In a recent studies we identify 991 volcanoes with the potential to impact the Association of Southeast Asian Nations (ASEAN) airspace, with a 100% probability of an eruption powerful enough to produce an ash plume to 25 km or higher within any given 10 year period (Whelley et al., 2015).
By refining nowcasting and forecasting of volcanic ash dispersal, timely action could be taken to close or open airspace and estimate potential long term damage to aircraft and engines (reducing economical loss by taking informed decisions), give enough lead time to shut down critical infrastructure such as power plants (reducing economical loss by preventing damage to the system) as well as rapidly estimating the potential hazard and impacts of ash on the ground (informing post-disaster needs assessments and mitigating impacts for populations and infrastructure).
The project build on data stream from infrasound, satellite and social media, and plan on including artificial intelligence and machine learning algorithm to mine the different sources of information.

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Depth Constraints on Seismic Anisotropy in Iceland from Shear Wave Splitting Measurements

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Earthquakes associated with volcanic and extensional processes in the Icelandic rift zone provide an excellent source of seismic data with which to investigate the anisotropic properties of crust generated at a mid-ocean ridge. Seismic instruments deployed by the University of Cambridge and the Icelandic Meteorological Office over the last decade have recorded a large catalogue (> 100,000) of seismic events in the central part of the northern volcanic rift zone in Iceland, straddling the Askja and Bárðarbunga central volcanoes and their associated rift segments.

Shear wave splitting is a key indicator of the presence of seismic anisotropy. A shear wave entering an anisotropic medium is polarised into two quasi-S waves which travel with different velocities. Measurements of the orientation and accumulated delay time between these two components allow us to extract information on the underlying anisotropic fabric. We utilise MFAST, an automated shear wave splitting routine, to examine local earthquakes between 2009 and 2016. We observe a shallow anisotropic layer in the upper 4 km with an average delay time of 0.1s (approximately 5% anisotropy). The measured orientation of the fast axis correlates with the strikes of mapped surface features (e.g. surface fissures), which are generated by the rifting process. This is consistent with being caused by stress-induced microcracks, preferentially aligned parallel to the axis of the spreading ridge.

The coincidence of the mid-Atlantic ridge with the Iceland plume results in a region of anomalously thickened crust in Iceland. This thick crust hosts pockets of deep seismicity that occur in swarms largely between 14-26 km depth within the otherwise aseismic lower crust. This seismicity allows us to investigate anisotropy at greater depths beneath a mid-ocean ridge than would otherwise be possible elsewhere in the world. A potential second layer of anisotropy, contributing an additional 0.2s of delay time, is consistently observed between 8 km and 15 km depth across the network. At this depth brittle fractures have closed, so we require an alternative mechanism to explain the source of the observed seismic anisotropy.

The Oct. 2nd 2016 long-period seismic swarm Tenerife (Canary Islands)

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On October 2, 2016, a relevant seismic swarm of long-period events, was recorded on Tenerife (Canary Islands, Spain). The swarm lasted more than 5 hours and consisted of at least 766 transient detected events. We found a positive correlation between the amplitudes of each event and the preceding inter-event time, a substantial stability of the spectral properties and waveform similarity during most of the swarm duration. Towards the ends individual events merged into a continuous tremor.

Using a standard deconvolution approach, we obtained the source function of the whole swarm, including the volcanic tremor toward the end. This function revealed a hidden pattern within the tremor consisting of isolated pulses repeating at non-regular intervals. We analyzed the time series of the source function computing the time-varying fractal dimension showing how it changed during the transition from discrete events to continuous tremor.

These observations can be explained postulating an unsteady transonic choked flow within a crack-like conduit as a source mechanism for this swarm. The flow results from a sudden discharge of magmatic fluids from a pressurized reservoir into the hydrothermal system of Tenerife. The injected fluids reached the surface starting about one month after the swarm, as evidenced by the macroscopic increase in the diffuse CO_2 emissions from the crater of Teide volcano.

The absence of ground deformation and relevant seismicity patterns at depths higher than 10 km, excludes the ascent of a basaltic magma batch as a causative source of the fluids. Instead we hypothesize the sudden release of fluids accumulated at the top of a magma chamber as a possible mechanism. Another possibility is the injection of a small batch of mafic magma into a cooling magma chamber, triggering a convective mixing. Both cases imply the presence of a magma chamber at depths higher than 8.6 km. These results have important implication in the development of the volcano monitoring system of Tenerife.

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Capturing, preserving & digitizing legacy seismic data from the Soufriere Hills (Montserrat) 1995-2010 eruption

An eruption of the Soufriere Hills Volcano began on July 18th, 1995, and an analog seismic network was installed just one week later, expanding on the regional network. In October 1996, a digital seismic network was added, with separate acquisition and analysis systems. The eruption intensified throughout 1996 and 1997. But during a pause in eruptive activity from March 1998 to November 1999, funding and staffing levels declined at the Montserrat Volcano Observatory (MVO), and by January 2000 seismic monitoring was compromised.

With pyroclastic flows re-occurring, it was urgent to rebuild the seismic monitoring. There was also a need to compare seismicity from the previous and current phases of the eruption. Hundreds of hours of effort began to recover, organize and robustly archive seismic data from hundreds of different media, increase storage and build databases and analysis tools. Many scientific papers benefitted from these previously undocumented efforts. But preservation of analog network datawas incomplete.

In 2015 we developed procedures to demultiplex, time correct and convert data from legacy SUDS format to the modern Miniseed format. However, event times and classifications (e.g. VT, hybrid, LP, rockfall) of more than 200,000 events existed only in hand-written logbooks: the only records of the seismic event catalog for the first 16 months of the eruption. Handwriting is not clear enough for OCR, so manual data entry is necessary.

We are able to classify 100-200 events per hour and have so far completed 5 out of 16 months. We aim to merge this catalog with the digital seismic network catalog. We also plan to take all seismic waveform data (event-detected from both networks, continuous from the digital network), and merge them for the first time into a single database accessible by modern seismic data analysis tools. This work will underpin efforts to objectively reclassify the Montserrat seismic event catalog with machine learning techniques.

This MVO seismic dataset is one of extraordinary scientific value. Moreover, there are many observatories that have data in these same legacy data formats, and might benefit from the procedures and codes that we developed. We aim to make all programs available by github.

Towards Fast Moment Tensor Inversion of Micro-Seismic Events by using Waveform Similarity and Neural Networks

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Despite advanced seismological methods, source characterization for micro-seismic events remains challenging since modelling of high-frequency waveforms and reliable hypocentre locations are required. Therefore, (near-) real-time and automatic moment tensor inversion procedures are difficult and not standard. In a micro-seismicity monitoring context, it is desirable to characterize the seismic sources in (near-) real-time and within a probabilistic framework that allows the quantification of the ambiguities and uncertainties. In practice, this typically involves some form of sampling-based approach in which many candidate source mechanisms are compared with the observations to project the space of acceptable models. However, adopting sampling-based methods for micro-seismic monitoring tasks with the robust characterization is not established and remains computationally intensive and expensive.

In this study, we investigate how a non-linear approach based on deep learning and a precomputed Green's function database can be used to rapidly invert seismic waveforms for source parameters. The inversion is represented in compact form by a deep neural network which yields probability distribution functions over source parameters. In other words, a deep learning algorithm is trained to encapsulate the information about the relationship between observations and underlying models. The learning-based model allows rapid inversion once seismic waveforms are available. In this study, we seek to demonstrate that this approach is viable for micro-seismicity monitoring tasks by implementing a system that enables (near-) real-time monitoring. As a demonstration test, we plan to apply the new approach to data collected at the geothermal field system in the Hengill area, Iceland, within the framework of the COSEISMIQ project funded through the EU GEOTHERMICA programme.

Magmatic and sedimentary structure beneath the Klyuchevskoy Volcanic Group, Kamchatka, from Ambient Noise Tomography

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The Klyuchevskoy Volcanic Group (KVG) is a cluster of the world's most active subduction volcanoes, situated on the Kamchatka Peninsula, Russia. The group of volcanoes lies in an unusual off-arc position within the Central Kamchatka Depression (CKD), a large sedimentary basin whose origin is not fully understood. Many gaps also remain in the knowledge of the crustal magmatic plumbing system of these volcanoes. We conducted an ambient noise surface wave tomography, to image the 3D shear wave velocity structure of the KVG and CKD within the 150 km x 100 km surrounding region. To do this a temporary seismic network was deployed across the area at a close and regular station spacing of 10-15 km between 2015-2016. Vertical component cross-correlations of the continuous seismic noise are used to measure inter-station Rayleigh wave group and phase travel times. We then perform a two-step surface wave tomography to model the 3D Vsv velocity structure. For each inversion stage we use a transdimensional Bayesian Monte Carlo approach, with a coupled uncertainty propagation. This ensures that our model provides a reliable 3D velocity image of the upper 15 km of the crust, as well as a robust assessment of the uncertainty in the observed structure.

Beneath the active volcanoes we image small slow velocity anomalies in the depth range of 2-5 km below sea level, but find no evidence for magma storage regions deeper than 5 km - noting the 15 km depth limit of the model. From the upper crustal shear velocity structure we map two clearly defined sedimentary layers within the CKD, revealing an extensive 8 km deep sedimentary accumulation. This volume of sediments is consistent with the possibility that the CKD was formed as a long-lived Eocene-Pliocene fore-arc regime, rather than by recent (<2 Ma) back-arc extensional processes.

Tom Winder

"Crustal seismic velocity responds to a magmatic intrusion and seasonal loading in Iceland's Northern Volcanic Zone"

Abstract:

"Seismic noise interferometry is an exciting technique for studying volcanoes, providing a continuous measurement of seismic velocity changes (dv/v), which are sensitive to magmatic processes that affect the surrounding crust. However, understanding the exact mechanisms causing changes in dv/v is often difficult. We present dv/v measurements over ten years in central Iceland, measured using single-station cross-component correlation functions from 51 instruments across a range of frequency bands. We observe a linear correlation between changes in dv/v and volumetric strain at stations in regions of both compression and dilatation associated with the 2014 Bárðarbunga-Holuhraun dike intrusion. Furthermore, a clear seasonal cycle in dv/v is modeled as resulting from elastic and poro-elastic responses to changing snow thickness, atmospheric pressure and groundwater level. This study comprehensively explains variations in dv/v arising from diverse crustal stresses and highlights the importance of deformation modeling when interpreting dv/v, with implications for volcano and environmental monitoring worldwide."

This work has just been accepted for publication in Science Advances, and will hopefully be out in the next couple of weeks! -- Donaldson et al., 2019