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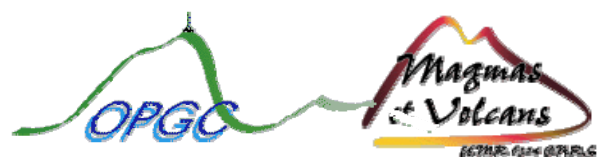


Massif Central, France

18-25 September 2010

**“Combining stochastic and deterministic models
to characterize seismo-volcanic source processes”**

ABSTRACTS



The April 2007 caldera collapse at Piton de la Fournaise, Réunion Island, imaged with InSAR and “tomography like” modelling

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Between April 2, and May 1, 2007, a major eruptive crisis occurred at Piton de la Fournaise (PDF) characterized by the volcano largest emitted volume of XXth and XXIth centuries and by a 300 m deep caldera collapse at the summit craters location. Ground displacements associated with this eruption were measured from interferograms computed from ENVISAT-ASAR and ALOS-PALSAR data. These data evidence complex patterns of displacements, resulting from a combination of eastward displacements of the whole Enclos Fouqué Caldera, the intrusion of several dikes, as well as a subsidence of the summit area. After lava stopped being emitted, concentric summit displacements continued at decreasing rates for several months. The extensive InSAR dataset spanning the post-eruptive period (more than 180 interferograms in 8 swaths) allowed us to determine the temporal evolution of the 3D displacement fields. Two methods are compared to determine the plausible sources for the post-collapse summit displacements and their geological interpretation. First, displacements are analyzed using a 3D Boundary element methods combined with a near neighbourhood inversion, assuming a single source is responsible for the summit deflation. These inversions show that the source of displacements is very shallow and at the same location as the presumed hydrothermal system, suggesting that the observed summit deflation is probably caused by the draining of the shallow hydrothermal system opened by the caldera collapse. Secondly, a procedure combining the superposition of point sources with a roughness criterion is used to solve for the spatial and temporal variation of the summit deformation sources. The joint analysis of GPS and interferometric data permits to draw a chronology of the displacements patterns, and to show the relation of cause and effect between these various events. Finally, from the time sequence of recorded displacements a scenario is proposed for the eruption and subsequent events.

Very Broad-Band seismicity related to the 2007 step-by-step collapse of the Dolomieu crater, Piton de la Fournaise Volcano (La Réunion Island)

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The March-April 2007 eruptive sequence of the Piton de la Fournaise volcano was characterized by the occurrence of a major collapse which led to the formation of a 320 m deep crater with a volume near 90 Mm³. We examined the seismic signals associated with this event recorded by a very broadband seismological station of the GEOSCOPE global network located 8 km from the summit of the volcano. The complex recordings display signals related to the different phases of the eruption. The most striking feature is the occurrence of a series of 46 high amplitude transient signals during the collapse of the Dolomieu which started on April 4, 2007. These collapse events, whose characteristics are clearly different from common tectonic earthquakes, occurred regularly over the first 2.5 days of the collapse with an inter-event delay ranging from half an hour to two hours. They indicate that the collapse occurred as a step by step process which continued until April 12. Low-pass filtering the recordings shows that these events are accompanied by long and very long period components with similar waveforms which appear on the vertical component as well as on the horizontal ones. At ultra long periods (> 100 s) the two horizontal components transformed into acceleration describe a sawtooth pattern with rapid steps at the time of the 46 transients separated by slow recovery processes. These resemble the deformation patterns measured by the tiltmeters and GPS instruments from the volcano monitoring network.

The different instruments display synchronized deformations with, however, reversed variations depending on their proximity to the summit. Stations in the vicinity of Dolomieu crater display motions which can be explained by a stick-slip process accompanying the piston-like collapse of the plumbing system situated above the magma chamber into the chamber. On the other hand, for distant stations like the GEOSCOPE station, reversed tilt pattern requires a different and/or complementary explanation. Inter-event tilt increases suggest a slow pressurization of a magma chamber while the rapid deflations observed at the time of each CE suggest deflation or depressurization of a source located below the summit. A 3D mixed boundary elements modeling assuming a spherical or ellipsoidal source below the summit, shows that the cumulative volume corresponding to the 46 downward tilt steps is in the range of the collapsed volume, suggesting these steps may be directly related to the formation of the crater.

APPLYING BLIND SEPARATION TECHNIQUES TO SEISMIC NOISE

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The continuous seismic noise recorded at or near an active volcano, which is often called volcanic tremor, often consists of a mixture of signals in a wide, usually overlapping, range of frequency bands, and not necessarily all of them have volcanic origin. In this presentation we will discuss the possibility of application of blind techniques to the problem of separating the sources of such signals composing the recorded seismic noise. The first kind of approach include Independent Component Analysis (ICA) and its derivations and requires the availability of a multi-sensor data set. The second kind of approach is based on the Nonnegative Matrix Factorization (NMF) and only requires a single input time series, thus having a potentially much broader possibility of application. Presented examples include data recorded at Merapi and Etna volcanoes - where ICA is applied in order to separate microseismic background noise from signals of potential volcanic origin – and Erta Ale volcano – where NMF is applied in order to separate a relatively transient “high lava lake convection phase” signal from an underlying, relatively continuous, “low lava lake convection phase” signal.

How Doppler radar can help linking surface explosive activity to magmatic conduit processes

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Ground-based Doppler radars are powerful tools in volcanology that enable the remote sounding of the interior of eruptive jets and ash plumes. Our Doppler radar (VOLDORAD 2) operates at 23.5cm wavelength and provides ejecta radial velocities along with echo power at an acquisition rate $> 10\text{Hz}$ in successive sampling volumes of the radar beam. Given some field constraints, these measurements can be used to quantify crucial plume dynamic parameters. The backscattered power, in particular, can be inverted to estimate the emitted mass of pyroclasts and other derived parameters, such as the mass flux rate, the ejecta volume, kinetic and thermal energies and particle concentration. Minimum estimates of gas fluxes can also be retrieved. In turn, radar time series can be used as feedback to refine models and improve our understanding of the eruptive conditions controlling the ascent dynamics of volcanic plumes.

Their all-weather, mobility and Doppler capabilities make radars particularly useful for monitoring active volcanoes as well as to investigate the dynamics of explosive activity near the source for a wide range of eruption intensities. They can allow assessment of the evolution of eruption intensity in real-time and give early information for the ash load of the plume, ejection velocities, and transport speed of the ash cloud as it drifts in the wind. Radar data at the emission source can also be input into models for tephra dispersion to improve the risk assessment, in particular regarding tephra fallout and impact on air traffic. Such a radar system (VOLDORAD 2B) has been integrated in 2009 into the INGV instrumental network monitoring Etna and has already captured several eruption from Buocca Nuova and SE Crater.

A promising direction if we are to improve our understanding of explosive eruptions is the coupling of Doppler radar observations with broadband seismic and acoustic data characterising ash emissions. While seismic and acoustic records provide information on rapid mechanical processes and mass transfers in the magmatic conduit and at the magma-air interface, their combination with a Doppler radar can bring a more complete picture of magma degassing and eruption dynamics from depth to the surface. Examples of radar signals associated with tremor and explosion quakes will be shown in various volcanic contexts at Etna, Yasur, and Arenal. We find, in particular, that amplitude or energy relationships between seismic signals characterizing the source in the conduit and their surface ash emissions captured by the radar are generally not simple.

Auvergne Seismic Network : An Overview

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In Massif Central, volcanism has been active since 65 My, with the last eruption 6900 years BP. The most recent volcanism generated the “Chaîne des Puys” and it is still considered as potentially active. One of the main goals of Observatoire de Physique du Globe de Clermont Ferrand (OPGC) is the study of volcanoes. Another component is a long-term involvement in regional seismic studies through the maintenance and management of the Auvergne Seismic Network (ASN). OPGC manages seismic stations since the beginning of the 80's and continuously upgrades them. ASN is specifically associated with all the main metropolitan national networks: RéNaSS (short period network), RLBP (broadband network) and RAP (strong motion network). It is also involved in the national educational network ‘Sismo à l’Ecole’. Nowadays, 21 stations are deployed to monitor the Massif Central seismic activity. Velocimeters and accelerometers send data in near real time, to the OPGC. To control data quality and the state of health of stations, we recently installed a web interface which displays helicorders and spectrograms using EarthWorm and SeiscomP softwares. These dedicated servers enable us to disseminate information about the local seismicity to the public as well as to media and local authorities and to share miniseed data with the national networks in near real-time.

Since 1962, less than 3000 events have been localized by ASN. The "normal" seismic activity in Auvergne, is a hundred of tectonic events per year with one or two major events of magnitude 3 or 3.5. This activity shows a weak correlation with major faults in the shallow seismogenic crust. It mostly outlines a diffuse seismicity, with a few swarms mainly linked to grabens and secondary fault systems. Though, ASN is located near a volcanic region and should be able to record an eventual volcanic reactivation, at this day no events directly linked with volcanic activity have been reported.

Despite a significant increase in the number of stations since 2000, the average spacing between stations is around 40 km with a detection threshold near 1.8. In order to monitor precisely the activity in the Montchal-Pavin area and check for the presence of any microseismicity, the OPGC installed a temporary seismic network for 9 months. During this study, we did not record any tectonic nor volcanic events in the vicinity of the lake. But the low anthropic quakes, undetectable with ASN, were well recorded. This portable network is also planned to carry temporary seismic experiments on active volcanoes in collaboration with other monitoring techniques existing at the OPGC such as the Doppler radar, DOAS and INSAR measurements.

Radon Anomalies and Seismicity related to extraordinary volcanic activity. Arenal and Turrialba volcanoes, Costa Rica.

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Radon measurements were made at several stations around Arenal and Turrialba volcanoes, Costa Rica, using LR-115 detectors (passive). Meanwhile seismicity was recorded during the same observed periods. Radon measuring stations and seismic stations are located around volcanic edifices. Radon flux anomalies occurred just before the pyroclastic flow event of March 24, 25 and 26, 2001, triggering anomalous seismicity. More recently, Turrialba volcano had a seismic swarm (April 2007) that correlates with physical changes and enhanced degassing.

Both, radon and seismicity are possible precursors of such events. Precursory seismic signals (LP and tremor) have also been studied and documented in Redoubt, (Alaska) and Galeras Volcano, (Colombia) (Fischer, T. et al. 1994) during extrusion events (Power, J. et al. 1994.) nonetheless radon measurements have not been correlated. No specific studies have undertaken correlations between radon gas, volcano seismicity, pyroclastic flows and phreatic eruptions. Other similar events observed and documented for these and other Costarrican volcanoes will be subject to similar analysis in the near future.

Seismic data will be analyzed and contrasted with extraordinary activity and particular changes on both volcanoes.

Fracture Reactivation and Magma Intrusion: The Case of the 1989 Fissure System at Mt Etna, Italy

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We focus on the role of a dry (without lava emission) fracture system, consisting of extension fractures and normal faults, which opened at Mt Etna, Italy, during the 1989 flank eruption. The NNW-SSE fracture system is located on the mid-upper SE flank of the volcano, and has experienced significant seismic activity during the past two decades. By using excellent documented records of seismic and volcanic activity on 24 November 2006 (the latter encompassing Strombolian activity, lava fountaining, ash fallout, pyroclastic flows, and lava emission from multiple vents at the Southeast Crater), we analyze the interaction between seismic radiation and the afore-mentioned fracture system. Our results highlight the importance of this system in controlling the polarization properties of seismic waves 17 years after its formation. In addition, the SE end of the 1989 fracture zone extends into several active faults, suggesting that they represent a single long structure, which plays an important role in the volcano-tectonic dynamics of Etna. Finally, this study shows how fracture reactivation can also occur by means of magma intrusion, strongly controlling the transfer of magma within a volcanic edifice.

On the relationship between great earthquakes and volcanic eruptions in Chile since 1900, with an application to the damage caused by the recent $M = 8.8$ offshore Maule event.

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In history records, chilean volcanoes have shown an interesting spacio-temporal relation with the great regional earthquakes ($M > 8$). In this work we analyze the influence of them in the volcanoes by taking in consideration the static stress changes due to seismic displacement and a model of a magma chamber which include rectified diffusion as a mode of earthquake-volcano interaction. We find that, historically, earthquakes could have promoted no more than 5 eruptions in a period of a year after it occurred. With this in mind, and considering the state of the chilean volcanoes before the recent $M = 8.8$ offshore Maule event, we make an estimation of the ones that were most affected by the seismic movement. These volcanoes are Quizapu, Peteroa, Nevados de Chillán, Llaima, and Villarrica.

Real-Time monitoring of ash clouds dispersion using HotVolc Observation System (HVOS): Insights from MSG-SEVIRI measurements

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Volcanic ash clouds represent a real threat to global economic activities as witnessed during the chaos caused by the April-May 2010 eruption of Eyjafjöll (Iceland). On the first day of the eruption, air space closure caused more than 3,000 flights to be cancelled, disrupting 371,000 passengers. Assessments of air space impact are based on ash cloud dispersion models. However, the lack of quantitative input parameters in these models can limit the accuracy of ash cloud dispersion forecasting. Here we show that the location, extent, ash concentration and radius distribution, mass flux and altitude of the ash cloud have been extracted using high temporal resolutions satellite data. The HotVolc Observation System presented here was operational and routinely provided all of these parameters from the onset of the eruption, which would have permitted ash dispersal simulations executed by the ash cloud monitoring agencies to be run with higher degrees of confidence.

Seismo-acoustic monitoring as part of integrated studies of Crater Lakes

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In recent years GNS Science has considerably improved the seismic network on and around the active volcanoes in New Zealand, but the level of activity and seismicity has been rather low and has limited our studies on these volcanoes. Despite the low activity levels, we have increased our understanding of processes in volcanic crater lakes through an application of short term scientific monitoring efforts at Waimangu, Ruapehu and White Island.

In the last year we have attached a hydrophone to our Ruapehu Crater Lake datalogger, recording short samples of the acoustic waveforms, as well as telemetering spectral power values. New results from this monitoring suggest that the acoustic power has significant energy at frequencies of hundreds of Hz, as well as a broad range of low frequencies compared to the low level seismic tremor which in recent years has been dominated by persistent 2 Hz tremor.

At the Inferno Crater in the Waimangu thermal area, in a crater created during the 1886 Tarawera eruption, we see periodic tremor associated with thermal and lake level peaks. This very hot lake regularly cycles in level by up to 8 metres, with a vigorous overflow at the peak of the cycle. A broadband seismometer run in conjunction with a gravity meter near the lake has shown that both wide-band and harmonic tremor occur as the cycle approaches a peak and they shut off abruptly just before the overflow stops. Just before ceasing, the harmonic tremor frequencies increase, suggesting a shortening of the resonator. From looking at temperature and volume changes, the seismicity seems more closely related to the heat input, which our model suggests comes from a 2-phase heat-pipe, than to the inflow of water. Microgravity results seem to show a gravity increase just before the peak of the cycle. The gravity meter is a distance of more than 20 metres from the Inferno lake edge, so it is not likely to be the direct effect of the rising lake, but it suggests that the groundwater level rises in coincidence with the lake. This can be related to previous resistivity studies, which showed changes related to the lake cycling which were apparently the result of substantial groundwater movement.

The gravity meter is now installed at White Island volcano, and we are planning a seismic deployment there for next year. The new work will improve our understanding of heat and mass transfer processes below volcanic crater lakes in New Zealand.

Eruption source processes derived from seismic and acoustic observations of the 25 september 2007 Ruapehu eruption – North island, New Zealand

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Mt. Ruapehu erupted on 25 September 2007 at 20:26 PM NZDT (8:26 UT) generating a steam column to about 4600 m, a directed ballistic and surge deposit of coarse blocks and ash to the north of the Crater Lake, and initiated lahars in the Whangaehu catchment and Whakapapa ski field. The eruption was recorded on three broadband seismometers and two acoustic pressure sensors which indicated broadly coherent waveform characteristics across the network. The eruption had duration of less than 1 minute as indicated by strong seismic and acoustic pulses. The acoustic wave coincided with observed very long- period (VLP) seismic signal (2-25 s period). The acoustic pulse had positive pressure (indicating an explosion) and travelled at a velocity of ~320 m/s. The syn-eruptive VLP was composed of surface waves having strong radial and transverse components. The immediate aftermath of the eruption produced about 4 minutes of continued high amplitude spasmodic tremor signals that probably resulted from post-explosion phase associated vent backfill/stabilisation. The eruption was preceded by minor volcano-tectonic earthquakes and tremor bursts which began 10 minutes before the main eruption. Two smaller VLP signals were associated with these tremor pulses at 20:17 and 20:25. These pre-eruptive VLP signals had particle motions indicating body waves from a subsurface source region. Modelling of the VLP sources using a 3D finite-difference method shows that the pre-eruption VLP signals are consistent with a volume fluctuation at 3-7 km depth from a radially symmetric source. The main eruption VLP was consistent with a south and downward directed single force in response to a northward directed jet and northward directed ballistic deposits.

Jolly et al., 2010 - JVGR – 191, 33-45

First geophysical ground observations for volcanic risk mitigation within MIAVITA FP7 project: examples from Kanlaon (Philippines), Merapi (Indonesia) and Fogo (Cape Verde) volcanoes.

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The MIAVITA project aims at developing tools and integrated cost effective methodologies to mitigate risks from various hazards on active volcanoes (prevention, crisis management and recovering). Such methodology is being designed for developing countries and will be helpful for European stakeholders to improve their experience in volcanic risk management. The project multidisciplinary team gathers civil defence agencies, scientific teams (earth sciences, social sciences, building, soil, agriculture, Information Technologies and telecommunications) and an information technology private company.

One of the scientific goals is to design cost-effective monitoring tools for poorly monitored volcanoes, including remote (satellite based) and ground geophysical (e. g., volcano-seismology and deformation) and geochemical techniques (e.g., gas monitoring using MiniDOAS). We set up new volcano monitoring facilities at targeted volcanoes in the Philippines, Indonesia and Cape Verde. We present observation networks and first observations.

Kanlaon volcano (Negros Philippines) is an andesitic volcano, which was not well monitored before the start of MIAVITA project. A permanent network of 3 short-period seismometers has been upgraded with 3 broadband seismometers; a series of GPS benchmarks and levelling lines have been setup and monitored twice since 2009. Results indicate a low level of seismicity and no deformation up to now.

Merapi volcano (Java, Indonesia) is a well known active andesitic dangerous volcano located at 40 km north of Yogyakarta. A permanent network of 4 short period and 1 broadband stations has been upgraded with 5 broadband seismological stations. The network has also been upgraded with local ISP telemetry system. A first series of DOAS observations has been performed. A network of 3 automated DOAS scanners for a continuous monitoring of gas emissions will be set-up in the next future. Results indicate a low level of seismicity and low gas emissions. We aim at understanding better the link between observed seismicity and degassing.

Fogo volcano (Cape Verde) is a basaltic volcano in Cape Verde. A permanent network of 7 stations (including 5 short-period stations and 2 broadband stations) is being upgraded with 4 broadband stations. Furthermore the telemetry is being also upgraded, namely using VSAT and local ISP to data broadcast.

Seismic Tomography and Long-Period Earthquakes Observation and Modelling at the Hengill Geothermal Volcanic Complex, Iceland

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Structural features of hydrothermal and volcanic systems allow us to infer the location of magma chambers or geothermal productive areas. One of the great advantage of studying geothermal systems targeted for economic purposes is that on the one hand, they are much less dangerous than volcanic active systems, due to the hazard associated with magmatic and hydrothermal eruptive activity, and on the other hand they exhibit the same kind of structural features and processes. Therefore, the study of geothermal systems may of great help for the understanding of structural and hydrothermal features at active volcanic systems.

The Hengill volcanic complex is located at a triple-junction between two segments of the spreading ridge between North American plate and European plate, and a transform fault (South Iceland Seismic Zone). It has a well-developed geothermal system, exploited to extract hot fluids that are used for electrical power and heat production. This area is subject to intense seismic activity, which is monitored continuously by a permanent seismological network, the SIL network of the Icelandic Meteorological Office.

In the framework of the I-GET project (European Commission FP6), we set up a 4-month temporary seismological network including seven high-dynamic broadband instruments, and we performed 1-D Transient Electro-Magnetic soundings and 3-D Magneto-telluric surveys, in order to improve our understanding of the relationships between structural features, seismic activity and vapour production at the Hengill geothermal system. The analysis of MT and TDEM data set is described in another work. The analysis of the seismological data set allowed us to detect and classify more than 600 earthquakes, amongst which long-period (LP) earthquakes were observed for the first time in this area. This work focuses first on a joint inversion for the 3-D velocity structure and hypocenter location determination, by using about 250 local volcano-tectonic earthquakes with clear P- and S- wave arrival times. Our results confirm results from earlier tomography studies in this area. We integrate the two models in a semi-quantitative approach by cross-plotting resistivity model with the ratio V_P/V_S , between compression V_P and shear V_S velocities. We find a structural body with high ratio between seismic velocities and low resistivity interpreted as the main heat source of the geothermal system.

The new structural features at Hengill provides opportunities for studying the relation between local seismicity and fluid exploitation. We find that LP observed earthquakes happen close to exploitation wells when extraction rate is changed. We model LP earthquakes using a wave propagation modelling finite difference scheme with topography, velocity model and attenuation. We find that the synthetic LP earthquake has frequencies similar to those recorded in the observed LP earthquakes. This suggests that the resonance of a part of the geothermal system may explain characteristics of low-frequencies and that a sudden change of pressure due to exploitation rate change may be the trigger for LP seismicity.

Our results may be extrapolated to hydrothermal systems around active volcanoes where drilling may be hazardous.

THE CYCLE OF A DISASTER

A.Jolly

The occurrence of a disaster/incident, whether that be a seismic event, terrorism, or man-made, is never stand-alone. A cyclical process follows any disaster that includes the recovery and rehabilitation of an area. Learning points from this allow us to plan and mitigate for a more effective recovery and response on a like for like recurrence.

This discussion will explore the 6 stages of the disaster cycle. Understanding the importance of each stage and some of the key elements that define it. A practical case study of the Kobe earthquake in 1995 will also be used to develop some of thinking behind each stage.

Relationships between earthquakes, hydrothermal systems and eruptions: the case of Piton de la Fournaise.

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The role of the hydrothermal systems in volcanic activity has been increasingly considered during the last decade, but mostly in the case of large silicic calderas. Here, we investigate the possible interactions between a shallow hydrothermal system and the activity of a shield basaltic volcano, Piton de la Fournaise. We note that during all the volcanic crises, a zone located beneath the summit craters, from about sea-level to near the surface, is always seismically active. This cylindrical zone corresponds to a block that has repeatedly collapsed over an inferred magma reservoir located near sea-level during historical times, the last episode being in 2007. This volume of rock is therefore a major geological heterogeneity within the edifice in which high permeability allows preferential circulation of hydrothermal fluids.

Our model is based on two key structures: a magma reservoir surmounted by a well developed hydrothermal system in a permeable cylinder. During the repose periods, the hydrothermal system is heated by the magma reservoir. As a result of the increase in temperature of the hydrothermal fluids, the pore-pressure builds up and generates fractures in the column. When the hydrothermal fracturing (pre-eruptive periods) becomes intense, the formation of fractures at the base of the hydrothermal system creates transient low pressure regions that act as nuclei for magma decompression, thus triggering the magma intrusion process.

Though qualitative, this model fits well with the pre-eruptive pattern for Piton de la Fournaise. It should encourage complementary investigations to refine, or invalidate, this new interpretation of the crises at Piton de la Fournaise and at comparable volcanoes.

Broad band seismic observations of vulcanian explosions, during the 2005 eruptive crisis of Volcán de Colima, Mexico.

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During 2005, several major vulcanian explosions with ash-rich columns and pyroclastic flows occurred at Volcán de Colima. They were recorded by a broad-band seismometer located at about 4 km from the crater. Explosions are thought of as complex phenomena involving multiple sources with different mechanisms, depths, energy releases and frequency ranges. In this work, we analyze and compare the main features of the 17 largest explosions in four frequency intervals: the VLP (30-10 sec), LP (0.1-1 Hz), SP (1-10 Hz) and HF (10-50 Hz) bands.

In the VLP band, 14 events recorded on the vertical component of the seismometer display similar waveforms with correlation coefficient higher than 0.8. However, much larger variability of the waveforms is observed with the horizontal components yielding only 2 and 5 events with high correlation on the N-S and E-W components, respectively. The particle motions show also highly variable and complex patterns. These observations suggest that the source of VLP events at Colima is poorly repetitive and/or the waveforms are strongly dependent on complex path effects. No clear correlation are found between the amplitudes in the VLP, LP and SP ranges, reflecting low or non-linear coupling between the corresponding sources. On the other hand, significant correlation is obtained between the VLP's amplitude and the duration of pyroclastic flows estimated from the HF bands. This relationship may indicate a possible link between the VLP source and the volume of erupted material.

Mission Impossible : moment tensor inversion for volcanic events

Jurgen Neuberg & Tom Roome

Moment tensor inversions form a very important component of the seismological analysis of volcano related seismicity, as this analysis provides an important insight in the actual source process of the event. So far the influence of topography and the velocity model on the inversion results have been intensely studied. We extend this investigation in a different direction and test more complicated source models against the usual point-source assumption, and discuss implications for the interpretation of such moment tensor inversions.

An up-date on gas storage, transport and mass balance in volcanic systems

Jurgen Neuberg & Amy Collinson:

A number of different models will be shown that address the numerical modelling of gas storage, transport and loss in a volcanic plumbing system. Starting with a simple combination of mass conservation, Darcy's Law and the Ideal Gas Law, we extend the modelling to incorporate gravity and time dependence. In this way we combine pressure boundary conditions with (anisotropic) permeability in different volcanic sub-domains to generate the gas velocity distribution and the resulting motion of gas concentration through time.

This methodology can now be applied to cases of a dome collapse, opening of cracks and other sudden degassing events.

Locating sources of explosion quakes and long-period events at Yasur volcano, Vanuatu

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Yasur is a small scoria cone located on Tanna Island (South Vanuatu). The cone is composed of 3 vents: two vents (A and B) in the southern crater and one vent (C) in the northern crater. The volcano is going through a permanent strombolian activity, characterized by explosions of gas bubbles and small ash plumes. The activity generates thousands of seismic signals per day, mostly explosion quakes (EQs) and long-period events (LP). From January 2008 to February 2009, seismic activity has been recorded by 12 seismic antennas, each composed of 7 short-period sensors: a 3 components seismometer surrounded by six vertical sensors. Distances between the central seismometer and the others sensors was 20m or 40m. In May 2008, 10 broadband stations have been installed to complete the seismic network. In this work, we present source locations obtained for EQs and LP recorded during the experiment. Each signal, classified in different families of similar events, is located using a seismic triangulation method. This method is based on the calculation of the time delays between each pair of seismometers, allowing to estimate the slowness vector (which contains back-azimuth and apparent velocity) for each antenna. Using a probabilistic approach, the probability density functions of back-azimuth are computed providing the directions of propagation of the wave field. The position of the source is determined by intersecting these directions. To estimate the source depth, we used a method based 1) on the differences of propagation time between the P and the acoustic waves, and 2) on the differences of apparent velocity associated to each family of events. The combination of these two methods allowed to show that the majority of the EQs recorded during the 2008 year came from the south crater and have been located between 250 meters and 700 meters below the surface. Nevertheless, during a few periods lasting for a few days the EQs activity has been located on the north crater roughly at a hundred meters below the surface. In contrast to the EQs whose sources were relatively stable, the long-period activity showed different behaviors according to the periods of time. These behaviors, stability or progressive variation of back-azimuth and apparent velocity, have highlighted source displacements of several hundred meters towards North-East and surface, then towards South only. The comparison of the EQ activity with the LP activity showed few similarity. In general, changes in source location of EQs were not correlated with changes in source location of LP events and conversely. Comparing all these results with previous studies realized at Yasur and Stromboli volcanoes, several assumptions on the volcanic dynamics (depth and mechanisms governing the gas coalescence zone) will be presented.

Insight into the dynamics of the magma plumbing system through seismicity rate evolution.

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Based on two different examples, we show how the study of seismicity rate evolution through time can provide useful constraints on the dynamics of the magma plumbing system at basaltic volcanoes. Firstly, the exponential increase of the cumulative number of earthquakes observed between 1975 and 1984 at Mauna Loa volcano, Hawaii, is interpreted using a physical model. The reservoir pressure increase produced by the accumulation of magma into a shallow reservoir connected to a deep magma source at constant pressure, explain well the exponential decay of the deformation rate. Using the derived magma pressure evolution as an input for a simple model of damage, where damage episodes are equivalent to earthquakes, allows us to reproduce the exponential increase of the VT activity. This VT activity can thus be a direct indication of the accumulation of magma at depth, and therefore can be seen as a long-term precursory phenomenon. It also bring constrain on the strength of the hydraulic connection between the shallow reservoir and the deep magma source. Secondly, the constant seismicity rate observed during the intrusive period of the August 2003 Piton de la Fournaise eruption is modelled considering a 2 step dyke propagation (vertical followed by horizontal propagation) characterized by a constant magma inflow. The constant magma inflow condition implies a minimum size for the magma reservoir of about 1 km³ and a maximum value for the initial magma reservoir overpressure of about 2.2 MPa. Considering similar magma inflow rates during vertical and lateral dike propagation phases, we reproduce independent estimates of propagation velocities, rise times, and injected volumes. We also estimate that the lateral dyke breadth has to be five time larger than the vertical dyke one.

Volcanic activity initiation inferred over a decade of micro-seismicity monitoring at Piton de la Fournaise volcano

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On average, Piton de la Fournaise has erupted three times a year over the past decade. Its eruptions lasted from a few hours to a few months and were associated with clear volcanic tremor. The studied time period (1999-2008) started and ended with two major eruptions, namely the March 1998 eruption (60 million cubic meters of lava emitted) and the April 2007 eruption associated to the 300 m collapse of the main Dolomieu crater (130 million cubic meters of lava emitted). During that time, one intrusion, 8 summital, 5 near-summital, 12 proximal and 6 distal eruptions have been recorded. The observed seismicity on Piton de la Fournaise is characterized mainly by inter-eruptive seismicity mostly composed of superficial volcano-tectonic earthquakes (-1 to 2 km above sea level) with magnitudes ranging from nearly 0 to 3 and pre-eruptive swarms of seismicity lasting a few hours. Deeper seismicity may be recorded as deep as 15 km below sea level. Volcano-tectonic seismicity is commonly described as being associated to magma-induced stress perturbations. However, volcanic seismicity may also reflect the processes of deformation associated to the regional stress field and to local stress field perturbations induced by the morphology and structure of the edifice itself. The study of volcano-tectonic seismicity may thus help to infer the processes of volcanic unrest and edifice growth and destabilization. In this study, we focus on the spatio-temporal analysis of shallow volcano-tectonic seismicity (-1 to 2 km above sea level) during inter-eruptive periods. We performed a massive extraction of 30,000 triggered shallow earthquakes from the continuous seismic records of Piton de la Fournaise Volcanological Observatory. We use a technique based on waveform cross-correlations to classify the dataset in clusters of repeating earthquakes and to calculate high precision time-delays between traces to obtain relative locations within each cluster.

The relocated earthquakes delineate a network of small-scale fractures with sizes of the order of tens of meters, between 0 and 1 km above sea level, mainly clustered beneath the Bory secondary crater located at the western part of the Dolomieu crater. A time extended series of repeating events, present before several eruptions independently of their eruptive fissure elevation, points towards a common process of injection initiation. Moreover, inter-eruptive seismicity seems to show a good correlation with an estimated tremor intensity factor. On the other hand, the temporal occurrence of inter-eruptive summit seismicity shows a long-term increase of average number of events per day, probably linked to the progressive damage of the edifice leading to the 2007 caldera collapse of Dolomieu crater. Inter-eruptive seismicity on Piton de la Fournaise thus seems to be associated to pre-eruptive processes (few months) of volcanic unrest such as magma pressurization, injection and also to longer-term processes of edifice growth and destruction.

Chugging signals at Reventador volcano, Ecuador

Ruiz Mario and Luis Manzanillas

Reventador is one of the most active volcanoes in Ecuador with eruptive episodes in the last century. After 26 years of quiescence, a climatic VEI 4 eruption occurred on November 3rd 2002, Reventador volcano. This eruption was followed by seven periods of activity on November 2004 - February 2005, April 2005-February 2006, March-April 2007, August-December 2007, July-November 2008, February 2009, and October 2009-September 2010. These reawakening periods are characterized by small lava flows, mild strombolian activity and seldom pyroclastic flows. Effusive volcanic phases are preceded by volcanic-tectonics, long-period events and harmonic tremor episodes. Infrasound sensors installed in conjunction with a broad-band seismic sensor inside the volcano amphitheater at the lower flanks of the resurgent cone, allow recording harmonic infrasound tremor, chugging sequences and explosion events. Explosion events with a large variation on time lapses between seismic and acoustic arrivals suggest multiple source depths. Infrasound tremor or chugging follow explosion events with a time delay between 0 to 26 min. Chugging duration has an average of 83 secs with events lasting about 12 min. Chugging inside three pulses at the same event (2009-09-18) exhibit a positive correlation between time lapses and pressure amplitudes at the first stage, and a negative correlation at the last pulse, suggesting a non-linear mechanism for triggering chocked gas emissions. Analysis of seismic and infrasound data suggests that Reventador volcano exhibits a non-typical strombolian eruption style during recent reawakening periods.

Pre-eruptive patterns from multi-parameter monitoring on Piton de la Fournaise volcano: implications for predictability.

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Because volcanic eruptions often represent a danger for the population, and because the volcanic risk might lead to heavy preventive solutions such as evacuation, volcanic hazard assessment is a necessary ingredient for decision-makers. However, the prediction of volcanic eruptions remains challenging due to the complexity and the non-linearity of volcanic processes.

Previous studies on Piton de la Fournaise volcano have identified several forerunners to eruptions. However, none of those forerunners show deterministic behaviour, ie if occurring, they don't lead necessarily to an eruption, and some eruptions are not preceded by any of those forerunners. That is why we used a statistical approach on the data in order to evaluate the predictability of eruptions expected from the pre-eruptive precursory behaviours of different kind of forerunners.

First, we analysed the time series of three data sets previously shown to behave as precursors: daily seismicity rates, displacements and seismic velocity changes (computed from seismic noise cross-correlations, *Brenguier et al, 2008*). This leads us to extract time specific patterns and therefore to better constrain the time scales of pre-eruptive mechanisms leading to magma transfers up to the surface. Second, following *Grasso et Zaliapin, 2004*, we used the formalisation of error diagrams (*Molchan et Kagan, 1992*) to quantify and to compare the predictability of eruptions obtained from the three studied forerunners, over the 2000-2007 period. We analysed their predictive power either when using a single dataset or when using merged data.

As results, we find that different time scales and dynamics emerge from the superposed epoch analysis of time series before eruption time. These mean pre-eruptive patterns of the forerunners emerge from stacked time series over all eruptions on the considered period. The daily seismicity rate shows a power law acceleration starting 10 to 15 days before eruption time. This divergence towards eruption is then a good candidate to predict time of the impending eruption, at intereruptive time scales. Both the aperture of a given sensitive crack on the volcano flank, and the variation of seismic velocities averaged over the whole volcano edifice, show a linear increase within hundred days from the eruption. Those early precursory patterns image earlier stages of the eruptive processes but the linearity gives poor information on the rupture time. Finally, the seismic velocity changes show longer relaxation durations. This inertial behaviour is enhanced after large eruptions.

A methodology is being developed to estimate and compare the prediction results of the different data, and to combine the informations given by each of them. Preliminary results on the predictability of Piton de la Fournaise eruptions show that seismicity is the most powerful forerunner to infer occurrence time of eruptions. With our first approach, prediction results obtained when combining the information of the different forerunners are largely dominated by prediction results due to the seismicity alone. Further investigation is under progress to better extract the information given by each of the forerunners.

Brittle seismic damage before eruptions, an insight on the pre-eruptive mechanisms.

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Volcanic eruptions and surrounding earthquakes are shown to interact at different time and space scales, from a few hundreds of km for VEI>5 eruptions (*Linde and Sacks, 1998*), down to a few tens of km for smaller VEI (*Lemarchand and Grasso, 2007*). The latter suggest that the seismicity rate before eruptions follows inverse Omori's law (*Omori, 1896*) similar to the one observed for earthquakes, but with possible different parameters values. Given this similarity, we were interested in further compare the properties of the upper crust damage (expressed through the seismicity) contemporary to worldwide eruptions with damage triggered by classical tectonic loading of worldwide earthquakes. Using a few empirical laws (Gutenberg-Richter law, Omori law) ETAS model well reproduces the main observed properties of tectonic seismicity. It will here be considered as null hypothesis. Differences from ETAS model or global tectonic seismicity will give us constrains on the specificity of the magmatic loading and the pre-eruptive mechanisms.

First, we analyzed the properties of the damage processes regarding crust loading, thanks to patterns of seismicity before i) main earthquakes (mag>7) of a USGS worldwide catalog, ii) main earthquakes of a synthetic ETAS simulation, iii) worldwide eruptions from the SI catalog. Using stacked sequences of seismic events around eruption times (for different classes of eruption's sizes), we found that the parameters of inverse Omori law significantly differ from expected values of ETAS model or real tectonic seismicity : i) The productivity in foreshocks, and the exponent of the power-law increase of foreshock seismicity appear to depend on the size of the eruption, ii) For small eruptions, the p-value of foreshock sequences (as well as for aftershock sequences) is smaller than for earthquakes. Those differences have to be interpreted either in terms of different forcing rates, or specific medium (temperature, presence of fluids). Given that small eruption processes (effusive volcanoes) show longer failure times than earthquake rupture propagation it possibly argues for the small eruption processes to impact the brittle crust the same way than slow earthquakes.

Second, we worked at smaller space scale by studying the damage processes expressed by local volcano-tectonic earthquakes prior eruption on a single volcano, Piton de la Fournaise, La Réunion Island. Evidences for crust loading have been highlighted thanks to seismicity within 10-15 days prior eruption time (*Collombet and Grasso, 2003*). Using stacked time-series of seismicity prior different classes of eruptions (small or large eruptive volumes), we find that the p-value of foreshocks sequences also depends on the size of eruption, similarly to worldwide eruptions. This result suggests some volume predictability of eruptions and offers new perspectives for volcanic hazard assesment.

Using Acoustic Emission Monitoring in the Laboratory to Help Understand Volcano Seismicity

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Although seismicity is integral to volcano monitoring, there is still much debate about the precise source processes of some forms of volcanic seismicity. Here we monitor acoustic emissions (AE) whilst deforming different types of magmas and volcanic rocks under controlled conditions in order to find how the AE vary during different eruptive processes, with an emphasis on the details of the ductile-brittle transition. Deformed rocks and magmas were also subjected to neutron computed tomography (NCT) and optical analysis to describe fracture mechanisms. The quantity and character of AE signals recorded during different experiments are compared to each other and to different types of seismic events recorded at volcanoes, in order to gain insights into the source processes that generate the diverse seismicity recorded at volcanoes.

We find that cracking of cold dacites, andesites, and basalts during triaxial deformation produces AE that are comparable and scalable to volcano-tectonic, or typical tectonic, earthquakes. Increasing the temperature of crystalline dacites to the onset of the brittle-ductile transition, such that the rock still maintains cohesion and exhibits brittle failure when deformed fast enough, produces measurable but lower energy and amplitude AE, despite similar macroscopic behaviour and strength to the low temperature tests. The timing of AE is also more localised to the time of sample failure, and the distribution of cracking in the sample is more localised to the shear failure plane.

Deformation of magmas at temperatures above the glass transition is strongly dependent on crystallinity. Crystal-free magmas behave as Newtonian fluids with aseismic deformation. When the strain rate exceeds their relaxation rate, the glass transition is crossed and cracking ensues, recorded as a near instantaneous release of AE. Increasing the crystallinity, widens the range of strain rates at which cracking occurs. Within the ductile-brittle transition of dacitic to basalt-andesitic magmas (containing 10-45% interstitial melt of rhyolitic to andesitic composition, 55-90% crystals and 5-20% pores), deformation is accompanied by an AE energy release rate that increases nonlinearly with strain rate. This observation is understood in the deformation mechanism, where the ratio of ductile to brittle deformation controls the total strain to failure. NCT and b-value analyses show that cracking is more homogeneously distributed for samples with more ductile deformation mechanisms and that much strain is required before failure of the sample, whereas when the mechanism was more brittle at a higher strain rate, the cracking is more localised and little total strain is required before failure. In all cases, failure of the sample is preceded by accelerations in released AE energy that can be used to forecast the time of failure.

AE recorded during fragmentation of volcanic rocks by rapid decompression are proportional to the energy stored in the pore space prior to fragmentation and to the particle sizes produced by the fragmentation. This correlation may help develop a method to infer the size of volcanic explosions from the seismic events it generates.

In the laboratory, AE are proving to be a useful tool to monitor experiments recreating diverse volcanic processes and conditions; they thus hold promise to help interpret diverse seismic signals recorded at volcanoes.

Lower crustal earthquakes at Askja volcano, Iceland: multi-location melt supply from the mantle within a single volcanic system

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The volcanic system of Askja within the north Iceland spreading plate boundary comprises a central volcano with a nested caldera system and a fissure swarm transecting it. Over 1000 lower-crustal earthquakes (13 – 27 km depth) have been recorded at Askja, using local arrays of broadband seismometers. The brittle-ductile boundary in the Askja region is well defined by a sharp lower cut-off of upper-crustal seismicity at depths of 5 – 7 km. The lower-crustal earthquakes are well within the normally aseismic and ductile part of the crust. The events often occur in swarms lasting several minutes, with hypocentres from a single swarm located close to one another. In average, 1.5 events per day are detected, although quiescences up to two weeks have been observed.

Our semi-continuous observations, starting from 2005, outline three distinct and persistent clusters of lower-crustal seismicity. The largest one is located at the northern boundary of the youngest of the nested Askja calderas. This cluster is adjacent to a geodetically proposed magma chamber and extends along the fissure swarm of the Askja volcanic system 10 km to the northeast. The second cluster is located 20 km further to the northeast along the fissure swarm, northwest of Herðubreið table mountain. The third cluster is 10 km east of Askja, north of Vaðalda shield volcano. The dimensions and locations of each of the clusters have not changed since we commenced continuous seismic monitoring in summer 2007. Each cluster has a stable upper cut-off depth, possibly the location of a magma body such as a sill.

Our interpretation is that these earthquakes are caused by magma movements within the lower crust, possibly between sills at different depths. The three spatially separated clusters of events could indicate positions of long term magma supply from the mantle. This suggests that this part of the volcanic rift zone is supplied with melt simultaneously at multiple localities along each segment rather than by lateral melt migration fed from a single input.

Source process of long-period seismic pulses, and non-linear dynamics of long-period volcanic tremors observed at Mt. Asama

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On September 1, 2004, a middle-scale eruption occurred at Mt. Asama. Before the eruption, we had observed several kinds of long-period earthquakes and tremors since October 2003. These long-period events are classified into three types depending on these waveforms. The first-type event consists of several one-sided velocity pulses with durations of 5 sec to 30 sec, calling long-period pulses. The second-type event is a long-period and long-lasting earthquake followed by two large high frequency earthquakes. The third-type event is a tremor whose tip of the waveform is sharp, suggesting a non-linear dynamics of the source process.

After the eruption activity, the long-period pulses have continued to occur until now. To reveal the source process of the long-period pulses, we had installed 14 broadband seismographs within 1 km of the summit crater from September 2008 to November 2008. These particle motions do not point to a single source location despite their rectilinear shapes, suggesting a non-isotropic source mechanism. We conducted moment-tensor inversion analyses for these events using the Green's functions of not only translational motions but also of tilt motions. The best-fit source locations are deviated to the area north of the crater center, at depths of 100–200 m below the crater bottom. The principal value ratios of moment-tensor solutions can be approximated as 5:3:2, which is indicative of a combination of a tensile crack and cylinder. The time histories of moment tensors are indicative of an initial sudden pressurization and subsequent gradual depressurization at the source region. We sought to model long-period pulses at Asama volcano by considering the inflow and outflow of gas generated by sudden boiling in a deep reservoir.

Before the 2004 eruption, the third-type tremors occurred at 4:25, 11:30, and 20:30 on June 24, 2004. We revealed the non-linear dynamics of the third-type events using an embedding method of time delays and surrogate data analysis. The first step for the nonlinear analysis of a single time series is to reconstruct a topologically equivalent attractor to the original in a relatively low-dimensional delay-coordinate space. The key questions are how the minimum embedding dimension can be determined for reconstructing the original dynamics, and how we select the delay time. We employed higher-order correlations to select an optimum delay time (Albano et al., 1991) and a practical method for determining minimum embedding dimension proposed by Cao (1997). It is made clear that there existed a deterministic non-linear dynamics in the tremor excitation, which could be modeled with the system dimension between 3 to 7. We also applied the same method to the second-type events and revealed that the source process of the these events could be modeled on a non-linear dynamics with a system dimension between 3 to 6, which is similar dimension range with the source process of the third-type tremors. Another way of saying, the apparent waveform characteristics of the second-type and the third-type events are quite different, however the both minimum embedding dimensions and the both correlation dimensions are almost same values to each other.

Modifying a hydraulic control valve model with the system dimension of 4, we succeeded to simulate long-period oscillations resembling with the long-period earthquakes and with the long-period tremors based on a same mathematical model. These two long-period oscillations are sharply distinguished by a discharge coefficient of vent. This model seems to be associated with the source process of the long-period pulses considering the inflow and outflow of gas. The remaining problem is how to excite seismic waves from the simulated valve oscillations.

Linking observations at active volcanoes to physical processes through conduit flow modelling. How is it done, What do we need?

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Low frequency seismic events observed on volcanoes such as Soufriere hills, Montserrat may offer key indications about the state of a volcanic system. To obtain a better understanding of the source of these events and of the physical processes that take place within a volcano it is necessary to understand the conditions of magma at depth. This can be achieved through conduit flow modelling (Collier & Neuberg, 2006). Fully compressible Navier-Stokes equations are solved through a Finite Element approach, for differing initial water and crystal contents, magma temperatures, chamber overpressures and geometric shapes of conduit. In the fully interdependent modelled system each of these variables has an effect on the magma density, viscosity, gas content, and also the pressure within the flow. These variables in turn affect the magma ascent velocity and the overall eruption dynamics of an active system.

What is surprising, are the magnitude of changes engendered in the flow by relatively small variations in model parameters. For example, slight changes in conduit geometry, initial water and crystal contents or magma temperature can cause not only profound local effects on the flow dynamics, but global effects too. One such example would be altering the width of a 5000m conduit over the top few hundred meters. This affects not only that localised area, but the ascent velocity of the magma within the entire conduit. This in turn has a feed-back on all aspects of the system. One of the most important and often overlooked aspects of conduit flow models are the bubbles, or more specifically their shape and number. Bubbles are ubiquitous in magma during an eruption and have a major influence on the rheology of the suspension (Llewelin & Manga, 2005). For the first time in a true conduit model, with no averaging of flow properties, the effects of bubbles on magma rheology are fully incorporated into a flow model, resulting in both lateral and vertical variations in the flow parameters.

The validity of evaluating conduit conditions using 2-D models, which are more representative of dykes, is also examined. These models, typically used by authors as a representation of a conduit system have two true dimensions, typically a X and Z direction, but are considered infinite in the Y direction, into the plane of the model space. While these models offer a good first approximation of a conduit system, it is shown that the derived flow parameters are markedly different from those of a true conduit model.

There have been some significant advances in conduit flow modelling over the last 10 years and the processes involved are consequently much better understood. However, there are still many unanswered questions which are addressed through this work, not least what is important to include in the model, what is still missing and what model inputs need to be better defined.

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Llewelin, E.W., and Manga, M. 2005. Bubble suspension rheology and implications for conduit flow. *Journal of volcanology and geothermal research*, **143**, 207-217.

Linking conduit and surface activity at Arenal volcano using broadband seismometers and Doppler radar: do we need a new conduit model?

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We carried out a cross-correlation of broadband seismic data and ground-based Doppler radar data obtained at Arenal (Costa Rica) in February 2005. Our aim was to gain insight into the subsurface source processes (i.e., fragmentation mechanisms operating in the shallow conduit system) and the subsequent pyroclastic emissions (i.e., plume mass loading and ascent dynamics) that characterize the transitory, mildly explosive activity at Arenal. Study of the radar and seismic waveforms revealed a non-systematic relationship between them, both exhibiting a large variety of behaviors and features, but no clear patterns could be distinguished. Pyroclastic emissions recorded by the radar also did not have a unique seismic signature: 44% of radar signals were found in association with explosion-type seismic events, 43% during episodes of tremor, and 13% during aseismic intervals. Over longer time-scales, radar event amplitudes showed no correlation with the seismic energy release rate (RSEM), nor with RSAM, nor with repose time intervals. Energy proxies obtained from coeval radar (plume energy) and seismic (explosion energy) data show significant scattering, indicating that the ratio of the seismic/radar energy was highly variable. Plume mass-loading and exit velocity thus seems only weakly correlated to the seismic energy generated by the explosion, suggesting that the seismic energy might not be a good indicator of the intensity of explosions at Arenal.

The occurrence of radar echoes in different range gates indicates that several vents were active, which is consistent with the clarinet-model for tremor generation at Arenal (Lesage et al., 2006), in which fractures in the plug act as valves that control degassing, with multiple conduits explaining the occurrence of different sets of harmonic frequencies in seismic data. Fragmentation is best explained by pressure build-up below a plug obstructing the conduit. This, when a resistance threshold is overcome, fails and yields sudden decompression, allowing gas bubbles in the magma to rapidly expand and fragment the viscous host magma. Nevertheless, this model fails to explain the full spectrum of activity, recorded signals, and seismic/radar energy partitioning. Variable source depth may, though, cause variation in elastic energy radiation, and variable fragmentation mechanisms may explain varying seismic signals associated with the emissions. It is possible that non-linear, inter- and time-dependent, processes explain unstable dynamic systems such as Arenal, and are required to trigger transitions from one fragmentation mechanism to another.

Forecasting Volcanic Eruptions in Extensional Tectonic Settings

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Volcano-tectonic (VT) seismicity is one of the first precursors to be detected before volcanic eruptions. The number of recorded events tends to accelerate with time and, in many cases, the increase is described by the Voight Relation, for which the acceleration increases as a power-law function of the rate (Voight, 1988). The Voight Relation has been field tested primarily with data from volcanoes in compressional tectonic settings. The aim of our current research programme is to extend quantitative evaluations to patterns of VT precursors in extensional settings.

At volcanoes in compressional tectonic settings, the rate of increase has been observed to evolve from an exponential to hyperbolic (faster than exponential) trend with time, corresponding to the acceleration changing from being proportional first to the rate and, later, to the square of the rate. Similar trends have been observed in the laboratory among rates of acoustic emission before the bulk failure of crustal rocks in compression (Meredith et al., 1990; Smith et al., 2009). The simplest interpretation is that rates change from exponential to faster trends as the process controlling the rate of fracturing changes from an increase in the number of growing fractures, under an increasing load, to an increase in the rate of growth of active fractures by self-acceleration at an approximately constant load (which corresponds to the load for bulk failure; Kilburn, 2003). The associated times for development are weeks-months for the exponential trend and about 14 days or less for the hyperbolic trend (Kilburn & Sammonds, 2005).

Within extensional settings, in contrast, VT precursors commonly evolve from an initial exponential trend (over weeks) to an abrupt, step-like increase within 1-2 days before eruption (Bell & Kilburn, 2010). Controls on the abrupt final increase will be investigated using field data from extensional-zone volcanoes, including Etna, Piton de La Fournaise and examples in Iceland, as well as laboratory data from new rock-physics experiments on extensional rock failure. The results will identify limits on forecasting times from deterministic models and these, in turn, will be applied to the design of appropriate responses during volcanic emergencies.

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Debris avalanches: relations between sedimentary aspects and kinematics of localized systems : interest of large scale models

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The recent models of the Socompa volcanic debris avalanche provide an introduction illustrating the interest of large scale models. Different experimental studies present the early stage of edifice failure, the different transport steps and involve different hypotheses to explain the long run-out distances. Some similar experiments seem possible at a large scale. Also some natural uncertainties constrain what can be modelled.

Our field observations in the French Massif Central show organized structures in specific kinematic contexts: in a proximal lateral levee at “Le Cheix”, at the base of a distal channelized volcanic debris avalanche at “Perrier”.

In “Le Cheix” unit, the clasts have different structures with a specific distribution on and between clasts. There is a general breccia structure with conjugate fracture systems. For blocks (=clasts) surface structures are an oriented abrasion and impact structures. Internal structures can be brittle or ductile and there can be schistosity development in sedimentary clasts, often associated with interactive structures and displacement between the clasts. We observe a preservation of preferentially orientated structures, which implies that a coherent and persistent structure is maintained in the deposit during transport. There is also a specific distribution of structures on blocks (e.g. upstream abrasion, lower downstream brecciation). This indicates a clear order to structural events imposed by the moving mass through its density, the interaction of forces and transport conditions.

In the Perrier unit 4, the sheared basal contact is well exposed. The kinematics and specific clast transformations are observed. Impacts and splash structures indicating local matrix motion are preserved. This requires a partial fluidisation (probably thixotropy) along a tangential and vertical gradient from the impact. A vertical deformation gradient changing from ductile to brittle response is observed over 3 horizons, (1) a lower layer with a high concentration of mobilized fluvial pebbles, (2) a middle zone with a concentration of sheared pumice indicating different densities and strains between the two layers, (3) an upper layer with matrix and fibrous pumices separated from the main avalanche body by a dark line (0,5-1 cm) composed of impacted, crushed and sheared pebbles.

Determining the processes and parameters that relate to the observed motions and structures requires modelling that can reproduce similar structures : this could best be done with the large scale models. Such models should be able to generate the observed sequential events and to reproduce the relationships in 3D. The energy necessary to generate the observed structures may still limit the validity of large scale models. An analysis of small natural landslides and geotechnical data could help the model design.