# Recent results of noise-based seismic velocity monitoring at Piton de la Fournaise Volcano, La Reunion

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Piton de la Fournaise Volcano, a shield basaltic volcano located on La Reunion island, has been strongly active these last 15 years with 2 eruptions per year on average. On April 2007, an unusually strong eruption occurred on the volcano's south-eastern flank, ejecting a volume of over 240 million cubic meter of lava, that is, ten times more than the typical value during the preceding decade. A few days later, the summit crater collapsed by 340 m. Since then, magmatic activity at PdF decayed until the last eruption of December 2010. Since 2000, Piton de la Fournaise Volcano Observatory records seismic signals continuously from 20 short-period sensors located on PdF Volcano. This set of data together with recent fundamental advances in ambient noise seismology have led to the development of a novel method to measure volcanic edifice seismic velocity changes continuously along time. Changes of seismic velocities of volcanic edifices are known to be sensitive to edifices deformation induced by magmatic activity or gravitational flank instabilities. Edifice seismic velocities may also be induced by external perturbations such as water content associated with rainfall, barometric pressure changes, temperature changes or tides.

In order to measure highly precise seismic velocity changes we deployed 15 new broad-band seismic sensors on PdF volcano between 2009 and 2011 in the framework of an international project called UnderVolc. During that time period, 5 eruptions occurred and the last 10 months of records were characterized by an unusual low volcanic activity. We focus on the location and characterization of edifice seismic velocity changes observed few weeks prior to the October 2010 PdF eruption. We show that precursory seismic velocity changes depend upon the frequency range of the filtered raw data. This observation seems to indicate a depth dependent process. We also present results of lateral location of seismic velocity changes for this precursory episode. We also study the long-term changes of seismic velocities during the low volcanic activity time period. Our results indicate a long lasting seismic velocity increase that we interpret as being associated with the slow compaction of the edifice following the 2007 crater collapse. We also study the link between seismic velocity changes and external perturbations such as in particular water content associated with rainfall. Finally, we have turned these fundamental developments into an operational computer routine called MSNoise for the purpose of continuously monitoring in real-time seismic velocity changes in volcanic domain.

# The 2012 Kilauea volcano, Hawai'i, slow-slip event captured by cGPS and satellite radar interferometry

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In the last decade or so, slow slip events (SSE) have been detected to occur along the southern flank of Kilauea volcano (Hawaii, USA). SSE have been recorded using continuous GPS stations and tiltmeters. Until now, no differential radar interferometry study has been presented conclusive results about the spatial pattern of vertical motion associated to these events, although GPS time series show a slight subsidence signal on the vertical component. Here, we use a dense network of continuous GPS stations and multiple different tracks from the Radarsat-2 satellite to map a nearly continuous ground deformation field during the 2012 SSE in the Southern flank of Kilauea. A fault-slip map associated to the 2012 SSE is inferred using elastic modelling of a realistic fault geometry of the decollement, the Koa'e fault system, Southwest and East rift zones and the caldera summit. The fault-slip distribution allow to simulate the elastic stress change due to the slip on the southern flank area. Stress change models are used to study the feedback relationship between intrusion of magma into the magmatic plumbing system and/or faulting/flank instability.

# Volocano-tectonic earthquakes correlated to stress rate in Izu-Oshima volcano

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It is well known that the seismicity around a volcano is one of the well-established indicators of volcanic activities. Many evidences show that increasing seismicity is followed by the volcanic eruptions or magma intrusion because magma migration makes large stress change. On the other hand, the increasing seismicity does not always result to volcanic eruptions. Therefore, seismicity around volcano is generally treated as a powerful but not definite indicator of volcanic eruption. It is partly because the stress change that generates earthquakes has not been estimated quantitatively and the cause of the stress change has not been studied systematically. Aim of this presentation is to reveal the effect of stress as well as stress rate on volcano-tectonic earthquakes occurring at Izu-Oshima volcano.

Izu-Oshima is located at central Japan and is a volcano island. The ambient tectonic stress affects largely eruptive activities in this volcano. In the latest eruption in 1986, fissure eruptions and large scale dike intrusion followed a summit eruption. The activity ceased in early 1990s. At present, the volcanic activity is low but distinct volcano-tectonic seismic activities synchronized with the ground deformations are observed every 2-3 years. The present activities are characterized as follows. 1) Seismic activities are clearly categorized in two groups: One is an earthquake swarm occurring at the depth of 1-2km beneath the summit caldera (caldera swarm, hereafter). The other is earthquake swarms that occur off the north and west coast of the island at the depth of 3 to 8km (off-coast swarms). 2) Hypocenters in the swarms are aligned on several sub-vertical planes. Each seismic swarm occurs on almost same plane repeatedly. 3) The pressure source of the ground inflation is located beneath the summit caldera at the depth of several kilometers.

We evaluate temporal change of Coulomb stress generated by magma intrusion and ambient tectonic stress on the supposed planes where earthquake swarms occur. For the off-coast swarms, burst-type of swarms are generated when Coulomb stress exceed 100-500 KPa from the level of the previous swarm. On the other hand, the caldera swarms are activated when stress changes rapidly, that is to say stress rate is high. The different stress response in the two swarms can be explained by rock property where earthquake occur. Seismic structure deduced from large scale seismic exploration shows that the layer in which the off-coast swarms occur is similar to normal upper crust structure otherwise the layer in the caldera swarm has more week medium composed by maybe volcanic deposits. We propose that there are two kinds of earthquake generating mechanisms around the volcano and the rock property control the stress response to the volcano-tectonic earthquakes. Further study at other volcanoes will be helpful to understand the volcano-tectonic earthquake systematically.

 

# Time-dependent stressing and failure of an andesitic magma reservoir

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Andesitic magmas account for two-thirds of subaerially erupted magmas world-wide and an understanding of the processes behind magma accumulation at depth prior to eruptions is critical for volcanic risk assessment. Of particular interest is the interpretation of geodetic time series prior to eruptions as they provide information on the spatial and temporal evolution of magmatic systems. Here, we exploit GPS timeseries data from Soufrière Hills volcano on Montserrat that records cyclic deformation vs. time history expressed by ground uplift during a period of repose between July 2003 and August 2005 and subsidence accompanying renewed dome growth over the subsequent 12 months. The data are consistent with a pre-eruptive pressurisation of a deep prolate magma reservoir at depths of around 12 km followed by depressurisation as a result of reservoir failure and eruption initiation. Using finite - element analysis we simulate the stress evolution in the magma reservoir using a time-dependent non-linear pressure history. Assuming reasonable values for the tensile strength of encasing rocks (1 to 10 MPa) we can use the deformation timeseries as a reservoir barometer. We find that assuming an elastic rheology for the upper crust beneath Montserrat requires unrealistically low rock rigidities with values on the order of 100 MPa - similar to rubber or beeswax - to fit both near and far-field deformation data. Although one might invoke such low rigidities in the immediate (heated) vicinity of an active magmatic plumbing system, they are unreasonable to assume over a large subsurface volume.

Invoking depth-dependent rock rigidity values deduced from published seismic data, the simulations require inelastic stress relaxation upon reservoir pressurisation in order to match observed deformation amplitudes while also satisfying tensile stress conditions consistent with reservoir stability upon recharge. We achieve a fit to the uplift data by invoking a visco-elastic response of the surrounding medium over a volume of seven times the pressurised volume. Time-dependent stress relaxation is applied using a generalised Maxwell model with a short-term relaxation time of four months. The reservoir excess pressures remain below a few MPa upon simulated periodic recharge over the 15 months of uplift reaching a maximum value of 8 MPa for a pressurised volume of 32 km$\hat{3}$ before reservoir failure and the onset of depressurisation. The failure excess pressure is consistent with published values for mode 1 extension failure of rocks and hence permits dyke injection. The simulated pressure-time history fits the observations well, although the data precision of the deformation time series do not allow constraint of a unique recharge history. These simulations provide important insights on the complexities of time-dependent reservoir dynamics in andesitic systems, which can only be poorly constrained by simplistic models invoking crustal elasticity in volcanic terrains.

# Geophysical signatures of magma chamber replenishment

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Many volcanic eruptions are shortly preceded by new magma injection into a pre-existing, shallow (< 10 km) magma chamber, causing convection and mixing between the incoming and resident magmas. These processes may trigger dyke propagation and further magma rise, inducing long-term (days to months) volcano deformation, seismic swarms, gravity anomalies, and changes in the composition of volcanic plumes and fumaroles, eventually culminating in an eruption. Although new magma injection in shallow magma chambers is a potentially hazardous event, its occurrence is still not systematically detected and recognized. Here we present the results of numerical simulations of magma chamber replenishment by buoyant magma of deeper origin, and the associated gravity changes, seismicity, and ground deformation. Synthetic gravity changes and ground deformation patterns are then inverted with classical methods, to check their capability to detect the source of signals. The results show that the invaded shallow chamber may be not revealed by inversion of ground deformation, as a consequence of non-homogeneous pressure changes resulting into substantial deviations from usual simplifying assumptions when inverting the data. While ground deformation patterns and volcanic seismicity tend to illuminate the deeper regions of the magmatic system, gravity changes are controlled by the shallow system where gas expansion dominates. These results suggest that i) classic simplifications in data inversion techniques may be largely inadequate for magmatic systems, and ii) more robust inversions require joint use of a variety of data including gravity changes.

# Geodetic data shed light on ongoing caldera subsidence at Askja, Iceland

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Subsidence within the main caldera of Askja volcano in the North of Iceland has been in progress since 1983. Here, we present new ground and satellite based deformation data, which we interpret together with new and existing micro-gravity data, to help understand which processes may be responsible for the unrest. From 2003-2007 we observe a net micro-gravity decrease combined with subsidence and from 2007-2009 we observe a net micro-gravity increase while the subsidence continues. We infer subsidence is caused by a combination of a cooling and contracting magma chamber at a divergent plate boundary. Mass movements at active volcanoes can be caused by several processes, including water table/lake level movements, hydrothermal activity and magma movements. We suggest that here, magma movement and/or a steam cap in the geothermal system of Askja at depth, are responsible for the observed micro-gravity variations. In this respect, we rule out the possibility of a shallow intrusion as an explanation for the observed micro-gravity increase but suggest magma may have flowed into the residing shallow magma chamber at Askja despite continued subsidence. In particular variable compressibility of magma residing in the magma chamber, but also compressibility of the surrounding rock may be the reason why this additional magma did not create any detectable surface deformation.

# Detection and interpretation of stress changes at restless volcanoes through analysis of VT earthquake fault-plane solutions

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Systematic changes in the orientations of double-couple fault-plane solutions (FPS) for volcano-tectonic (VT) earthquakes have been observed to accompany episodes of volcanic unrest. In some cases, the observed FPS reorientations are consistent with changes in stress induced by magma pressurization or ascent. For example, long-term increases in VT seismicity preceding eruptions at Mt. Spurr, Alaska, in 1992, and Soufriere Hills, Montserrat, in 1995-2007 were accompanied by sustained 90° horizontal FPS rotations consistent with dike inflation. In both cases, the rotated FPS were no longer observed once the eruption began, suggesting that pressure in the conduit driving dike inflation had been relieved. Short-duration precursory VT sequences, such as those preceding the 2004 eruption of Mt. St. Helens, Washington, and the 2009 eruption of Redoubt Volcano, Alaska, included short-lived but distinct changes in FPS orientation similar to those observed during longer-duration precursory sequences. 90° horizontal rotations are also observed during some, but not all, VT earthquake swarms that do not culminate in eruption, including a strong post-eruptive VT swarm at Crater Peak, Alaska, in late 1992, and a weak VT swarm at Mt. Martin, Alaska, in 2006. In other cases, for example at Iliamna Volcano, Alaska, in 1996, non-eruptive swarms may be accompanied by no evident change in FPS orientation, suggesting that the mechanism of seismicity in these cases is not directly related to magma ascent, or that conduit pressurization was too weak to overcome background tectonic stresses. In sum, careful analysis of VT FPS in the context of other available geophysical and geochemical data provides a powerful means for assessing the volcanic and/or tectonic processes causing increased seismic unrest at potentially active volcanoes.

# Structural controls on magma pathways beneath Asama volcano, Japan

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Asama Volcano, Japan, is one of the most active volcanoes in the Japanese islands. Recent development of geophysical monitoring in Asama Volcano allows us to infer the magma pathway and its structural controls beneath the volcano. Combining geodetic data and precise earthquake locations during recent eruptions suggests that the magma intrudes several kilometres to the west of the summit to a depth of about 1 km below sea level as nearly east-west trending dyke. The vertically intruded magma then move horizontally by several kilometres to beneath the summit before it ascends vertically to make the surface. Combining the P-wave velocity and the resistivity structure shows that the intrusions are under structural controls. Frozen and fractureless magma associated with volcanic activity until 24,000 years ago impedes the ascent of rising magma on its way to the surface. The S-wave velocity structure inferred from ambient noise tomography reveals a low velocity body beneath the modelled dyke. We inferred that this low velocity body is likely to be a magma chamber by combining with an observation that seismic sites and tiltmeters to the west of the volcano tilted toward the inferred dyking area almost simultaneously with an eruption on 2 February 2009.

# Moment- and Stress-Tensor-Inversion of volcanic earthquakes to constrain driving forces of the 2010 eruptions at Eyjafjallajökull (Iceland)

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The Eyjafjallajökull stratovolcano is located at the western border of the Eastern Volcanic Zone (EVZ) in South Iceland. Three eruptions have been documented in Eyjafjallajökull before 2010: In 920, 1612 and 1821-1823.

Following three episodes of persistent microearthquake activity in the 1990s, seismic activity resumed in spring 2009. The seismicity escalated throughout the year and culminated in an intense earthquake swarm in February-March 2010, beneath the northeastern flank of Eyjafjallajökull. Simultaneous inflation observed by GPS and InSAR data confirmed magmatic accumulation at shallow depth beneath the volcano which heralded the subsequent eruptions.

In early March 2010, the permanent seismic network around the volcano was augmented by additional stations to improve the reliability of hypocentral earthquake locations and focal solutions. Earthquake locations revealed several seismic clusters, interpreted as magma accumulation zones, at shallow (3-5 km) depth beneath the northeastern flank of the volcano throughout March 2010. The seismic clusters migrated eastwards during the week prior to the Fimmvörðuháls flank eruption on March 21st. The April 14th summit eruption was preceded by a seismic cluster beneath the summit crater of the volcano. Focal mechanisms derived from P-wave polarity analysis indicate E-W striking reverse faulting for the February-March earthquake swarm, same as for an intrusion event in 1994. Contrary, normal faulting events were observed beneath the summit crater prior to the second eruption.

The scope of this study is to constrain driving forces of the intrusive activity beneath Eyjafjallajökull in detail by inverting focal mechanism data towards the stress tensor. By applying a moment tensor inversion to stronger events, one may obtain more details about potential volumetric components due to gas or magma migration, as unstable T-axes of events below the summit crater suggest either a ring-fault structure or positive isotropic moment tensor components. Both analyses provide valuable information regarding location, size and driving forces of the repeated magmatic intrusion events represented by the separate earthquake clusters beneath Eyjafjallajökull.

# Insights from a model of pressurization and eruption in a system with two linked magma chambers

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A typical volcanic plumbing system contains a deep magma storage reservoir which supplies magma to higher crustal levels and the surface. The parameters which control the rates of magma flow, chamber pressurization, and eruption in such a system are studied using a mathematical model of two chambers linked by a conduit. The lower reservoir is hosted in (hot) viscoelastic rock and contains buoyant magma whereas the shallow chamber is hosted in (cold) elastic low-density country rock. The model describes the time evolution of pressure in both chambers, the rates of magma flow into and, during eruption, out of the shallow chamber, and the volumes of magma transferred. During inflation of the shallow chamber, pressures and flow rates can respond on two timescales controlled by either the elastic properties of the two chambers or the viscosity of the deep country rock. At short (elastic) timescales, the maximum achievable overpressure in the shallow chamber is determined by magma buoyancy in the deep part of the system and the elastic properties and volumes of the two chambers. If this overpressure cannot break open the chamber, then slow viscous relaxation of the deep reservoir's surroundings drives more magma to the shallow chamber, increasing the overpressure to a level now limited only by magma buoyancy. The time required to trigger an eruption is influenced by the elasticity of the system, strength of the shallow country rock, buoyancy, and the ratio of the magma and country rock viscosities in the deep part of the system.

During deflation of the shallow chamber, eruption rate is moderated by decompression of shallow magma and influx of deep magma. For large country rock viscosities and small deep reservoirs, the deep supply system behaves elastically and eruption rate falls to zero over time. Lower country rock viscosities around large deep reservoirs allow the deep reservoir to continuously leak magma, prolonging the eruption. Although many basaltic systems appear to operate in a solely elastic regime (e.g., Hawaii), the model suggests that large volume basaltic systems (flood basalts) and some viscous magmatic systems may operate in a regime controlled by viscous deformation of deep country rock.

# A two-magma-chamber model as a source of ground deformation at Grimsvotn volcano, Iceland

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On the three last decades, Grimsvotn volcano showed a regular volcanic activity, with eruption every 6.5 years in 1998, 2004 and 2011. We analyse the displacements recorded around Grimsvotn volcano during the two last eruptive cycles and the current one, using ten stations from the Icelandic GPS network. Displacement signals show a long-term trend, of tectonic and glacio-isostatic origin, whose amplitude are coherent with the values of plate motions and vertical rebound previously estimated. Residual displacements after correction for the glacio-isostasic and tectonic components are small except at GFUM station, located at less than 3 km from Grimsvotn volcano, where a significant volcanic component is thus identified. At this station, the direction of volcanic displacement is consistent for all three eruptive cycles, favouring a common source of deformation for the three eruptions. The temporal evolution of the three post-eruptive inflations presents a striking similarity, characterized by an exponential trend followed by a linear trend. This temporal behaviour is well explained by an analytical model of two magma chambers, a deeper and a shallower, connected by an open conduit and fed at the bottom by a constant magma inflow. The eruption tends to rapidly depressurize the shallow reservoir. During the early post-eruptive phase, a pressure re-adjustment occurs between the two reservoirs with an exponential replenishment of the shallow one from the deeper one. Afterwards, a phase of linear uplift is observed corresponding to the pressurisation of the system as a consequence of the constant inflow of magma at the base of the system. We consider both oblate and spherical shapes for the reservoirs, and discuss the parameters of the model that produce the observed displacements and volume of erupted magma.

# Seismic Imaging of the Uppermost Magmatic System and Strombolian Eruptive Variability Associated with Conduit Changes at Erebus Volcano, Antarctica

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Mount Erebus is a large polygenic volcano that forms the summit of Ross Island, Antarctica. The volcano has hosted a persistent convecting phonolite lava lake for over 40 years, which hosts small (VEI 0-1) Strombolian eruptions. Analysis of sparse ( 10-station) long-term and dense (> 100-station) short-term deployments of seismographs in the summit region during the past 12 years have yielded new observations of the Strombolian eruptive process and images of the sub-lava lake plumbing system. Complementary coda interferometric and tomographic seismic methods, using seismic illumination arising from both lava lake explosions and artificial sources, have been integrated into new images of the upper structure. These images show that the principal storage region of magma in the uppermost few hundred meters of the volcano is offset by several hundred m from the lava lake, and more towards the geometric center of the uppermost volcano. Detailed analysis of eruptive seismograms from near-repeating lava lake eruptions show systematic days-to-weeks long variations in the delay between short-period explosion and conduit system-associated very-long-period signal components that indicate variable response/communication times between the surface and the deeper conduit system. We suggest that this variation arises from changes in the uppermost conduit system geometry that affect elastodynamic communication within the system, and that these changes may be observable with seismic coda interferometric imagery. This work further suggests that background images obtained from dense temporary seismographic experiments can subsequently be leveraged for longer-term monitoring for temporal changes made at a smaller number of long-term stations.

# Seismic anisotropy on active volcanoes

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We summarize measurements of seismic anisotropy and its relation to other geophysical measurements of stress and cracks on eleven active volcanoes; Unzen, Sakurajima, Aso, Kirishima and Asama in Japan; Okmok in Alaska, Ruapehu and Tongariro in New Zealand, Soufriere Hills in Montserrat, Kilauea in Hawaii and Piton de la Fournaise in La Reunion. We used the same objective shear wave splitting code on all volcanoes to measure time delays (dt) and fast polarisation directions (phi). Where possible we used S waves from deep earthquakes to ensure that the movement of the earthquakes was not correlated with the volcanic activity. At some volcanoes we used families of repeating events with similar waveforms and at most volcanoes we also computed splitting at earthquakes local to the volcano. We compared the shear wave splitting measurements variation in time to eruption occurrences and to other available parameters including seismicity rate, b-values, focal mechanisms, isotropic velocity changes from noise cross-correlation, Vp/Vs ratios, Geodetic measurements such as GPS and tilt, and gas flux.

All volcanoes had some stations with excellent shear wave arrivals that yielded measureable splitting. Individual measurements showed scatter in most areas, but at most of the volcanoes, moving averages of phi or dt (or both) yielded time variations that correlated with other measurements related to volcanic activity or to stress changes or changes in crack-filling material such as gas flux. The multiplet studies did not yield slowly varying splitting but instead showed distinct jumps in splitting parameters at various times, which appears to be caused in part by cycle skipping.

# The interplay of crustal stress and structure at Kilauea Volcano inferred from seismic anisotropy

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Using shear wave splitting analysis, we have examined volcano-tectonic earthquakes with M >2 at Kilauea Volcano, Hawaii, recorded between April 2007 and December 2011, for seismic anisotropy. We use an the automated algorithm, MFAST, to calculate shear wave splitting parameters. The algorithm uses a grid-search inversion over the azimuth of the fast polarization direction and delay time, for a given time window. It incorporates cluster analysis over a range of time windows to find the most stable result, calculates the optimum three filters to apply to the data on the basis of signal-to-noise ratios and then grades each measurement and marks any null measurements in which no splitting result is obtained. We assume that the polarization of the fast shear wave is parallel to the maximum horizontal compressive stress or the orientation of geologic structures.

Stations more than 5 km from Kilauea's summit eruptive vent record fast directions that are strongly aligned in a NE-SW direction (mean of 071.3 $\pm$ 2.2°), consistent with previous studies from the 1980s and 1990s and suggesting that regional stress is stable over decadal time periods. We also observe fast directions aligned with prominent faults trending obliquely to the NE-SW regional shear wave splitting direction when the stations are close (<1 km) to the fault, and fast directions tangential to the summit caldera (parallel to the caldera ring faults) at stations close to the caldera. Our observations suggest that highly fractured zones associated with faulting overprint the anisotropy from micro-cracks that are aligned with the regional stress. The exception to these trends is in 2008, when anisotropy fast directions at stations on the caldera floor (within the caldera-bounding faults) rotated to be perpendicular to the caldera bounding faults. These changes were roughly coincident in time with the onset of Kilauea's current summit eruption in March 2008. Interestingly, the eruption was not preceded by a dramatic change in the numbers of discrete earthquakes nor by the usual inflationary ground deformation, but $SO_2$ emissions and seismic tremor began to increase several months prior to March 2008. We interpret the changes in anisotropy to be due to an increase in the gas filled pore and crack pressure associated with increased $SO_2$ emissions preceding the start of the summit eruption–an interpretation that is supported by corresponding decreases in $V_p/V_s$ ratio, calculated with the same dataset. Our result demonstrates that changing SWS should not solely be interpreted in terms of stress conditions.

# Geodetic and seismic models of the 2007 May 24 earthquakes at Kilauea Volcano, Hawai'i

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For two days beginning on June 17 (Father's Day), 2007 and following a four-year-long period of summit inflation, magma intruded into Kilauea's East Rift Zone and erupted through a new vent near Makaopuhi Crater, 7 km west of the long-lived Pu'u O'o eruptive vent. On the basis of concurrent summit deflation and observations of lava chemistry and temperature, the June 17-19 Father's Day event has been interpreted as the result of forcible intrusion driven by high magma pressure at the summit, as opposed to a passive response to rifting. The Father's Day event was preceded by two shallow M4+ earthquakes (M4.7 and M4.1) along the outermost caldera faults on May 24, 2007. The earthquakes have been interpreted as a response to inflation of and heightened magma pressure within Kilauea's summit magma reservoir system. Although earthquakes often occur in response to magma intrusion, it is rare for them to have magnitudes larger than M3. Here, we use a combination of geodetic and seismic analysis, as well as geodetic and Coulomb stress modeling, to investigate the links between summit inflation, the May 24 earthquakes, and structural features on Kilauea. The deformation field created by the May 24 earthquakes is visible in multiple Interferometric Synthetic Aperture Radar (InSAR) images (interferograms). Six interferograms were subsampled and inverted with a near-neighborhood algorithm. The best-fit model to the InSAR data includes almost pure right-lateral slip on a NE-oriented caldera-bounding fault and inflation of a pressure source south of Kilauea Caldera. Double-couple focal mechanisms calculated for the two May 24 earthquakes show pure strike slip motion along NE- or SW-oriented faults and are consistent with our best-fit geodetic model. Stress analysis suggests that magma supply to the south caldera reservoir resulted in strong Coulomb stress increases for both earthquakes, indicating that inflation of a shallow magma chamber beneath Kilauea's summit may have promoted slip on the faults.

# The stress shadow induced by the 1975 - 1984 Krafla rifting episode

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It has been posited that the 1975 - 1984 Krafla rifting episode in northern Iceland was responsible for a significant drop in the rate of earthquakes along the Hùsavìk-Flatey Fault (HFF), a transform fault that had previously been the source of several magnitude 6 - 7 earthquakes. This compelling case of the existence of a stress shadow has never been studied in detail, and the implications of such a stress shadow remain an open question. According to rate-state models, intense stress shadows cause tens of years of low seismicity rate followed by a faster recovery phase of rate increase. Here, we compare the long-term predictions from a Coulomb stress model of the rifting episode with seismological observations from the SIL catalogue (1995-2011) in northern Iceland. In the analyzed time-frame we find that the rift-induced stress shadow coincides with the eastern half of the fault where the observed seismicity rates are found to be significantly lower than expected, given the historical earthquake activity there. We also find that the seismicity rates on the central part of the HFF increased significantly in the last 17 years, with the seismicity progressively recovering from west to east. Our observations confirm that rate-state theory successfully describes the long-term seismic rate variation during the reloading phase of a fault invested by a negative Coulomb stress. Coincident with this recovery, we find that the b-value of the frequency-magnitude distribution changed significantly over time. We conclude that the rift-induced stress shadow not only decreased the seismic rate on the eastern part of the HFF but also temporarily modified how the system releases seismic energy, with more large magnitude events in proportion to small ones. This behavior is currently being overturned, as rift-induced locking is now being compensated by tectonic forcing.

# A precursory process of the 1914 eruption of the Sakurajima volcano inferred from experience of residents

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The 1914 eruption of the Sakurajima volcano was the largest eruption in Japan in 20th century. The eruption was commenced by plinean eruption at west and east flanks and followed by effusion of lava. Prior to the beginning of the eruption at 10 AM on January 12, abnormal phenomena were recognized by residents. Here, I try to interpret the abnormal phenomena based on recent knowledge obtained by volcano observations. 1) Discharge of $CO_2$. In July 1913, two people died in a valley of southern part of Sakurajima and it was recognized that the deaths were caused by lack in oxygen due to dense $CO_2$. Distribution of large discharge rate of $CO_2$ from soil gas and quite dense concentration in boreholes suggest a large gas reservoir. Concentration of $CO_2$ in gas from a hot spring increases when inflation of the volcano is detected by a strainmeter in present activity of Sakurajima. The discharge rate of $CO_2$ increased rapidly due to inflation of the volcano half year before the eruption. 2) Uplift of Sakurajima. In December 1913, water withered at a well, where the water had never withered even in low tides of spring tides. The water wells were located near the sea coast and the water level was balanced with tide level. Descend of water level was a relative displacement to uplift of Sakurajima. It is estimated that the ground was uplifted by 0.5 m and volume increase of a source was $1.4\times10^8$m3, assuming the source at a depth of 6km beneath central cones of Sakurajima. 3) Intense seismicity. Volcanic earthquake including felt one began to swarm at 3 AM on January 11 and the number of earthquakes increased until the beginning of eruption. 4) Acceleration of inflation. Sea bottom exposed at SW coast at 2 AM on the day of the eruption. An underwater rock, which had never appeared even in low tides of spring tides, was uplifted above sea water at least 60 cm. Taking theoretical tide level change into account, it is estimated that the rock was uplifted by 80 cm and the uplift was caused by volume increase $1.7\times10^8$m3 of a source beneath the central cones. The rapid inflation was associated with the intense seismicity. 5) Pressurization of underground water. Around 6-7 AM, it was found that water overflowed from wells and hot water was effused from sea coast. It is interpreted that the underground water beneath the volcano was pressurized due to ascent of magma to quite shallow parts at east and west flanks. It is estimated that intrusion rate of magma reached an order of $10^8$m3/day immediately before eruption. On the other hand, intrusion rates of magma were $10^5$m3/day during the period of frequent vulcanian eruptions at a crater of Minamidake from 1974 to 1992 and an order of $10^4$m3/day during the present activity at the Showa crater. Intrusion rate of magma is an important parameter to forecast scale of eruption.

# Revisiting the 1986 eruption of Miharayama, Izu-Oshima, Japan: new constraints on the magmatic system by combining strain, tilt and level line data.

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Deformation changes due to the 1986 eruption of Miharayama volcano on Izu-Oshima, Japan, were well monitored by using leveling surveys, tiltmeters and borehole strainmeters and a number of studies have used these data sets separately. We revisit this eruption in an attempt to determine model parameters that satisfy all the various data sets. The eruption consisted of two stages: activity from 15-20 November 1986 was followed by quiescence for about 1.5 days and then fissuring started on the 21st. For the first stage no precursory deformation can be recognized in the continuous tilt and strain records. Both types of records can be well fit by a depressurizing shallow (∼4km) reservoir, similar in depth to earlier models, but require a sub-vertical prolate spheroidal source rather closer to the surface breakout point. The strain and tilt records have very similar time signatures and, by comparison with the time history of eruptive volume, these data require replenishment of the shallow reservoir from a deeper (∼30km) source during and following the eruptive activity. The second stage was preceded by clear strain and tilt changes indicative of dike formation and both data types show that significant deformation continued for days following the cessation of eruptive product; in fact the majority of magma movement was from a reservoir into a large dike (extending to the south-east) that did not break the surface; the top depth is constrained primarily by changes at the on-island strainmeter site and by elevation changes determined by line level surveys before and following the eruption. By imposing, on a continuous basis, conservation of magma among the sources and the erupted material we obtain models, evaluated at one minute intervals, which agree very well with the strain changes and are consistent with the other deformation data. Including the large dike in the modeling is necessary to provide a good fit to the time history of all the strain sites that recorded the eruption (at distances greater than 50km), including one site for which a Mogi-dominated model would require changes of the wrong polarity.

# The surface manifestations of cyclic tilt at Volcán Santiaguito (Guatemala)

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The continuously active andesitic Volcán Santiaguito (Guatemala) is one of the world's foremost volcano laboratories for integrated geophysical and visual observations of dome volcanism. Birds-eye observations of eruptive activity, including pyroclast-laden explosions and lava effusion, are possible owing to the superior vantage point of Volcán Santa Maria, located 1200 m above and 2700 m distant from Santiaguito. Using photgrammetic methods we report here on new geodetic observations of the dynamic 150-m lava-filled vent occurring at second, minute, hour, and yearly time scales. In particular new high-resolution one-minute timelapse imagery from 2012 reveals steady-state flow patterns as well as dynamic surface distension. Episodic upward bulging (of up to 10 m) of the lava pad occurs near the presumed conduit and is evident over 10 minute time scales. Flow patterns and morphology of the lava plugging Santiaguito's crater is at times more reminiscent of a lava lake than a lava dome.

Many of the surface movements relate to a strikingly regular 20-minute radial tilt cycle, which was recorded with dual tiltmeters and seismometers 500 - 650 m from the vent. We consider that regular inflationary events ($>10^3$ $m^3$) correspond to volatile segregation and accumulation in the edifice because: 1) explosive degassing events coincide with peak inflation, and 2) a rapid tilt-inferred deflation immediately follows explosion onset. It is notable that inflationary cycles also often occur in the absence of explosions; in these cases the deflation is more gradual and coincides with noticeable passive degassing (which follows tilt by a 5 minute lag). Non-explosive tilt cycles also lack the VLP seismicity associated with explosions. We investigate the controls of explosive versus passive degassing and suggest that Santiaguito activity manifests a transition between open and closed-vent behavior.

# Shallow dike injection at Mt. Etna in May 2008 imaged by dense GPS and DInSAR data: interaction between magma and flank dynamics

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Global Positioning System (GPS) and Differetial Interferometric Synthetic Aperture Radar (DInSAR) data collected from July 2007 to July 2008 on Mt. Etna, are analyzed in order to define the dynamics preceding and accompanying the onset of the eruption, on 13 May 2008. Short and long-term comparisons have been made on both GPS and radar data, covering similar time windows. Thanks to the availability of three GPS surveys in the year preceding the eruption onset, an increase in the seawards movement of the NE flank of the volcano has been detected in the few months before the dike intrusion.

The GPS ground deformation pattern also shows a slight inflation centred on the western side of the volcano in the pre-eruptive long-term comparison (from July 2007 to May 2008). The GPS has been integrated with DInSAR data by the SISTEM approach, in order to take advantage of the different methodologies, providing high spatial sampling of the 3D ground displacement pattern. We inverted the SISTEM results in order to model the pressure source causing the observed pre-eruptive inflation.

The subsequent emplacement of the eruptive dike was imaged by two GPS surveys carried out on a dense network on the uppermost part of the volcano on May 6 and 13, i.e. a few days before and a few hours after the beginning of the eruption. We inverted this comparison to define the position, geometry and kinematics of the dike. The dike intrusion was imaged also by DInSAR data with temporal baselines of 2-3 months, which confirm strong displacements localized on the summit area, quickly decreasing towards the middle flanks of the volcano, as detected by very short term GPS data; furthermore, the comparison between DInSAR and GPS data highlighted the presence of a depressurizing source localized beneath the upper south-western area, acting just after the dike intrusion.

Finally, the long period (one year) GPS and DInSAR data were integrated by SISTEM in order to finely depict the 3D ground deformation pattern with the highest spatial resolution (taking advantage of the more complete GPS network surveyed). The long period data allowed the complex kinematics of the volcano to be finely imaged and highlighting the interaction between flank dynamics and magma injection.

# From subduction processes to volcanic unrest: unravelling domino effects at Lake Taupo caldera, New Zealand

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What triggers volcanic unrest remains a fundamental - yet largely unanswered - scientific question. Amongst potential candidates as driving factors, tectonic processes such as large earthquakes have been repeatedly invoked. In the North Island of New Zealand, it is not the usual large subduction earthquakes but slow slip events (SSEs) that dominated "seismicity" for events above Mw6 over the past ten years. Here, we present some multidisciplinary results about the most recent unrest episode at Lake Taupo caldera in New Zealand. We show how processes along the subducted slab in 2008 changed the strain regime at Lake Taupo caldera, resulting in a domino effect that ultimately led to the last substantial episode of unrest at Taupo. We suggest that a deep slow slip event along the subduction zone triggered some readjustments at the caldera boundaries and latest vent area. We also propose that the subsidence of the central part of the caldera in turn caused stress changes in the underlying magmatic or hydrothermal system, resulting in a subsequent period of fluid-driven ground inflation and increased seismicity in the caldera.

# Dynamic coupling of Mauna Loa and Kilauea, Hawaii

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The neighboring Hawaiian volcanoes, Kilauea and Mauna Loa have long been recognized as having anti-correlated periods of eruptive activity, thought to reflect a competition for the same magma supply. Yet recent observations also show correlated inflationary episodes. Furthermore, magmas erupted at both volcanoes are isotopically distinct, indicating that each volcano has a separate magmatic plumbing system and is supplied with melt by different parts of the same mantle source. We present a model, which illustrates the feasibility that both volcanoes are connected through a shared asthenospheric partial melt zone, which facilitates dynamic stress transfer between both volcanoes through pore pressure diffusion. If pressure changes can be transmitted effectively between this deep partial melt zone and shallow storage reservoirs, perhaps through an open magma-filled lithospheric plumbing system, a likely possibility given the persistent long-lived eruptive activity at Kilauea and to a lesser extent at Mauna Loa, then stress changes can be transmitted from one volcano to the other. For example, an increase in the deep magma supply can cause a pressure rise in the partial melt zone and eventually simultaneous inflation of both Kilauea and Mauna Loa. By the same token, eruptive activity at one volcano may inhibit eruptions of the adjacent volcano, if there is no concurrent increase in deep magma supply. We model surface deformation at both Kilauea and Mauna Loa during the past decade, when a surge in asthenospheric melt supply resulted in simultaneous inflation at both volcanoes. Our model couples porous melt flow in a hypothetical partial melt zone with magma flux to and from magma storage reservoirs, and predicts geodetic observations of surface deformation at both volcanoes, as well as observed gas emissions at Kilauea. We find that despite the changes in pore pressure, and diffusion thereof within the partial melt zone, each volcano persistently captures a different part of this partial melt region, consistent with the long-lived isotopic differences in erupted magmas at each volcano.

# Deep magmatic unrest: ground uplift and magma rise at Uturuncu volcano

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Uturuncu volcano in southern Bolivia has been steadily inflating since at least 1965, and combined with shallow seismicity and near–summit active fumaroles represents a volcanic system showing significant signs of unrest. This study focuses on the mechanism driving the 70 km wide region of ground uplift. Using Finite Element Analysis we test for first–order parameters that constrain a viable model for the observed maximum InSAR line of sight uplift rate of 1–2 cm/yr between 1992 and 2006. Stresses and strains from pressurised finite sources are solved numerically using COMSOL Multiphysics, accounting for homogeneous and heterogeneous subsurface structure in elastic and viscoelastic rheologies. Crustal heterogeneity is constrained from seismic velocity data, which indicates a pervasive large low–velocity zone approximately 17 km below the surface. This is deduced to represent one of the world´s largest known regions of partial–melt, the Altiplano–Puna Magma Body (APMB). Contrasting crustal heterogeneity and homogeneity highlights the significant effect of a mechanically weak source–depth layer. This alters surface deformation patterns by absorbing relatively more of the subsurface strain than its surrounding layers, thereby acting as a mechanical buffer. Monotonic time–dependent deformation and an anomalously high crustal heat–flux preclude elastic conditions so we induce a viscoelastic crustal rheology using the standard linear solid model. The elastic models can also only account for the spatial component of the observed uplift so their results are used solely to guide the parameters tested in the viscoelastic models. We explore a range of possible source geometries but reject spherical and oblate shapes on the grounds of their depth below the APMB and likely unsustainable pressurisation given the expected crustal mechanics. Our final preferred model suggests that pressurisation of a magma source extending upward from the APMB is causing the observed surface uplift and requires a continued increase in this pressure to explain both the spatial and temporal patterns. We thus also demonstrate how a pressure–time function plays a first–order role in explaining the observed temporal deformation pattern.

# Crustal deformation during the 2011-2013 volcanic activity of El Hierro, Canary Islands, monitored by continuous GPS observation

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Seismo-volcnic activity of El Hierro started in the middle of July of 2011 and resulted in the active submarine eruption after October 12 south off La Restinga, the southern tip of the island. We have been operating one continuous GPS site on the island (Valverde) since 2004. Responding to the activity, we quickly installed 5 more GPS sites. Including another site operated by the Canary Islands Cartograhical Service (GRAFCAN), we have been monitoring 7 GPS sites equipped with dual-frequency receivers. After the submarine eruption, the volcanic activity gradually calmed down and the crustal deformation stopped in December 2011. However, in June 2012, the volcanic deformation resumed with active seismicity. In this second activity, deformation source moved to the southwest of the island, and it calmed down in July without a surface eruption. In January 2013, there was an additional inflation episode in the northern part of the island and the critical situation still continues. The whole sequence of activity has been monitored with continuous GPS in a quasi-real-time manner. Deformation data indicates that the magma first intruded in the central part of the island and migrated southward (first sequence) or southwestward (second sequence). We summarize the crustal deformation detected by our GPS network and propose a quantitative model of magma intrusion and migration during the whole seismo-volcanic activity. In addition, we discuss possible precursory deformation signal detected at Valverde at the northeastern part of the island before 2011.

# Tracking magma migration in near-real time, the FUTUREVOLC supersite approach

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Our ability to predict the onset and evolution of eruptions depends, in part, on our ability to image the movement of magma beneath the surface, and model the associated changes in stress. To date, this has been achieved primarily using GPS and seismic data gathered in situ, with satellite-borne radar data being used, in the main, to analyse eruptions retrospectively. With the more frequent revisit times of the current generation of radar satellites, and the upcoming launch of the Sentinel-1 mission, we are now in the position where radar imaging can also be used to monitor volcanoes. One of the aims of FUTUREVOLC, a collaborative project encompassing 26 partners in 10 countries, is to develop a system that will automatically ingest synthetic aperture radar (SAR) images and output deformation maps in near-real time. FUTUREVOLC is a supersite project, where Iceland has been selected as the target area. The main objectives of FUTUREVOLC are to establish an integrated volcanological monitoring procedure through European collaboration, develop new methods to evaluate volcanic crises, increase scientific understanding of magmatic processes and improve delivery of relevant information to civil protection and authorities.

In order to achieve the goal of analysing SAR images in near-real time, a new approach is needed. We have developed a system that uses pre-analysis of the SAR archive to identify pixels that have similar noise characteristics, but not necessarily the same deformation history. This information can be used to very quickly identify coherent pixels for interferograms formed using a new image acquired in a time of crisis. We have also developed new methods for 'unwrapping' the phase of these new interferograms, which utilise the redundancy of the interferogram network to automatically and robustly detect unwrapping errors. We use data acquired prior to, and during, the 2010 Eyjafjallajökull eruptions to test our algorithms. A subsequent aim of FUTUREVOLC will be to take the output from this SAR processing chain, together with other in situ data, and produce models of magma migration and stress evolution, also in near-real time.

# Detection of cyclic behaviors and characterization of magma storage at andesitic volcanoes using regional InSAR time series surveys

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Despite the threat posed to millions of people living in the vicinity of volcanoes, only a fraction of the worldwide 550 historically active volcanoes have geodetic monitoring. Indonesian and Mexican explosive arc volcanoes are sparsely monitored with ground-based methods but especially dangerous, emphasizing the need for remote sensing monitoring. In this study we use used over 1200 ALOS InSAR images to survey the entire west Sunda arc and the Trans Mexican volcanic belt (TMVB). We use 2 years of data to monitor the background activity of the west Sunda arc, and 4 years of data at four volcanic edifices (Sinabung, Kerinci, Merapi, and Agung), as well as 4 years of data to survey the entire TMVB. We derive time-dependent ground deformation data using the Small Baseline technique.

We show that while InSAR time series successfully constrain cyclic behavior at both regularly active and previously inactive Indonesian volcanoes, detecting pre-eruptive inflation and post-eruptive deflation, it fails to identify deformation at Mexican volcanoes. We thus identify 2 types of eruption cycles. The first type corresponds to closed volcanic systems where eruptions are preceded by inflation and followed by deflation detectable by InSAR. Observation of such cyclic deformation illustrates the traditional model of magmatic systems and eruption cycle assuming that overpressure in a reservoir eventually opens a conduit leading to eruption. The second type of eruption cycles corresponds to open-system volcanoes where no significant pressurization of the magmatic system is taking place prior to eruptions and thus no ground deformation can be detected. This is the case of regularly active, dome growing volcanoes such as Colima and Popocatepetl, in the TMVB, and Merapi, in the west Sunda arc.

We model the observed deformation in term of depth of magma storage, an important parameter for volcanic hazard assessment. We show that seven Indonesian volcanoes have shallow magma reservoirs at 1-3 km depth below the average regional elevation. We perform a global data compilation to evaluate the potential influence of regional parameters on the depth of magma storage beneath explosive andesitic arc volcanoes. By collecting data at 70 andesitic volcanoes in 8 continental and transitional arcs we show that volcanoes in extensional and strike-slip settings can develop shallow reservoirs whereas volcanoes in compressional settings lack them. Thus, magma ascent through the upper crust seems influenced by intra-arc tectonic settings.

# Can seismicity rates recorded on a volcano be used as a stress gauge ?

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Dieterich and Cayol (2003) have related seismicity rate and stress changes in the Kilauea south flank (Hawaii), where most earthquakes are nucleated on a large décollement plane. In this case, the rate and state formulation (describing friction on large faults, Dieterich, 1992) can be used, and the seismicity may be thought as a stress gauge of the volcano. However, in most volcanoes, Volcano-Tectonic (VT) earthquakes do not nucleate on such large faults and the use of a rate-and-state formulation may be questioned, this is the case on Piton de la Fournaise volcano where the seismicity (36000 earthquakes recorded between 1999 and 2009) occurs in a large number of swarms occupying a 1 km3 volume. Using these data, we therefore explore the various ways to relate VT earthquake rate and stress changes in a volcano and the resolution we can get for the stress changes and the various parameters that control each of these relations. We finally explore the joint inversion of surface deformation and earthquake rate as a mean to better constrain stress changes.

# Insights on the deep activity of Piton de la Fournaise Volcano from long-term seismic velocity changes

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We study Piton de la Fournaise (PdF) Volcano dynamics through the observation of continuous seismic velocity changes during the period 2009 to 2013. We compute cross-correlations of ambient seismic noise recorded at 21 broad-band stations of the Undervolc and PdF Volcano Observatory networks. The velocity changes are estimated from the travel time delay measured on the coda of noise cross-correlations. The portion of the coda we use to measure velocity changes consists predominantly of surface waves. The sensitivity at depth of the coda waves thus varies with the frequency, similarly as the one of the Rayleigh waves. The short period waves are sensitive to the shallow structure of the volcano, while the long period waves are sensitive to its deeper structure. Using this property of the surface waves, we seek to estimate the velocity perturbation at different depth. We observe a dependence of seismic velocity change with the period band considered. At short period (0.5-4s), in addition to the short-term velocity changes produced by the volcanic eruptions (October 2010 and December 2010), a long-term increase of velocity is measured between 2009 and 2013. This is consistent with geodetic measurements, which indicate a deflation of the volcanic edifice since April 2007. At longer periods we observe velocity changes that do not correlate in time with PdF eruptive activity. Yet, distinctive episode of velocity changes are observed at different period bands suggesting changes in the elastic properties at different depth.

# Multi-disciplinary continuous monitoring of Kawah Ijen volcano, East Java, Indonesia

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Kawah Ijen volcano (East Java, Indonesia) has been equipped since June 2010 with 3 broadband seismometers, temporary and permanent short-period seismometers. While the volcano did not experience any magmatic eruption for more than a century, several type of unrests occurred during the last years. Apart from the seismometers, temperature and leveling divers have been immerged in the extremely acidic volcanic lake (pH≅0). While finding instruments capable of resisting in such extreme conditions has been particularly challenging, the coupling of lake monitoring techniques with seismic data improves the understanding and monitoring of the volcanic-hydrothermal system.

To detect small velocity changes, the approach developed by Brenguier et al. (2008) and Clarke et al. (2011) has been implemented to monitor Ijen volcano. Several artifacts that arise when using the later method (e.g.: stationary of the source position and amplitude, interference with volcanic tremor,...) will be investigated. We will present the results of this technique compared to other seismic parameters (e.g.: polarization and spectral attributes of the wavefield, seismo volcanic events spectral analysis) and temporal changes in lake temperature, color or levels. The benefits of monitoring Kawah Ijen magmatic/hydrothermal system using those techniques to identify precursors will finally be discussed.

# Deformation in Agung volcano: a preliminary result from GPS measurements

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Agung is an active volcano located in Bali, Indonesia. The last eruption occurred in February 1963, after being dormant for 120 years, produced voluminous ash fall and devastating pyroclastic flows and lahars that caused extensive damage and many fatalities.

The campaign GPS measurements were conducted on Agung volcano in April and November 2012 by measuring 12 points that located around Agung volcano and 1 reference station. The network consists of five continuous stations established by United States of Geological Survey and Center for Volcanology and Geological Hazard Mitigation, 8 campaign stations established by ourselves. Continuous and campaign stations are observed during field campaigns. For observation, it used Javad TreG3th Sigma 3.4.1 receivers for continuous stations and GPS Leica Geosystem 1200 series with dual frequency using static differential methods for campaign stations.

Temporal results of GPS observations show a movement away from the crater at all stations and dominated by extension patterns. A nonlinear optimization technique was used to find the source location of April and November 2012 GPS measurements. Estimated location of source is found to be beneath the crater with depth about 2.1 km and 3.3 M m3 of volume change.

# Interaction system between tectonic earthquakes and volcanic activity increase with Talang volcano (Indonesia) as area of study

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The tectonic processes may cause an increase in volcanic activity due to stress accumulation. By calculating the magnitude of stress accumulation occurred in volcanic regions over periods of surrounding tectonic earthquakes will help to forecast an increase in volcanic activity. This paper focuses on comparative study between the strain caused by the earthquake and tectonic stress in volcanic areas around Talang volcano.

The research use earthquake data from USGS and GPS campaign data (2007-2009) around Talang volcano to analyze strain distribution caused by tectonic earthquakes, horizontal displacements, and possible interaction system between volcanic activity and regional tectonic.

Talang volcano is in the compression zone as consequence of co-seismic deformations caused by the Mentawai earthquakes of 10 April 2005 and 30 September 2009. In the co-seismic deformation of Singkarak earthquake 6 March 2007, Talang volcano is on the extension zone. These three seismic events lead to increase in volcanic activity, although there are might be also other factors that affect the activity of the Talang volcano. The 2007-2009 deformation which is analyzed as a time series showed inflation at the southern slope of Talang volcano, an increase in pressure in the body of Talang volcano. Fault model derived from horizontal displacement of July to August 2009 GPS measurement period shows an oblique fault (right reverse fault) shear zones that cut the top area of Talang volcano. The fault model is consistent with the pattern of epicenter distribution which have a southeast-northwest trend. Also the fault model has similar pattern to the focal mechanism of volcanic earthquakes recorded in Talang volcano in the period of 2007 to 2009. Those data show that the activity of seismicity and deformation in Talang volcano are dominated by the movement of local structures that are affected by regional tectonic movements of the right lateral Sumatran fault.

Keyword: stress accumulation, tectonic earthquake, volcanic activity, horizontal displacement, inflation, regional tectonic

# New insight into the microfracturing dynamics of Etna's edifice during the 1994-2001 period

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Between 1994 and 2001, systematic gravity fluctuations were observed, due to mass redistributions in a volume located below the SE sector of Mt. Etna, at a depth range of 2 to 4 km b.s.l. The phases of gravity decrease coincide with increases in the rate of strain release, with many hypocenters clustered in the volume containing the gravity source. The joint gravity/strain release anomalies may reflect changes in the rate of microfracturing along the NNW−SSE fracture zone that cuts the SE slope of the volcano. Increases in the rate of microfracturing imply a local density (gravity) decrease, and an increase in the release of seismic energy, thus explaining the observed coupling in time and space. A phase of gravity decrease/strain release increase culminated in the breakout of the 2001 flank eruption. Previous studies suggested that the magma in a pressurized deeper reservoir used the inferred zone of increasing microfracturing as a path to the surface. The process proposed to explain the coupling between gravity and seismic data is mirrored in the mechanical behavior of rocks under deformation, with cracks that form, link up and grow, determining increasing damage and dilatant processes during the pre−failure stages. Under the hypothesized scenario, there are two main issues that need to be addressed. The first one concerns the mechanism that induces the inferred changes in the rate of microfracturing along the NNW−SSE fracture zone. The second one concerns the strain effect at the surface associated to the inferred changes in fracturing rate at depth. Indeed, the ground deformation, expected to be induced by the inferred volume changes at depth, was not observed. In order to address the above issues, we use a finite−element modeling approach and we assume for the NNW−SSE shear/damage zone a lower Young's modulus than the rest of the domain. Preliminary results suggest that tensile stresses across the fracture zone may be induced by a pressure source below the Western flank of Etna, a location of known magma storage that was active during the studied period. We also find that, if a different Young's modulus is assumed for the NNW−SSE shear/damage zone, a considerable extension across it may correspond to a relatively small deformation effect at the surface. The latter would be swamped by the effect of the pressure source below the Western flank of the volcano.

# Links between volcano seismicity and small-scale deformation of the volcanic edifice - exploring new ways of detecting small static deformations

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Deformations of volcanic edifices have been measured and analysed in numerous studies involving different methods and techniques. Thus far, these studies, including GPS and differential InSAR methods, are limited to larger scales, either temporally or spatially, or both. Hence while we can observe higher rate and/or stronger seismicity with increasing inflation or deflation rate over weeks or months, we cannot yet relate the individual volcano-seismic events to small, spatially limited static deformations.

In volcano seismology, seismic events are usually characterised as volcano-tectonic (VT), long-period (LP) and very long period (VLP) events and tremor. VT events are short and impulsive and appear to have brittle failure sources and thus present an equivalent to tectonic earthquakes. LP and VLP events and tremor are commonly thought to have fluids and resonance involved in the source process, but they are still not completely understood. The complexity of the volcanic edifice and the fact that many events are recorded in the near-field make it difficult to locate event sources and to distinguish actual source properties from path effects.

We are trying to explore new ways of detecting small, spatially limited static displacements in the summit region to get a better understanding of how and when deformation takes place and to understand the relationships between deformation and individual seismic events. This can give us valuable clues to the processes involved in generating different types of volcanic seismicity and their connection to the evolution of the volcanic edifice. As a first step, we are investigating possibilities of using broadband seismometer data to retrieve static displacement information. This will require looking at seismic data in a more detailed way, but could enable us to perform this kind of analysis for many existing datasets.

We are currently undertaking (i) analytical/numerical experiments using a variety of source models and seismometer response functions (ii) physical laboratory experiments with step tables, applying well-defined displacement steps on different types of seismometers and tiltmeters. These results are being used to constrain possible deformation related signals observed in a high-density temporary seismic network installation on Mt Etna, Italy, in 2008.

# Repeating volcano-tectonic earthquakes at Mt. Etna volcano (Sicily, Italy): characterization and evidences of crustal changes

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Repeating volcano-tectonic (VT) earthquakes, taking place at Mt. Etna during 1999-2009, were detected and analyzed to investigate their behavior. We found 735 families amounting to 2479 VT earthquakes, representing 38 percent of all the analyzed VT earthquakes. Over 70 percent of the families comprise 2 or 3 VT earthquakes and only 20 families by more than 10 events. More than half of the families have a lifetime shorter than 0.5 day and only 10 percent longer than 1 year. On the basis of these results, most of the detected families were considered 'burst-type', i.e., show swarm-like occurrence, and hence their origin cannot be explained by a temporally constant tectonic loading. Indeed, since the analyzed earthquakes take place in a volcanic area, the rocks are affected not only by tectonic stresses related to the fairly steady regional stress field but also by local stresses, caused by the volcano, such as magma batch intrusions/movements and gravitational loading. We focused on five groups of families characterized by the best repeatability over time, namely high number of events and long lifetime, located in the north-eastern, eastern and southern flanks of the volcano. Unlike the first four groups, which similarly to most of the detected families show swarm-like VT occurrences, group 'v', located in the north-eastern sector, exhibits a more 'tectonic' behavior with the events making up such a group spread over almost the entire analyzed period. It is clear how both occurrence and slip rates do not remain constant but vary over time, and such changes are time-related to the occurrence of the 2002-2003 eruption.

We searched for waveform variations in VT earthquakes belonging to the group 'v' and found changes that took place mainly in the 2002-2003 period. These consisted in a decreasing similarity of the late seismogram windows, highlighted by cross correlation analysis, as well as in delays, increasing proportionally to lapse time, detected by coda wave interferometry. Such variations, mainly evident at the stations located in the north-eastern flank of volcano, were likely due to medium changes taking place in this region. In particular, medium velocity decreases were inferred to occur in 2002-2003, followed by successive increases. The velocity decrease was interpreted as being caused by the opening or enlargement of cracks, produced by intruding magma bodies, ground intense deformation and/or VT earthquake activity, accompanying the 2002-2003 Mt. Etna eruption. On the other hand, the subsequent velocity increases were interpreted as resulting from healing processes.

# Mt. Etna's flank instability, insights from rock deformation experiments.

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Mt. Etna's (Italy) edifice is 1200 km2 wide and 3300 m high, made up of a succession of extruded lava flows above a thick sedimentary sequence. A number of flank eruptions have occurred in recent years, in all cases preceded by intense seismic activity and high rates of ground deformation, eventually leading to abrupt opening of eruptive fracture systems in the eastern flank. To better understand this deformation, the basaltic rocks of Mt. Etna volcano have been the subject of a number of experimental studies in recent years with the aim of better determining the mechanical parameters needed for ground deformation, and how these data might be rated to the seismicity for improved modelling.

Although the focus is often on these basalt units, sub-volcanic morphology show that only around 373 km3 of the bulk total volume of around 1400 km3 of the edifice at Mt. Etna and its substratum is comprised of volcanics. The rest comprises a laterally-extensive culmination of sedimentary rocks that reach a vertical thickness of about 2 km. An increase in instability, promoted by the thermal weakening of these sedimentary rocks has therefore been suggested as an important mechanism for the deformation of Mt. Etna. For this reason, a detailed understanding of the influence of high T on the mechanical properties of representative rock that forms the sub-volcanic basement of active volcanoes is essential.

Previous results carried out at high temperature and room (ambient) pressure on Comiso Limestone, a key lithology for the Etna's basement, provide evident of a predominantly brittle mode of deformation for temperatures to 760 C, together with a significant reduction in strength (Heap et al., 2013; Mollo et al., 2011). Here, we report new data on the rock mechanical properties of numerous rocks that for the edifice and basement of Mt. Etna, with particular focus on the key formation known as Comiso Lst.

Using an internally heated Paterson-type pressure vessel, we recreated conditions at 2-4 km depth together with high T, expected in this region of up to 600 C. We find the brittle to ductile transition occurs at a relatively low temperature of 300 C when confining pressure is applied, compared to no ductile behavior at unconfined experiments (Mollo et al., 2011). A significant decrease in strength occurs when the rock is exposed to temperatures exceeding 400 C. We note an increase in the yield-strength of the Comiso limestone when comparing samples that are drained as compared to undrained samples. We interpret this as due to the buildup of a pore pressure as a result of decarbonatization.

In conclusion: when compared to similar experiments on basalt, Comiso Lst. is significantly weaker, as expected, due a direct mechanical effect and as a result of decarbonatization. Magma intrusion-driven deformation could potentially increase edifice instability by activating shear zones or localizing sub-surface deformation at stresses much lower than expected.

# Vertical ground deformation associated with the volcanic activity of Sakurajima volcano, Japan during 1996-2012 as revealed by repeated precise leveling surveys

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Sakurajima volcano is an andesitic stratovolcano located in southern Kyushu, Japan. It is situated on the southern rim of Aira caldera. The flank and summit eruptions have been repeated during historic times. The current eruptive activity at the summit crater began in 1955. In addition, the eruptive activity at Showa crater on the eastern slope of the volcano started in June 2006 and the activity has increased in recent years. The total number of explosive eruptions since 1955 exceeds 11500 in 2012.

Repeated precise leveling surveys have been conducted in and around this volcano. Associated with the intense eruptive activity since 1973, the ground subsidence around the northern and the central parts of Sakurajima had continued until 1991. The ground around the northern part of Sakurajima was observed to be uplifted when the eruptive activity was gradually decayed since around 1991-1996 (Eto et al., 1997).

In this paper, we discuss the recent vertical ground deformation in and around Sakurajima volcano revealed by the repeated precise leveling surveys conducted in 2007-2012. The ground uplifts are detected in Sakurajima volcano and around Aira caldera to be centered in the caldera as the main feature during the period from 1996 to 2012, similar to the previous results during 1991-1996. From the detailed analysis based on a spherical source model, the inflation sources are located at 8.8-10.8 km depth beneath the center of Aira caldera during the periods of 1996-2007, 2009-2010 and 2011-2012. It is indicated that the magma storage at the magma reservoir inferred at 10 km depth beneath Aira caldera is progressed during the periods. In the period of 2007-2009, a shallow inflation source is located at 4.3 km depth beneath the northern part of Sakurajima. It suggests the magma movement towards shallow part of Sakurajima volcano from 10 km depth beneath Aira caldera, although the estimated amount of magma input is small. In the period of 2010-2011, on the other hand, a shallow deflation source is located at 3.5 km depth beneath the summit crater, caused probably by the recent increase of the volume of the ejected magma associated with the eruptive activity at Showa crater.

Considering the estimated volume increase at the inflation sources, it is indicated that the total of about $1.2 \times 10^8$ $m^3$ magma is inferred to have additionally stored beneath Aira caldera during the period from 1991 to 2012. The ground uplift around the northern part of Sakurajima at the time of December 2012 caused by the progressing magma storage recovers and further exceeds the height level in around 1973, when the intense summit eruptions during the 1970s and the 1980s started. These results suggest the immanent potential of the next intensive eruptive activity of this volcano.

# Estimation of magma chamber related to the 2011 eruption of Shinmoedake volcano, Japan

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The estimation of location and geometry of a magma chamber is essential for understanding characteristics of volcanic activities including possible aspects for the future. Previous studies show that t here is a strong relationship between the movement of magma and the surface displacement (Dzurisin, 2006). Basically, when magma injection into the magma chamber causes the pressure increase at the depth, corresponding surface bulge can be observed. The surface area sinks as magma removes from the chamber. In this study, we analyzed GPS data and estimated the magma chamber related to the 2011 eruption at Shinmoedake volcano of the Kirishima volcano group in southwest Japan.

Shinmoedake volcano is one of the most active volcanoes in Japan and started to erupt in January 2011 after long-lasting earthquake swarms which occurred directly beneath the volcano. Prior to the eruption, an extending trend in displacement was observed between Ebino and Makizono from September 2010. After several explosions in February 2011, small-scale eruptions occurred intermittently till September 2011. (JMA report, 2011) There was no eruption in 2012, although the seismic activities continued. (JMA report, 2012)

The data used in this study were GEONET GPS displacement data provided by Geospatial Information Authority of Japan (GSI) from 2003 to 2012 around Shimoedake volcano. The GEONET is a permanent observation station network established for crustal deformation observations. These stations were installed with spacing of approximately 25-30km. In this study, we mainly used nine observation points around Shinmoedake volcano for our analyses. In addition to that, we included southern points from the volcano in order to evaluate ground deformation signals from Sakurajima volcano, which is another active volcano located about 40 km southwest of Shinmoedake volcano. We divided 2003-2012 into five separate terms so as to examine the variations of displacements and calculated possible magma chamber models for each term. The results showed that displacement changes may be explained by a combination of a spherical pressure source and a tensile fault with northwest trend.

# Crustal deformation due to sub-Pulinian eruption in Shinmoedake, Kirishima,Japan in 2011

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Kirishima volcano is one of the active volcanoes in southern Kyushu, Japan and is categorized into a composite volcano whose active summits are Shinmoe-dake and Ohachi. It started to erupt at Shinmoe-dake on 19 January, 2011, and was followed by sub-Pulinian eruption on 27 January. Eruptive activity gradually ceased since February 2, and moved toVulcanian activities. Nakao et al. (2012) presented crustal deformation of sub-Pulinian eruption and that before and after the eruption by continuous dual-frequency GPS receivers. They also estimated the single inflation and deflation source. The deflation source is located about 5km north-east from Shinmoe-dake and whose depth is about 10km. GPS sites with the single GPS receiver are operated by Japan meteorological agency near the volcanic vent of Shinmoe-dake. We analyze GPS data of dual and single GPS receivers and estimate the position of magma source.

We deployed three GPS sites, which are KVO, KRSP and YMNK on March in 2007 and added a station KKCD on October, 2010. NIED installed two stations: KRMV and KRHV in April, 2010. GSI manages three GEONET(nation-wide GPS network) stations around the volcano. Kyoto Univ. has been installed a station YOSG northwestward of the summit. Six single GPS sites are located in the mountain side and near top of the mountain. Bernese GPS Software Ver. 5.0 is used for the analysis for all data.

We assume that there are two magma sources (Mogi's model) when sub-Pulinian eruption occurred. One is the main deflation source and the other is near the summit of Shinmoe-dake. Simulated annealing method is applied when position of magma source is estimated. The main deflation source is about 5km WNW-ward of the Shinmoedake, whose depth is 8.9km. Volume defect is estimated about 12 million cubic meters. The other source is located in very shallow part near the summit of Shinmoe-dake, whose volume change is 0.08 million cubic meters. This shallow source is needed when the crustal deformation observed at the single receiver GPS site of the summit of Shinmoe-dake.

# Constraints on Deformation at the Summit area of Kuchinoerabujima Volcano in Japan from SAR Interferometry Time Series Analysis

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Kuchinoerabujima is an active volcanic island located on the volcanic front of the Ryukyu island arc. Recent eruptive activities of Kuchinoerabujima volcano occurred at two active craters of Shindake and Furudake. Eruption was not observed for more than 30 years; however, seismic swarms were accompanied by a radial outward pattern from the summit crater repeated almost every two years since 1999 (Iguchi, 2007). Ground displacements near the summit area of Shindake were also detected by interferometric synthetic aperture radar (InSAR) analysis using the Phased Array type L-band Synthetic Aperture Radar (PALSAR) onboard the Advanced Land Observation Satellite (ALOS) data (Yamamoto, 2009).

We applied the InSAR time-series analysis using the software package StaMPS/MTI (Stanford Method for Persistent Scatterers/Multi-Temporal InSAR) (Hooper, 2010) to the ALOS/PALSAR data acquired on both ascending and descending orbits from May 2006 to March 2011. This analysis identified enough coherent pixels to successfully resolve the spatial and temporal deformation. The line-of-sight (LOS) displacements show a rather complicated pattern compared with previous results obtained using GPS measurements and InSAR analysis. The mean velocity maps show two focused areas of LOS shortening located beneath Shindake and Furudake at a rate of 20 mm/year, confirming the inflation trend. The observed deformation near the summit area of Shindake was consistent with previous results. Also, it suggests another deformation source beneath Furudake, which was not clearly accounted for previously.

We model the Kuchinoerabujima volcano sources that produced clear and distinct fringe patterns using a Markov Chain Monte Carlo optimization. Two regions of inflation were modeled by two point sources located at depths of 0.5 and 0.3 km and with volume changes of $1.7 \times 10^4$ and $6.3 \times 10^3$ $m^3$ respectively. The location, depth, and volume change of a point source beneath Shindake is consistent with that of inflation and demagnetization at the summit area of Shindake, indicating expansion and heating of shallow region at about a few hundred meters beneath the Shindake summit.

# Magma mass transport in the volcanic vent at Asama Volcano in the central Japan revealed by physical corrections of hydrological gravity disturbances

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Continuous gravity observation is one of the most powerful methods to monitor time variations in mass distributions (e.g., Imanishi et al., 2004). Especially at volcanoes, absolute and relative gravimeters have been utilized for detecting magma mass transport associated with volcanic eruptions (e.g., Furuya et al., 2003). However, the gravity signals are often masked by hydrological gravity disturbances at humid climate areas like Japan (e.g., Okubo, 2005). Although the hydrological gravity disturbances have been empirically corrected by estimating response functions of gravity to rainfall, water distribution geometry and nonlinear water flow often make the response functions vary according to place and time (e.g., Kazama et al., 2005). In order to detect the volcanic gravity signals with high accuracy, time variations in three dimensional water distributions should be adequately modeled with nonlinear physical equations.

We were thus motivated to correct hydrological disturbances in observed absolute gravity data at Asama Volcano in the central Japan with physically-based hydrological modeling, in order to detect volcanic mass transport during eruptions in 2004. In an original software G-WATER [3D] (Kazama and Okubo, 2009), nonlinear diffusion equations of water flow in soil were solved for time variations in distributions of soil water and groundwater at Asama Volcano, by using observed precipitation data, digital elevation model and measured soil parameters. Then, the hydrological gravity disturbance was calculated with the spatial integral of the water distributions for each time.

The estimated time variation in soil water at Asama Volcanic Observatory (AVO; 4 km east of Asama summit) agreed with the observed one within the observation error range, since the measured soil parameters and the physical water flow equations were applied to our hydrological model. In addition, the calculated hydrological disturbance was consistent with the observed absolute gravity data at AVO from 2004 to 2009 within 3 micro-gal in root-mean-square. After subtracting the estimated disturbance from the observed gravity (i.e., correcting the hydrological effect in gravity data), 5-micro-gal gravity change was detected in the observed gravity during Asama eruptions in 2004. We concluded that the gravity change was caused by transporting magma in a volcanic vent of Asama Volcano, because the gravity change correlated with the existence of a lava cake at Asama summit in September 2004 and increases in B-type earthquakes and emitted mass of $SO_2$ and ash.

In principle, this hydrological correction method can be utilized for any gravity data, if required data (such as precipitation and ground elevation) and soil parameters are prepared. In the future, we will apply the real-time disturbance correction to observed gravity data, in order to immediately understand magma transport in active volcanoes such as Sakurajima Volcano in the southern Japan.

# Movement of magma at depths within mt. asama, japan, revealed by ground deformation and volcanic gas studies

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Detection of magma movements under a volcano is very crucial to understand the volcanism and the magma plumbing system. For this regard, ground deformation studies provide insights of magma injection and changes of inner pressure within a volcano. On one hand, volcanic gas studies give us information of the amount of degassed magma and volumetric decrease of the magma body as a result of gas release to the surface. A combination of volcanic gas and ground deformation studies can open a new path for understanding volcanic mechanisms which cannot be achieved when each method is applied alone. However, there are only a few reports which describe correlations between them. In this study, we show the correlation of volcanic gas emission and GPS data to reveal the magma movement at Mt. Asama, Japan.

At Mt. Asama, there were very minor eruptions in August 2008. Volcanic $SO_2$ flux observed by a UV spectrometer increased from a few hundred to several thousand ton per day at the same period (Ohwada et al. in prep.). Ground deformation associated with the eruptive events preceded these surface phenomena by 3-4 months. The inflation at a deep dike modelled by Aoki et al. (2005) started in March 2008 and continued until April 2009. The inflation at a shallower depth within the conduit followed in April 2008. This pressurization at the shallow part ceased with the abrupt increase of volcanic $SO_2$ emission in August 2008.

To compare GPS and volcanic gas data sophisticatedly, a degassing mechanism is needed to be assumed. The long-term constancy of volcanic gas composition and huge $SO_2$ emission at Mt. Asama suggest magma convection in the conduit. When assuming this convection model, a speed of convection is one candidate to control volcanic gas emission. As mentioned before, the pressurization of the deep dike started 4 months before the eruptions and the increase of $SO_2$ emission in August 2008. This pressure increase at the depth should have driven the convection of magma in the conduit more efficiently so that the increase of $SO_2$ emission and the small eruptions followed. The observed deformation is likely to be due to the shear stress applied to the conduit wall at shallow depths. The synchronism between the deformation cessation and the increase of $SO_2$ emission in August 2008 implies the depressurization of the conduit by reason of the huge gas release.

# Ground deformation of Izu-Oshima volcano in magma accumulation period

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Izu-Oshima is one of the most active volcanoes in Japan. Although no eruptions occurred after the latest eruptions in 1986-87, an inflation of volcanic edifice has continued over 20 years since the latest eruptions, suggesting magma accumulation so as to prepare for future eruptions. Meteorological Research Institute, JMA started GPS observations in 1998, in order to monitor subsurface magmatic activities and to reveal a magma plumbing system of the volcano. The long-term more than ten years and high dens ground deformation observations by GPS revealed shorter-term deflation - inflation events having periods of about one to two years overlie on the quasi-continuous long-term inflation.

The areal and principal strains obtained from GPS baseline analyses during the short-term deformations approximately show isotropic patterns and indicate that sources locate beneath the northern part of the caldera for both deflations and inflations. Because of the isotropic patterns, we estimated source parameters of single Mogi model for three deflations and two inflation events occurred from 2009 to 2012. Both the deflation and inflation sources are located at depths from 3.7 to 5.1 km b.s.l., when three-components of the relative displacement data are used. The volumetric change of each deflation and inflation reaches of the order of million cubic-meters. However, a cumulative volumetric change due to the short-term deformations from 2009 to 2012 is trivial, because repetition of the deflation and inflation processes cancels out the net volumetric change. Therefore, it can be thought that magma accumulation associating the short-term deformations does not much contribute to the amount of mass increase. Deflations without any magma extrusions may be due to sinking of subsurface magma to deeper region or to degassing of volatile contents from magma, although we do not have substantial supporting evidence.

Preliminary analysis adopting single Mogi model for the quasi-continuous long-term inflation was performed, though there still exist residuals of observed relative displacements from calculated ones so as that the source model should be improved. The result shows that the deformation source locates below the northern part of the caldera as ones of short-term deformations, while a depth is 6.7 km b.s.l., slightly deeper than the short-term ones. Mass increase rate is estimated as to be $7.1\times10^{6}$ ton/year, which is about five times and twice greater than averaged mass eruption rates of last 140 and 1,500 years, respectively. This may indicate importance of evaluation of intrusion rate to understand the magma mass budget.

# Crustal deformation of Miyakejima volcano, Japan since the eruption of 2000 using dense GPS campaign observation

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Miyakejima Island is an active volcanic Island located about 175 km south from Tokyo, Japan. Miyakejima volcano has had at least 15 historical eruptions and erupted about every 20 years in the past 100 years. The latest eruptive activities began in 2000. These activeties included forming a caldera for the first time in 2500 years and gigantic volcanic gas emission that foced islander to evacuate over four and half years. This style was different from the style of the last 100 years.

A dense GPS observation campaign had begun at Miyakejima volcano in cooperation with University of Tokyo, Kyushu University, and Nagoya University in 1995. At the eruption in 2000, the state of the magma intrusion was captured in detail from the observed displacement. However, this campaign observation had stopped from 2002 to 2010 because of the landing restrictions to the island due to the large amount of volcanic gas emission. We rebuilt the dense GPS network and restarted the campaign observation from 2011. In this study, we examined the magma-plumbing system under Miyakejima volcano by means of GPS observations to get insights about the future activity of Miyakejima volcano.

We used the data of our campaign observation of 2011 and 2012 recorded by 45 stations, and the data of four GEONET sites of Geospatial Information Authority of Japan (GSI) in this analysis. The observation data were analyzed by RTK-LIB (Takasu et al. 2007) using GPS precise ephemeris from IGS. We estimated the crustal deformation of Miyakejima from 2011 to 2012 from the obtained coordinate values, and calculated the position and volume of spherical source using the software named Magnetic and Geodetic data Computer Analysis Program for Volcano (MaGCAP-V). The result showed there was the small inflation source at a depth of about 3 km beneath Mt. Oyama, which is the central cone of Miyakejima volcano. From this result, we can say Miyakejima have the possible that the magma supply to the magma chamber leads to the next eruption has begun. We will carry out the observation this year and examine whether the expansion trend continues or not.

# Spatiotemporal strain distribution around Kussharo caldera, eastern Hokkaido, Japan, measured by GPS

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The Kussharo caldera in eastern Hokkaido, Japan, is one of the active caldera in Japan. This caldera is a typical island-arc volcanic complex associated with the subducting Pacific plate. Post-caldera volcanism stated just after the caldera forming (35ka) and has still continued. Sub-caldera formations in main caldera by large volume eruptions with more than 10 km$^3$ deposits were recorded at 20ka, 12ka and 7ka. Although episodic expanding (1993-1995) and contraction (1995-1998) has been detected from InSAR at the center of caldera, no significant magmatic eruption has been recorded during recent a thousand years.

This area has high shallow seismicity relative to other area in Hokkaido. Four moderate (~M6) earthquakes are recorded in the past one hundred years. In addition, subsurface structure surveys showed low seismic velocity zone in upper mantle and low resistivity body in middle to upper crust beneath caldera. Ground temperature profile along deep boreholes also indicated high geothermal gradient around this area. These facts implied that weak structure in crust and upper mantle induces high stress build-up in the upper crust and generates active seismicity.

In order to investigate the strain accumulation/release process in and around Kussharo caldera, we analyzed GPS data obtained from continuous and dense campaign-mode surveys. From continuous data, we picked up three periods and estimated velocity and strain rate fields in each terms (term1: 1998-2011, interseismic period without any large earthquake, term2: 2007-2009 postseismic period of the 2003 Tokachi-oki earthquake (M8.0), term3: postseismic period of the 2011 off the Pacific coast of Tohoku Earthquake (M9.0)). In term1 and term2, regional compressional strain field around the caldera, which is driven by interplate coupling between the subducting Pacific plate and the overriding plates, was dominant. Term3 also indicates compressional strain field with a little higher rate. Some effect of postseismic deformation of the 2011 earthquake is attributed. The strain rate map clearly indicated a stable, high dilatational strain rate of 0.2 microstrain per year over a decade only in Kussharo caldera.

Data from the dense campaign GPS observation provides one coordinate set every year from 1997 to 2001, and 2012. We estimated 11 years displacement from the coordinate difference between 2001 and 2012 to see recent crustal deformation. Although deformation rate is not stable for 11 years, because there are some interplate earthquakes near Kurile trench and Japan trench, total deformation and strain field indicates local strain concentration toward the center of caldera appears.

These results show that the strain concentration process in Kussharo caldera is in progress for at least a decade, even the large earthquake occurred around Hokkaido. Therefore, it is important to continue monitoring the tectonic behavior using multi geophysical data.

# Widespread deflation at Cotopaxi Volcano, Ecuador

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Cotopaxi Volcano is one of the potentially active great stratocones of the NVZ. Its past VEI 3-5 level andesitic eruptions produced significant tephra falls, pyroclastic flows and long-distance lahars, affecting populations on all flanks. Future eruptive events will likely deal harshly with the dense human settlements now situated beside lahar flow paths and under tephra fall trajectories. The volcano is monitored by the Instituto Geofisico with a broad array of instrumentation and is also the focus of the collaborative VUELCO (2013-2015) project.

Real-time seismic monitoring since 1986 shows that seismic background levels averaged 20 events/day through 2001. This threshold was exceeded in late 2001 to early 2002 when events topped 180 VTs/day, followed by numerous VLPs events. EDM measurements then showed a total shortening of up to 6 cm. The inflationary signal, the increase in VT events, the migration of hypocenter locations and the later occurrence of VLP events were interpreted as representing a magma intrusion and its later degassing (Molina et al, 2008). Other milder seismic swarms occurred in 2005 and between 2008-2010. Actual seismic background levels have now returned to 20 events/day.

Monitoring with 7 cGPS stations shows overall continual deflation of -3 to -5 mm/yr since mid 2009 on the W, SW and NW flanks and a mild inflationary pattern on the E-NE flanks which is where the 2001-2002 magma intrusion was emplaced. Our modeling of the EDM, tiltmeter and cGPS datasets strives to explain the observed long-term deformation patterns, to determine the presumed magma volumes that were intruded in 2001-2002 and present an explanation for the actual deflationary signals observed in the GPS data set.

# Topographic and deformation source interaction effects on surface displacement modeling

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Topography influences the deformation of volcanic landscapes during magmatic and/or tectonic activity. This is particularly relevant if the deformation sources are shallow. Although the high spatial resolution of InSAR data enables us to detect and identify such topographic effects, most of the related modeling approaches still rely on a flat free surface in a half-space.

To include topographic effects in models, we develop a method based on triangular dislocation elements (TDEs). TDEs have accuracies similar to their rectangular counterparts, but are much more flexible during discretization of complex surfaces (magmatic sources and topography). First, we present a way to solve the problem of singularities along the sides or beneath the vertices of TDEs. Utilizing the method, we can simulate open and closed surfaces of any complex geometry. Second, we apply this approach to develop a code based on the displacement discontinuity method as an indirect boundary element method (BEM). We apply this code to study topographic effects during magma chamber inflation or deflation, as well as during fault displacements. In systematic tests, we explore the mutual interaction of the topography and the source location. We furthermore show that the existence of deep craters and valleys strongly affect the surface deformation. Finally, we use this approach for modeling an 8-year time series of surface displacement detected by InSAR around Lastarria volcano, located in the Lazufre volcanic region of the central Andes. We infer the interaction of two sources (potential magma bodies): a huge sill-shaped source at a depth of 12 km, and a small spherical source at a depth of 0.7 km. These findings from our new numerical inversion method are compared to previously applied half-space solutions. This demonstrates that topographic effects and source interactions, which are accounted for in our approach, have an important contribution to the signals and hence their accurate interpretation.

# Viscoelastic finite element models of an active magmatic intrusion at Uturuncu Volcano, Bolivia: Insights into vertical ascent through stratified continental crust

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Uturuncu is a dacitic stratovolcano in southwest Bolivia, located at the center of a 3,800 km$^2$ region currently uplifting at up to 1 cm/yr. Although the youngest lava flows from Uturuncu have been dated at 270 ka, the summit has active fumaroles, it is positioned in an area of intense silicic Miocene volcanism (the Altiplano Puna Volcanic Complex), and InSAR data shows that uplift has been occurring steadily since at least 1992. Combining two decades of InSAR data also shows evidence for a 'moat' of subsidence, up to 4 mm/yr over a 13,000 km$^2$ area. The unique combination of concentric surface uplift and subsidence could result from vertical ascent of magma from the lower crust (70 km) to the upper crust (20 km), or may result from the initiation of diapiric rise in the hot upper crust. Both mechanisms suggest magma migration at approximately 20 km depth, which coincides with a geophysically imaged zone of partial melt known as the Altiplano Puna Magma Body (APMB). Whether the current deformation is primarily due to the lateral migration of partial melt within the APMB toward a central diapir, due to the underplating of a recent intrusion, or due to an entirely different process, is an open question.

Surface deformation at Uturuncu can be replicated by vertically stacked finite pressure sources in a viscoelastic medium. However, rheological constraints imposed by compositional gradients, temperature gradients, and a layer of partial melt such as the APMB play a fundamental role in the transmission of shear and normal stresses from pressurization at depth. We therefore explore a range of realistic subsurface conditions with 3D finite element forward models using PyLith software. Combing over 750 Envisat and ERS interferograms from two descending (t282, t10) and two ascending tracks (t3, t89) we calculate representative profiles of vertical and radial surface displacement to validate model output. Models are constrained by regional and local geophysical and petrological datasets including: seismic tomography, gravimetry, heat flow, and compositional analyses of surface deposits. Results are therefore tuned to the unique conditions at Uturuncu, but give general insight into volcanic deformation resulting from pressurization below the brittle-ductile transition.

# InSAR data reveal superimposition of local flank instability and volcano-wide inflation at Lastarria volcano, Chile

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Lastarria volcano is located in the north Chilean Andes, at the northern part of Lazufre, an area of long-term and large-scale uplift. Lastarria volcano is characterized by long-lived fumarole activity, concentrating at its summit and the northern and western slopes of the volcano. Recent InSAR observations show that Lastarria is subject to inflation, starting around the year 2000. The inflation is attributed to a magmatic or hydrothermal source at a depth of 1 km that may have an effect on the volcano's flank stability.

Here we investigate ENVISAT time series data to identify regions of flank movements on the slopes of Lastarria volcano. We further analyze the dimension and spatiotemporal characteristics of areas affected by slow landslide motion using data collected by the TerraSAR-X satellite in High Resolution Spotlight mode. We aim to identify and analyze potential coupling of the different deformation processes at work, including (a) the volcano-wide inflation, (b) slow landslide movements, and (c) localized fumarole activity. Landslides and active fumaroles in particular are situated in close proximity or are overlapping so that the deformation signals associated with these processes interfere with each other. Using ground-based infrared camera observations we directly observe how locations of fumaroles and landslides are linked. We also discuss how these different deformation signals might be related to the inflation of the magmatic or hydrothermal source at depth, and infer mechanisms of process coupling.

# Enhanced sub-daily near real-time surface deformation analysis at Deception (South Shetland) and El Hierro (Canaries) Islands

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A methodology for near real-time surface deformation analysis was developed and applied at Deception Island. It relies on a minimum of three strategically deployed benchmarks' position variations at sub-daily rates determined by GNSS-GPS (Global Navigation Satellite Systems - Global Positioning System) geodetic techniques. The benchmarks' positions were reached every 30 minutes with the double-differenced ionosphere-free combination, a 10 degrees cut-off angle and precise ultra-rapid ephemerides, along with pre-processed 3-hourly ambiguity solutions and hourly tropospheric zenith delay corrections. Multipath and residual loading and meteorological effects were further dealt by a discrete Kalman filter. The method's position accuracy was accessed at 1mm in the northing and easting components and 2mm in the height component, when applied to baselines up to 300km, with a reference benchmark that is far away from the volcano's dynamic influence. Supported on accurate benchmarks' positions, a normal vector analysis was applied to triangles covering the monitored surface determining instantaneous strain and inclination.

In Deception Island significant ground deformation was identified in the 2003-2004 campaign before a three years extension process with an acceleration present throughout the 2006-2007 campaign. Along the 2003-2004 campaign the highest number of LP events was detected since the Spanish Antarctic campaigns are carried out, and an increase in the sulphur dioxide flow was detected. As the geodetic campaign ended in 2003-December while the LP events increase begun in 2004-January, ground deformation was precursory to the LP events and sulphur dioxide flow increases. Conversely, the three years extension process had no reported significant seismic activity or increase of gas emissions, with the 2006-2007 austral summer having one of the lowest number of detected seismic events per day. This seismic calmness contrasts with the campaign's 23 ppm/year triangle's extension rate. These methods were also applied in El Hierro Island during its unrest and eruption. Along the process all available benchmarks' position time series were made accessible in near real-time. Nine days before the eruption is detected through a volcanic tremor, a sudden southwards deformation for two days followed by a strong northwards compensation is identified. Some larger magnitude seismic events accompany these strong trend shifts. This sequence may be related to a rupture along the magma pathway, with fluid pressure decrease and its stabilization after. A correlation was also identified between ground deformation and larger magnitude seismicity. Several times an increase in height precedes a sequence of seismic events while heights decrease. The same can be observed in the northing component where these seismic events accompany southwards deformation. The ground deformation was precursor to the seismic activity, but also was influenced by seismic activity.

# Numerical modeling of deformation and stress fields around a magma chamber: constraints on failure conditions and rheology

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We present a stress-strain analysis using the Finite Element Method to investigate failure conditions of pressured magma chambers embedded in an inelastic domain. The pressure build-up induces variations in the stress field until failure conditions are reached. Therefore, the definition of the failure conditions could have a significant impact on the volcano hazard assessment. Using a numerical approach, we analyze the stresses in a gravitationally loaded model assuming a brittle failure criterion, to determine the favorable conditions for magma chamber failure in different source geometries, reference stress states, rock rheologies and topographic profiles. The numerical results allow us to pinpoint the conditions promoting seismicity near the magma chamber. The methodology places a limit on the pressure that a magma chamber can sustain before failing and provides a quantitative estimate of the maximum uplift expected at the ground surface. Thermally-activated ductile regimes, which may develop in the region surrounding a heated magma chamber, are also investigated. The stress relaxation in a ductile shell may prevent the wall rupture, favoring the growth of large overpressured chambers, which could lead to considerable deformation at the ground surface without significant seismicity. The numerical results suggest that a shallow spherical source, compressive regime, gentle edifice topography, and growth of a ductile shell are important factors for the initial formation and the mechanical stability of magma storage systems. These findings could help in gaining insights on the internal state of the volcano and, hence, in advancing the assessment of the likelihood of volcano unrest.

# Crustal Deformation at the Okataina Volcanic Centre, New Zealand using GPS measurements from 1998 to 2011

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At large intra-rift calderas, measured ground deformation does not always indicate an impending eruption. Scientists attempting to forecast volcanic activity in these locations must also understand their relationship with regional tectonic processes, as well as the possible influence of local hydrothermal activity. In the Taupo Rift of New Zealand, rift structure is believed to influence and control volcanism at the Okataina Volcanic Centre (OVC). Here, we present crustal strain and GPS velocity models at the OVC and Taupo Rift. We use these models to show a local rotation of strain southwest of and within the OVC boundary. We note that this rotation coincides with a documented step in the rift axis and a proposed strain accommodation zone in previous literature. Within the OVC boundary, a volcanic source for this variation cannot be immediately accredited, as volcanic deposits cover rift faults and high levels of hydrothermal activity occur here. Further investigations and modelling are necessary to resolve this problem.

# Temporal changes in seismic anisotropy near the times of the 2012 Tongariro Volcano eruptions, New Zealand

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On 6 August 2012 Tongariro Volcano erupted for the first time in over 100 years. The eruption was not specifically predicted, but pre-eruption signals of volcanic unrest had caused GNS Science to lift the alert levels for possible volcanic activity. Some of those signals included a swarm of earthquakes just north of Ngaruhoe Volcano. About two weeks before the eruption GNS deployed a set of four seismometers to record the swarms; one of the seismometers was located directly on top of, and was destroyed by, the future eruption. A second, smaller eruption occurred on 21 November. Combined with data from the existing GeoNet permanent seismic network sites, there will be an excellent dataset to test methods of monitoring volcanic activity. Here we examine changes in shear wave splitting, or seismic birefringence on the permanent network. We used the same objective shear wave splitting code on all volcanoes to measure time delays (dt), and fast polarisation directions (phi). If anisotropy is caused by stress-aligned, fluid-filled cracks, then the dt depends on the numbers and aspect ratios of cracks, while phi depends on their orientation; phi is expected to be parallel to the cracks and to the maximum principal stress.

Preliminary results from the GeoNet permanent stations suggest that there may be a general increase in shallow seismicity at the beginning of July. The increase is accompanied by rotations in statistically significant changes of average phi of between 30 and 90 degrees at the five stations examined so far. Average delay times also change significantly at three of the stations, some of which may be affected by cycle skipping. Scatter in phi and dt also changes with time. The changes are not apparent for earthquakes deeper than 50 km but are present at earthquakes both above and below 15 km in the crust. Further breakdown for earthquakes at different azimuths and examination of the portable data will help to determine if the earthquakes are responding to temporal variations in anisotropy or spatial variations in anisotropy coupled with changes in earthquake source locations.

# Automated Grading Analysis for Shear Wave Splitting

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Shear wave splitting is a useful tool for determining anisotropy in the Earth using seismograms of earthquakes. The measured anisotropy can in turn be related to mineral orientation and deformation or cracks and stress. Changes in anisotropy as monitored via shear wave splitting have been proposed as eruption precursors. However, it is important to ensure the results are reliable through a grading of the quality of the observations. We developed a method to automate the manual grading process in the Silver and Chan (1991) method of estimating shear wave splitting delay times and fast directions, which usually involves visual inspection of adjusted waveforms, and other graphical diagnostics. The grading process is time consuming and conclusions may differ between different graders, and a grader may also find it difficult to grade a large number of events consistently. Therefore, we automated grading first by manually grading 146 nearly identical events obtained from station BOR on Piton de la Fournaise volcano on Reunion Island hotspot. We then developed a set of numerical criteria that as far as possible characterised the features that the manual grader used to classify the events. Finally we performed a multiple linear regression analysis on the set of numerical criteria as predictors of the manual grade. A stepwise model selection procedure was used to select the most important of the numerical criteria.

The automated method produced grades that roughly match the manual grades and the method can clearly distinguish between good results and bad results. The most strongly predictive of the numerical criteria are related to the contour map of the eigenvalues and the corrected polarisation waveform. The process of automation led us to review some of the manual grades, which were discordant with the predicted grades from the automated system, confirming the inconsistencies that can occur with manual grading. We also plan to test our regression model using another, more diverse, dataset from stations situated near Mount Ruapehu.

# Estimated pressure source and vertical deformation in Tatun volcano group, Taiwan, detected by precise leveling during 2006-2013

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Tatun volcano group (TVG) including more than 20 volcanoes is located in the 15 km northeastward from Taipei, Taiwan. Although TVG has a hydrothermal activity characterized by some strenuous fumarolic activities and hot springs, it was evaluated that there is no resent eruptive activity and the nuclear power stations were constructed on the mountainside. Seismological network installed in 2003 detects a micro-seismic activity such as the volcano-tectonic earthquakes, tremors, monochromatic events and long-period earthquakes in and around Chihsing volcano (Lin et al., 2005). To monitor the volcano activity, the government established the volcano observatory in TVG in 2011.

Since the volcano-seismic swarm occurs just around some fumaroles, it strongly suggests that the micro-seismic activity and the hydrothermal activity are closely related. Basically, the swarm activity around volcano is often accompanied by the deformation (e.g.: Daita et al., 2009). Since these deformations are sometimes localized to a small region and few mm scale, a precise leveling survey is the most efficient survey to detect the deformation successfully.

Therefore, we established a 10km leveling route crossing the Chihsing volcano from south to north to detect the vertical deformation in June 2006. Additionally, the leveling route was extended to the fumarolic area in the east part of the Chihsing volcano in August 2007. Our leveling surveys were re-conducted five times of June 2006, March 2007, August 2007, March 2009, and March 2011.

The overview of the deformations detected after the leveling route extension is as follows. we detected the deformations in two areas. One is the subsidence of 5 mm in the mountainside, and another is the uplift in the fumarolic area for 19 months from August 2007 to March 2009. The similar deformation pattern to the preceding observation was observed in March 2011. However, the subsidence in the mountainside was relatively larger than the uplift close to the fumarolic area.

Based on the observed deformation in the period between August 2007 and March 2011, we estimate the volume changes and the locations of two spherical sources on that condition by employing a genetic algorithm (GA).

As a result, shallow pressure sources are estimated. One pressure source is estimated at 3 km depth beneath the northeast foot of the Chihsing volcano, and another source is estimated with at 0.7 km depth in the fumarolic area. It suggested that the estimated pressure sources are related to the hydrothermal activity. In the study period, the subsidence in the mountainside was detected to be caused by a major deeper deformation in TVG. The hydrothermal fluid supplied to the shallow sources in TVG may not be significant in this period.

Additionally, we plan on the leveling survey in March 2013. The deformations in 2013 are expected to be reported in the IAVCEI 2013 meeting.

# Volcano ground deformation caused by surface sediment loading

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Ground displacements at active volcanoes are often interpreted in terms of pressure changes at depth in the magmatic system. Numerical models may be used to estimate the elastic response of the crust - and thus the ground surface - to pressurisation at depth. Inversions of observed deformation often use such models to constrain location, size, shape, and volume or pressure change of magmatic sources. Such approaches require a number of simplifying assumptions and typically neglect the influence of complicating factors, such as compressibility of magma in the system, surface topography, inhomogeneity of crustal rheology, and the effect of surface loading of erupted material. We explore the extent to which volcanic ground deformation may be influenced by surface loading due to the accumulation of volcanogenic sediment during the eruption on Montserrat, West Indies.

The eruption at Soufrière Hills Volcano, Montserrat, has generated over a cubic kilometre of lava since 1995. Much of that material has moved offshore, but there remain substantial subaerial and submarine sediment deposits around the volcano's flanks. We measure the thickness of deposits emplaced around the volcano over 15 years by differencing topographic survey data and then derive a surface load estimate assuming typical density values. We use finite element modelling to estimate the crustal response to the deposit load, in terms of expected associated ground deformation. We show the sensitivity of loading-derived deformation to the model's elastic parameters for a range of plausible configurations, applying constraint for rock rigidity profiles derived from seismic survey data, Results are compared to continuous GPS timeseries data recorded on Montserrat throughout the eruption. We discuss the extent to which loading the volcano's flanks with erupted sediment has contributed to the observed ground deformation and how this contribution may mislead typical schemes for inverting measured displacements at volcanoes.

# Stress coupling between magmatic and hydrological systems during explosive eruptions

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Multiparametric geophysical data of the July 29, 2008 Vulcanian explosion at the andesitic Soufrière Hills Volcano (SHV) in Montserrat (West Indies) shows a statistically significant increase in gravity accompanying dilatational volumetric strain as a result of conduit opening and initiation of explosive activity. The peak gravity increase coincides with maximum decompression of the shallow plumbing system as a result of conduit emptying.

Syn-eruptive mass and volume changes in the shallow magmatic plumbing system can be excluded as a source for the gravity transient. Instead, we propose a dynamic response of an aquifer to the eruption leading to a change in the water table as the cause for the transient. First order approximations support this hypothesis by indicating that the required hydraulic head changes are realistic. The mechanisms which induce changes in the hydraulic conditions of the aquifer and thereby affect the pore pressure are still to be investigated but may include seismic excitation and volumetric strain changes or a combination of both. Although cause-effect relationships between magmatic activity and hydraulic head changes have previously been proposed at several volcanoes, the quantitative understanding of this coupling is incomplete. Here, we present results from a hydrogeophysical study using a suite of finite-element models of the sub-surface stress transfer accompanying the July 29, 2008 Vulcanian explosion at SHV. The models simulate porous flow through an aquifer as a result of changing stress conditions by conduit evacuation. Resultant poro-elastic effects are then solved numerically to test whether the gravity transient can be explained purely by a mass variation or also by ground deformation caused by pore-pressure changes in the aquifer. The quantitative investigation of stress transfer at active volcanoes permits new insights on complex interactions between subsurface reservoirs which may be exploited in the future for pre-eruptive hazard assessment.

# An experimental study of the volcano-sagging to volcano-spreading transition

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Volcanoes on Earth and other planets undergo gravitational deformation on a variety of timescales. Two end-member modes of gravity-driven deformation are volcanic sagging (or volcani flexure) and volcano spreading. It is widely known and accepted that the mechanical and geometric properties of the basement rocks below the volcano strongly influence such gravitational deformation modes. One key parameter allowing deformation is the presence of a zone or a layer that is sufficiently widespread and that has an effective viscosity low enough to produce ductile behavior in response to the load of the overlying volcanic edifice. Key geometric properties controlling deformation behavior include the ratios between (1) volcano height and ductile basement thickness and (2) volcano height and brittle basement thickness. Despite such longstanding knowledge, a thorough parametric exploration of these properties has hitherto not been carried out experimentally. Consequently, the circumstances under which one gravitational deformation mode transitions to the other (i.e. the recently proposed spreading-sagging continuum) is imprecisely defined. To address this issue, we conducted a series of scaled analogue experiments involving a sand-plaster cone overlying a simple basement structure that comprises a single sand-plaster (brittle) layer and a single silicone (ductile) layer. By systematically varying the aboce-mentionned geometric ratios, we comprehensively define the transition from volcano-spreading to volcano-sagging for a simple conically-loaded two-layer basement system. 3D displacement veolocities of the model surface are documented and allow to track and quantify the deformation. These results form a robust experimental base for distinguishing and interpreting the structural and morphological features of volcanoes subject to combined gravitational deformation processes, as observed in the field or in remote sensing data.

# Coupled geodetic and volcano-tectonic precursors to eruptions

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The two precursory signals most commonly recorded before eruptions are increases in the rate of ground deformation and the rate of occurrence of local volcano-tectonic (VT), or microseismic, earthquakes. A popular expectation is that both parameters will accelerate with time during a precursory sequence. The behaviour of each parameter is thus typically analysed as an independent time series and changes in the rates are used to evaluate whether an eruption is imminent.

Although rates of precursory VT events commonly accelerate with time throughout a precursory sequence, the accompanying rates of ground deformation more usually tend to approximately constant values and may accelerate only during the final stages of the sequence (e.g., Refs. 1 and 2). A constant rate of ground deformation, therefore, cannot be used to indicate a stable change in a magmatic system. Indeed, geodetic and seismic changes are directly coupled: whereas ground movement measures total deformation (e.g., elastic and inelastic), microseismicity is a proxy for the inelastic component of deformation due to fracturing. The conditions for bulk fracture are determined by the amount of damage accumulated in a rock and so are related to the proportion of total deformation caused by fault movement. As damage proceeds, inelastic deformation contributes an increasing proportion to the total deformation and, hence, the corresponding VT event rate accelerates (Ref. 3). Even though deformation rate alone may have limited application for forecasting eruptions, its behaviour with time determines the contemporaneous accelerations in VT event rate that may, in turn, constrain deterministic forecasts of eruptions.

Recent theoretical studies suggest that the amount of damage, measured by the total number of VT events, follows an exponential increase with total deformation until shortly before eruption, at which stage the two parameters may increase in proportion to each other (Ref. 3). To obtain greater insight into how damage accumulates in the crust, therefore, future monitoring strategies should be designed to analyse changes in VT event rate with the rate of ground deformation, in addition to recording how the individual rates vary with time.

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# Magma flow between summit and Pu‘u ‘Ō‘ō at Kīlauea Volcano, Hawai‘i

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Volcanic eruptions are often accompanied by spatiotemporal migration of ground deformation, a consequence of pressure changes within magma reservoirs and pathways. We model the propagation of pressure variations by eruptive magma withdrawal during the early episodes of the ongoing Pu‘u ‘Ō‘ō-Kupaianaha eruption of Kīlauea Volcano, Hawai‘i. Tilt measurements show that the onset of fountaining episodes at Pu‘u ‘Ō‘ō was typically accompanied by abrupt deflation and followed by a sudden onset of gradual re-inflation, once the eruptive episode ended. Tilt at Kīlauea’s summit underwent similar patterns of deflation and inflation, albeit with time delays of several hours during most episodes. The observed delay times for different episodes vary between 3 and 12 hours. These can be reproduced by modelling the space-time evolution of pressure variations within an elastic-walled dike that connects Kīlauea’s summit to its east rift zone. As pressure changes travel through the dike, the interplay between elastic response of the dike wall and viscous resistance of the fluid determines the delay time. Magma withdrawal beneath Pu‘u ‘Ō‘ō causes a decrease in pressure and deflation. The resultant increase in magma flow rate causes deflation of the Halema‘uma‘u magma reservoir at the summit, although delayed in time because of the finite propagation velocity of both the pressure changes and the surge in magma flow rate within the dike.
The time delay depends on dike dimensions, elasticity of the wall rock, magma viscosity, as well as magnitude and duration of the pressure variations themselves. The dike width is the most important parameter in determining delay times: pressure changes propagate noticeably faster (slower) in a slightly wider (narrower) dike, as a consequence of smaller (larger) viscous dissipation. It is unlikely that the east rift zone magmatic pathway is of uniform dimensions: variation of its width could represent spatially localized changes, possibly due to removal of a constriction or partial collapse of wall-rock during repose periods. A transport efficiency for the dike system can be defined, providing a measure of the ease of flow for magma along the east rift zone and its variations in time, and thus an insight on the evolution of the magmatic system of Kīlauea Volcano.

# Volcano-tectonic interactions captured by decade-long GPS monitoring in the Azores

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The Azores archipelago is located across the Mid-Atlantic Ridge, where three mega tectonic plates meet: Nubia, North America, and Eurasia. The archipelago has many active volcanic systems. The Fogo - Congro area in S. Miguel Island has been recognized as one of the most active seismo-volcanic fields. This area has been repeatedly suffering from intense earthquake swarms, at least in last few decades, such as in 1989, 2003-2006, 2008-2009, and 2011-2012. No geochemical and hydrothermal evidences for a magmatic intrusion were reported during these seismic crises. However, geophysical data, both seismic and ground deformation, indicate possible volcanic sources. To understand these repeating seismic swarms and eruption triggering mechanism, the mutual relations between the regional stress field and volcanic deformations were studied.

In the scope of tectonic and volcanic monitoring 11 continuous GPS stations are currently operating in the archipelago. The GPS time series for 2008-2011 shows an extensional stress regime at Monte Escuro - Congro Area (MECA), between the NE flank of Fogo volcano and the western rim of Furnas Caldera. It plays about 38 percent contribution of the total plate spreading. The rest is maybe taking place in other regions from either tectonic or volcanic contributions in different periods. The existence of this extensional regime plays important roles for the present-day magma ascent (failed and possible eruptions) in the area.

One of the stations inside MECA represents an episodic displacement on late 2008 which was accompanied by two seismic significances; (1) the seismic migrations (from NE flank of Fogo to Furnas) and (2) the localized deep swarms (at the depth of 4-7km). The former suggests the close link between Fogo and Furnas volcanic systems through the regional tectonic structures and the latter can be interpreted as minor-scale magmatic injection from upper mantle. On the other hand, the seismic swarms in 2003-2006 and 2011-2012 were accompanied by the edifice-scale deformation. The time series shows the months to years of gradual pressure accumulation inside Fogo volcano. These volcanic inflations may have resulted from successive magma injections at the shallow crust.

Decade-long GPS monitoring has revealed volcano-tectonic interactions in the Eurasia-Nubia plate boundary and enabled to distinguish volcanic unrests in S. Miguel Island from the steady-state present-day plate movements. For better characterizing ongoing volcano-tectonic phenomena and assessing the volcanic risks in real time, it is fundamental to reinforce the present continuous GNSS network and extend it to all the active volcanic systems in the archipelago. A new network with 30 new GNSS stations is being prepared which will enable high rate data acquisition (50Hz). Detailed source process of the seismo-volcanic phenomena including co-seismic rupture propagation and time-dependent magma emplacements will be better constrained in the Azores.