"The eruption of September 15, 2018 at Piton de la Fournaise : precursors and evolution "

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Abstract: On September 15, 2018, the fourth eruption of the year began at Piton de la Fournaise. This eruption was preceded by about two weeks of edifice inflation, i.e. a sign of shallow reservoir pressurization (at 1.5-2 km depth) and by about 3 hours of seismic crisis indicating that magma had started propagating towards the surface. The eruption started between 04:25 (i.e. the beginning of the tremor recorded on the OVPF seismic stations) and 04:39 local time (i.e. the first lava emissions visible on the OVPF's webcams. Initially, 5 en-echelon fissures opened on the south-southwest flank of the terminal cone. During the first hours of the eruption, a time-averaged discharge rate of 22.7 and 44.7 m3/s was estimated from satellite data acquired by the MIROVA platform (University of Turin). The five eruptive fissures remained active simultaneously during the first hours of the eruption with lava fountains of ~30 m height. Photogrammetric processing of aerial imagery allowed

for the 3D reconstruction of the cone growth and its morphological features in high spatio-temporal resolution. While the cone was open towards the south until September 24, it completely closed to form a more or less circular feature thereafter. At the same time, lava flows started to form and travel through lava tubes feeding outbreaks at 150-200 m downstream of the cone. Aerial and ground-based photographs were used to accurately map the evolution of the lava flow coverage over time. On September 18, the lavas had travelled as far as 2.8 km with an active flow front at about 500m from the southern wall of the Enclos Fouqué caldera. As of September 21, lava flows had advanced 150m eastward. Thereafter lava flow progression had slowed down as a result of the development of lava tubes, which contributed in the vertical growth of the lava field downstream of the cone.

Annual seasonal variations in relative seismic velocity in the Northern Volcanic Zone, Iceland

Clare Donaldson, Robert S. White, Corentin Caudron, Jonathan D. Smith, Tom Winder

Measuring changes in relative seismic velocity (dv/v) in the subsurface using ambient seismic noise is being used increasingly as a monitoring tool in volcanic regions in an attempt to identify pre-eruptive changes. In this study, we measure consistent annual seasonal changes in dv/v, of the order of 0.1%, over the top 1 km of crust in Iceland’s Northern Volcanic Zone. Seismic velocity is fastest in the spring when snow depth is greatest. We also study dv/v before and after a major volcanic event, the 2014-15 Bárðarbunga-Holuhraun rifting episode and consider the stress sensitivity of dv/v to a dike intrusion.

Data from more than 40 broadband seismometers is used, recorded since 2008 across Iceland’s Northern Volcanic Zone, particularly around Askja volcano. Using the MSNoise software, cross-correlation functions are calculated between pairs of seismometers and small changes in arrival times are measured using the Moving-Window Cross-Spectral method. We filter in several frequency bands in order to measure dv/v at different depths in the crust. Using available weather data, including snow depth, precipitation and temperature, three mechanisms of generating a seasonal change in seismic velocity are tested: effects of elastic loading due to snow; pore-pressure change due to rain, snow melt and glacier melt; and frost. This study is important for volcano monitoring, particularly in Iceland where seasonal trends may mask volcanic signals but could be removed using modeling approaches.

How well can we trust moment tensor inversions?

Dinko Šindija, Jürgen Neuberg

Active volcanoes are often covered with a sparse seismic network. In the case of a volcanic crisis, this number can even be more reduced due to noise saturated data at certain stations, electrical failures, or stations being destroyed by the volcanic material. Using the seismic network configuration at Soufriére Hills volcano, Montserrat, numerical tests are performed to examine how well different source mechanisms (isotropic, double-couple, CLVD) can be resolved depending on their orientation and depth. The number of stations included in the moment tensor inversion is varied mimicking an eruption scenario.

Deformation induced topographic effect (DITE) in volcano gravimetry

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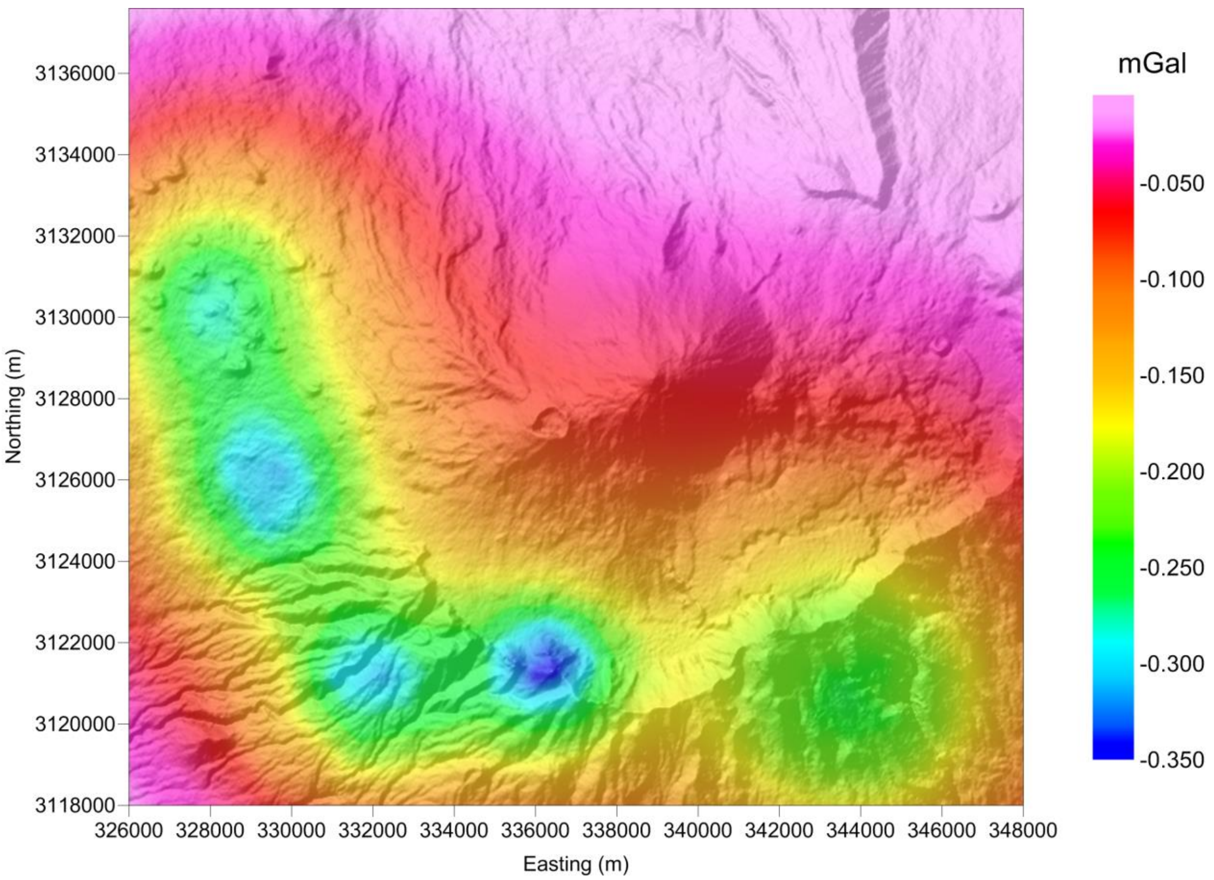
Abstract
We take a look at the origin and implications of deformation–induced gravitational effects in interpretation of spatiotemporal gravity changes. We review the traditional approaches to handling the attraction of subsurface and surface deformations. These effects are relevant when inferring magmatic processes in volcano gravimetric studies. We focus on the surface constituent, the deformation–induced topographic effect (DITE), which consists of the gradient effect called free-air effect (FAE) and the attraction effect coined here the topographic deformation effect (TDE). We present several expressions for evaluating the DITE: the exact DITE, the quasi–exact DITE, the Bouguer approximation of DITE, and the normal–FAE approximation of DITE, as well as derive alternate expressions equivalent to the exact and quasi–exact expressions of DITE. The alternate expressions shed light on the physical nature of DITE. By simulating numerically synthetic displacement fields in a referential volcanic area of prominent rugged topographic relief we compare numerically the differences between various approximate evaluations of the DITE for various model magmatic sources placed at various locations and depths, using high-resolution high-accuracy DEMs of the area and the Toposk software for evaluating topographic Newtonian attractions. We discuss the particularities and complications in numerical evaluation of each of the DITE expressions. We conclude with recommendations for which expressions are most suitable for computing the DITE under what circumstances.

Keywords: volcano gravimetry, spatiotemporal gravity change, vertical displacement, vertical gradient of gravity, topographic effect, interpretation



The DITE respective to the synthetic deformation field of five spherical overpressure sources located within the Santiago Rift Zone and the Las Caňadas caldera of Tenerife.

Acknowledgements
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Tracking a subglacial flood in real-time in Iceland

Eva P.S. Eibl, Christopher J. Bean, Kristin Vogfjörd, Bergur Einarsson, Tomas Johannesson, Finnur Palsson

The unique setup of active volcanoes and ice caps lead to the generation of various hazards such as subglacial floods in Iceland. These floods endanger people but also villages and infrastructure such as bridges and the ring road that encircles the island. As multiple floods occur every year the ring road is usually partly destroyed at least once a year. Early warning of these floods is mainly based on hydrological instruments in the glacial rivers, but also GPS instruments that are deployed on top of some of the lakes. We interpret the recordings of two seismic arrays in southeast Iceland west of Vatnajökull glacier jointly with the observations made with hydrological and GPS data.

These arrays recorded about 7 floods from August 2013 to December 2016. We present multidisciplinary results from the largest of these floods which occurred in September/ October 2015. The flood could be tracked using a seismic array based on a moving seismic signal that started about 20 hours before the flood reached the uppermost hydrological station and could therefore be used as a precursory signal.

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Seismic tomography of the Torfajökull volcano, south Iceland

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Torfajökull volcano with a caldera 12 km in diameter has a curious location, at a propagating rift of the western branch of the Icelandic neovolcanic zone. Old crust is being reworked by current volcanic activity, creating the most prominent area of silicic volcanism and the largest geothermal field in Iceland. The latest eruption has occurred in 1477, but intense geothermal activity, deformation, and seismicity suggest a long-lasting magmatic system.

Ambient-noise tomography is used to image the magmatic system beneath Torfajökull. Ambient-noise data from 23 broad-band seismometers covering 100 days show consistent presence of double-frequency microseismic noise with significant power in the frequencies ~0.1–0.5 Hz. Beamforming results indicate microseismic noise with persistent higher energy propagating from the west and south-east, and apparent velocities below 3 km/s.

Ambient-noise seismic interferometry is used to retrieve Rayleigh waves, introducing a method to estimate the reliability of the retrieved surface waves. A stable estimation of surface-wave phase velocities is found at 0.16–0.38 Hz. Azimuthal velocity variations show a trend of higher velocities in the NE/SW direction – the strike of the rift zone intersecting Torfajökull and orientation of erupted lavas on a NE-SW fissure swarm. Tomographic results indicate low-velocity anomalies beneath the caldera (between -5 and -10%), and even lower velocity variations in the south-east and south-west parts of the study area (below -10%), outside of the caldera. Low anomalies may indicate the existence of hot material, being more prominent outside of the caldera. High-velocity variations (≤10%) outlining the Torfajökull caldera are identified at the 4–5 km depth and interpreted as a possible caldera collapse structure. More pronounced velocities (≤15%) at shallower depths are found in the northern part of the caldera, interpreted as solidified intrusive magma of old conduits.

Dyke-induced earthquakes during the 2014-15 Bárðarbunga rifting, Iceland: 3D evolution of a dyke

Jennifer Woods, Tom Winder, Robert S. White, Bryndís Brandsdóttir

The 2014-15 Bárðarbunga rifting event, Iceland, was accompanied by intense seismicity. We here present relocations of earthquakes induced by the lateral dyke intrusion, using cross-correlated, sub-sample relative travel times. The approx. 100 m spatial resolution achieved reveals the complexity of the dyke propagation pathway and dynamics (jerky, segmented), and allows us to address the precise relationship between the dyke and seismicity, with direct implications for hazard monitoring. The spatio-temporal characteristics of the induced seismicity can be directly linked in the first instance to propagation of the tip and opening of the dyke, and following this - after dike opening - indicate a relationship with magma pressure changes (i.e. dyke inflation/deflation), followed by a general ¤post-opening¤ decay. Seismicity occurs only at the base of the dyke, where dyke-imposed stresses - combined with the background tectonic stress (from regional extension over > 200 years since last rifting) - are sufficient to induce failure of pre-existing weaknesses in the crust, while the greatest opening is at shallower depths. Emplacement oblique to the spreading ridge resulted in left-lateral shear motion along the distal dyke section (studied here), and a prevalence of left-lateral shear failure. Fault plane strikes are predominately independent of the orientation of lineations delineated by the hypocenters, indicating that they are controlled by the underlying host rock fabric.

An alternative physical model to explain eruption forecasts results from the material Failure Forecast Method.

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Increased seismicity is one of the tell-tale signs of an impending volcanic eruption. Yet, increased seismicity can also send false positive signals. How can we then assess whether an eruption is likely? This challenge can be tackled by optimizing monitoring networks to get more useful data, developing robust methods to analyze these data, or proposing new models to explain the data.

Here, we present a potential alternative and robust model to explain eruption forecasts results using the well-known material Failure Forecast Method (FFM) on seismicity increases.
During an upward migration of seismicity, the distance between the seismic source and the monitoring site decreases, as does the attenuation. This leads to an overall increase of seismic intensity recorded by monitoring network.
Assuming that the seismicity is concentrated at the tip of a propagating dyke, and that it follows a reasonable frequency/size distribution, we produce synthetic data for different migration scenarios recorded at seismic stations located at increasing radial distances from the eruption location.
We then explore how combinations of parameters for the FFM could explain these different datasets, and evaluate how the method performs to forecast eruption onset.

This alternative interpretation of increasing seismicity preceding eruption, might provide a robust explanation to the success/failure of the FFM to forecast the onset time of an eruption.

Seismo-volcanic events:
can we (should we) recognize them automatically?

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A continuous and large amount of data is produced by modern volcano monitoring systems, which feature an always growing network of sensors. These observations must 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 and before most eruptions up to thousands of events can be recorded in a few hours or days. These events have different characteristcs and can be associated to different physical mechanisms at the source. Their classification and interpretation requires therefore a “labelling” that, if carried out 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 also for the recognition of seismic events. Several research groups have proposed applications and have developed prototypes for this purpose. Good results – often >80% of events correctly classified – are generally obtained using diverse methods such as Artificial Neural Networks, Hidden Markov Models, Random Forests, Self-Organizing Maps, Support Vector Machines and Deep Learning. Independently from the chosen algorithm, the success rate of classification depends strongly on the quality of the training databases, on the number and characteristics of the event classes, and on the features used to describe the signals.

We will present an overview of the application of such methods of automatic recognition to the classification of seismo-volcanic signals. We will also discuss the problems related to the integration of these tools in routine monitoring systems and highlight the need for sharing reliable and large databases of seismic events recorded at the different volcanoes.

Franco Cortese

Abstract

Could knowledge of the diagnostic factors that control volcanic activity one day be considered for a new classification for explosive eruptions, aiding the assessment of hazard?

The importance of deeply understanding the processes involved in controlling a volcanic explosive eruption, as in which type of eruptive event will occur as a consequence of those specific physical and geochemical processes, is crucial to the whole comprehension of the phenomenon. Whilst the research and knowledge on many factors that do influence the eruptive outcome such as melt composition, ascent rate, bubble density, surface tension, pressure at conduit exit, magma temperature, water content, slip length of brittle failure of melt, conduit shape and size and many others is being undertaken, this talk aims to trigger a discussion on the idea that a future classification of explosive eruption might actually one day take these diagnostic parameter in consideration. The auspicable advantages of a classification which actually differentiates eruptions that are also based on a series of parameters that are diagnostic of volcanic activity rather than descriptive of the outcome of the event that only partially represent the natural complexity of the activity (e.g. Walker 1973; Newhall and Self 1982; Pyle 1989; Bonadonna and Costa 2013), would be of great help in assessing hazard and planning security measures.

Tom Winder

"A Surge in Seismicity in a Network of Cross-Cutting Conjugate Strike-Slip Faults Triggered by the 2014 Bárðarbunga-Holuhraun Dike Intrusion

Repeated tectonic earthquake swarms between Askja and Herðubreið volcanoes in Iceland□s Northern Volcanic Zone have been detected and located using a dense local seismic network operational since 2009, producing a catalogue of >30,000 earthquakes. This unusual seismicity is an example of how continued plate spreading is accommodated during an amagmatic inter-rift period at an active spreading centre.

Refined automatic hypocentre locations have been obtained through waveform cross-correlation and double-difference relocation, giving relative location uncertainties <100m. A subset of events were manually picked, producing tightly constrained fault-plane solutions. Inferred fault orientations from both datasets show excellent agreement; combined analysis reveals that a network of conjugate strike-slip faults is accommodating rift-perpendicular spreading. The kinematics and cause of this atypical style of extensional tectonics are investigated by comparison with deformation studies from the region over the same time period. Such high-resolution observations of active faulting offer new insights into examples of complex faulting at rift axes in the past, observed in seismic reflection and field surveys.

In August 2014, a lateral dike intrusion propagated 48km from Bárðarbunga volcano to Holuhraun, roughly 40km southwest of the region of strike-slip faults, triggering a sharp rise in seismicity rate and moment release. This observation links tectonic spreading with concurrent magmatic rifting in an adjacent rift segment, providing an insight into the interplay between these two styles of rifting over the life of a spreading ridge.

The induced seismicity was initially confined to the southwest of the fault network; its extent migrated northeast as the dike propagated towards the fault system. Coulomb stress modelling reveals that the position of this front equates to a triggering threshold of <0.05MPa. Intriguingly, this migration continued after the dike had reached its full extent and the main-phase eruption had begun."

Time-domain multi-array analysis of volcano-related seismicity around Fogo and Brava, Cape Verde

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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. It is known from several previous studies that most of the seismic activity occurs in the vicinity of Brava. Based on these findings, a possible link of the plumbing system of Fogo to a magmatic source near Brava was proposed. However this could not be confirmed by our more recent studies.

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, earthquake epicenters can be obtained directly from the intersecting beams. As the three intersecting beams, generally, lead to three different solutions, we determine the epicenter by combining individual probability functions for the arrays. These are derived from the energy stack and its variation as function of slowness (backazimuth) close to the maximum. 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. We test our approach by comparison with results from a classical earthquake localization applied to events located between Fogo and Brava and using the 7 single stations of the network.

From ‘state-of-the-art’ Volcano-Seismic event Recognition (VSR) to ‘state-of-the-art’ Volcano Observatories: the *VULCAN.ears* project

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Organizers:

- European Seismological Commission – Working Group "Seismic phenomena associated with volcanic activity"
- IASPEI/IAVCEI Inter-Association Commission on “Volcano Seismology & Acoustics”

Abstract:

The evolution of the seismic activity of volcanoes is one of the most reliable precursors used for Eruption Forecasting and Early Warning Systems. The usual way to track the seismicity is to *detect* relevant events in a continuous stream and to *classify* them into groups or classes according to their physical origin in a process named *Volcano-Seismic Recognition* (VSR). To provide a fast response in hazard assessment, modern Volcano Observatories

(VOs) demand automatic and nearly real-time VSR tools.

The EU-funded project *VULCAN.ears* (*Volcano-seismic Unsupervised Labelling and ClAssificatioN Embedded in A Real-time Scenario*) aims to bring state-of-the-art VSR technologies to fulfill actual, state-of-the-art VO requirements as the '*UUU*' goal: a) *'U'nsupervised 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.

In this talk we shortly present *VULCAN.ears* project and past, present and expected achievements towards real-time, unsupervised VSR:

- ✓ VSR system via Hidden Markov Models (HMMs) and a parallel approach composed of specialized VSR channels, each designed to recognize events of a single class from continuous data streams.
- ✓ Waveform standardization as a tool to reduce local, volcano-dependent, signal artifacts and noises.
- ✓ Joint databases built from several volcanoes allowing the building of universal models to recognize events from other volcanoes.
- ✓ GUI front-end (*geoStudio*) to easily integrate the VSR back-end into VOs and monitoring equipment.
- ✓ VSR application to eruption forecasting giving statistical support for the Bayesian-based material Failure Forecast Method.

J. Neuberg

On Volcanoes and Earth Tides

Time and again volcanic eruptions are linked to a trigger mechanism caused by the stress field of Earth Tides. In this talk I will demonstrate how to distinguish a potential tidal excitation from a purely 24h excitation that could be caused by solar related processes like temperature, pressure or even anthropogenic mechanisms. Using a long gravity time series from White Island, New Zealand, and putting it into context with very long period seismicity I will outline how hydrothermal activity could explain the VLPs and the gravity record, Furthermore, following the slogan “One man’s noise is the other man’s signal” I will outline how so-called tidal admittance might be used to identify period of higher than usual volcanic activity and enhanced heatflow.

Complex Sources in Volcanic Environments: Radiation Modelling and Moment Tensor Inversions

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Abstract

Long period (LP) signals are special seismic events observed at volcanoes, which comprise both a high frequency onset due to brittle failure and a more energetic low frequency part due to resonance in a fluid-filled conduit. They are critical for volcano monitoring since they can be used as a volcanic forecasting tool. Classic seismology assumes planar faults for seismic sources; however, there is increasing evidence that suggests different fault shapes such as dyke-embedding faults and ring faults. We model these complex sources by superposing vertical single double couple (DC) sources arranged along these fault structures with inner upward movement. We calculate net radiation patterns and synthetic seismograms for a dyke-embedding rupture, three different partial ring ruptures and a full-ring rupture. Results show that planar faults are the most effective at radiating energy. The more they deviate from a planar fault the smaller become the amplitudes and therefore the Moment Magnitude. For example, the amplitudes decrease to 2% of the planar radiation for a full-ring rupture and to 0.7% for a dyke-embedding rupture. The waveforms produced by partial ring ruptures are in accordance to the far field theory, they represent the derivative of the source displacement and emulate radiation of a DC with different azimuths; however, the dyke-embedding and full-ring sources produce waveforms that appear to represent the second derivative of the source displacement and negative first onset polarisations. Moment Tensor Inversions support similarities between DC ruptures and partial ring ruptures; however, they show ambiguous solutions for the other sources. This assumption can lead to misinterpretations of slip history on the fault and a consistent underestimation of magnitudes which has direct implications for magma ascent estimations.

IAVCEI/IASPEI workshop, October 2018, La Réunion

Very- and ultra-long-period seismic signals prior to and during caldera formation on La Réunion Island

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The largest historical caldera collapse of the summit of the Piton de la Fournaise volcano (on La Réunion Island) started on April 5 2007 and continued over a 9-day period. A ~ 340 m deep collapse of the caldera floor was measured at the end of the collapse episode. The volcano's most voluminous eruption in the last two centuries started on the southeast volcano flank, 7 km of the summit, ~ 3 days before the first collapse. A deflation period of the volcano summit was recorded before the beginning of the caldera collapse. As a whole, 48 caldera collapses occurred from the onset of the surface subsidence and 37 collapses happened in the first 30 hours when the highest effusive rate was observed at the distal vent. Each collapse was coeval with very-long-period (VLP) and ultra-long-period (ULP) seismic signals recorded by a nearby very-broad-band seismic station from the GEOSCOPE network. A few ULP signals preceded the collapse episode, starting on March 30. The strikingly constant duration of the VLP signals (around 20 s) related to each collapse event, and their occurrence both before the collapse initiation and during it, suggest a physical control of the volcanic edifice. Waveforms of the various caldera collapses show homogeneous patterns, suggesting a similar and repeating volcano-tectonic process associated with the VLP signals. The moment tensor inversion of the seismograms from the M_s 4.8 earthquake associated with the main collapse suggests a dominant isotropic volume decrease. Continuous monitoring of ULP signals accompanied by VLP signals by a nearby very-broad-band seismic station allowed the identification of eight previously undetected collapse events. This study also shows the possibility of detecting the first collapse at depth from the identification of ULP signals accompanied by VLP signals.

Combined magma flow and deformation modelling to investigate the role of shear stress

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Periods of activity at Tungurahua volcano, Ecuador, between 2013 and 2014, were associated with cyclic tilt variations of up to around 170 µrad and an increase in low frequency seismicity. Attempts to link the significant near-field deformation observed at many silicic volcanoes to realistic pressure variations in the upper part of the edifice require the source to be very large or the edifice to be exceptionally weak. Previous work has shown that shear stress of around 20 MPa, exerted on the conduit walls as magma ascends through the conduit, can explain the tilt variations observed. However, whether such shear stresses are achieved in nature is so far unclear. Here, we combine flow and deformation modelling to investigate whether sufficient shear stress to explain the observed tilt variations can be achieved through realistic magma ascent. We show that the depth of the head of the ascending magma column, the volatile content, and the driving pressure gradient are key parameters in driving changes in tilt through time. Additionally, we show that even where the edifice is modelled as weak, shear stress can explain the observed deformation more easily than a shallow pressure source.

The 2014-15 Bárðarbunga, Iceland Caldera Collapse

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On 16 August 2014 an unusual sequence of earthquakes began near the SE rim of the ice-covered Bárðarbunga caldera in central Iceland. Over the course of 2 weeks a dyke propagated 48 km beneath the glacier northeastwards and into the Holuhraun lava field, where it erupted for 6 months. It became the largest eruption in Iceland for 230 years. During this time, a gradual, incremental caldera collapse took place at the central volcano. We use accurate earthquake locations to analyse the caldera collapse. We define the thickness of the seismogenic crust under Bárðarbunga as ~ 7 km, based on the depth extent of observed seismicity. The bulk of the seismicity directly beneath the volcano is located at 1-4 km below the surface, whereas the dyke exited the caldera at 4-6 km depth, propagating at ~ 6 km b.s.l..

Approximately 5,000 of the recorded earthquakes are associated with the caldera collapse, delineating faults accommodating the subsidence and showing good correlation with geodetic data. The seismicity reveals activation of both inner and outer caldera faults with ~60° inward dipping planes, but with an order of magnitude difference in the cumulative seismic moment on the northern and southern sides. Detailed analysis of the source mechanisms shows that ~90% of the events can be explained by double couple failure. We find the dominant failure mechanism during the collapse to be steep normal faulting, with sub-vertical P-axes, and fault planes striking sub-parallel to the caldera rim. The southeastern part of the caldera, whilst experiencing less activity, shows a mixture of failure mechanisms, owing to the interaction of the caldera collapse and the dyke exit. We suggest a complex asymmetric caldera collapse, not controlled by a single caldera ring fault, and compare this with other model of caldera collapse.