Erebus volcano: an open-vent archetype

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Erebus is well known for its lava lake, alkaline intraplate character, and, of course, its southerly latitude. It also serves as a paradigm of open–vent volcanism, with persistent degassing and sporadic Strombolian eruptions associated with the long–lived lava lake. Its proximity to the largest station in Antarctica (McMurdo), and the comprehensive logistical support from the US Antarctic Program, provide an exceptional research infrastructure such that Erebus ranks among the world's outstanding laboratory volcanoes. On one level, the behaviour of Erebus simple, stable and sustained but the magma differentiation (basanite, through intermediate terms, to phonolite), mantle–to–surface degassing (and associated redox changes), and the moderate viscosity of the surficial (phonolitic) magma, superimpose fascinating complexity on the long–lived lava lake. The gases emitted from the lava lake are dominated by carbon dioxide (by mass), symptomatic of the important role played by carbon dioxide in magmatic evolution beneath the volcano. In addition to the signature of deeper magmatic processes evident in the surface gas signature, cyclic changes in gas composition and lava lake height and velocity highlight aspects of magma convection and degassing in the uppermost parts of the magma conduit and the lava lake itself. This presentation will provide an overview of recent research findings form Erebus and link to several other contributions on Erebus being given at the IAVCEI meeting.

Zonation in anorthoclase feldspar megacrystals reveals dynamics of the magma conduit feeding the lava lake at Erebus volcano, Antarctica

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Anorthoclase megacrysts are a striking feature of many peralkaline trachyte and phonolite lavas. At Mt Erebus volcano (Antarctica) they reach up to 7 cm long, and display two interesting properties: perfect oscillatory zoning and large melt inclusions. By combining experimental and analytical approaches we can recreate the P-T-H_2O-fO_2 history of these crystals and illuminate the magma dynamics of the plumbing system feeding Erebus' lava lake. Phase equilibrium experiments indicate a correlation between the anorthoclase composition and both pressure and temperature. After imaging the melt inclusion by X-ray tomography to assure they are fully enclosed, melt inclusions confined within anorthoclase zones of known composition were analyzed by electron probe, ion probe and Fe K-edge micro-x-ray absorption near-edge structure spectroscopy (XANES). We found a correlation between the CO_2 content in melt inclusions and the chemistry of their host zone suggesting that oscillatory zoning in these megacrystals reflects crystallization at different depths within the conduit. This finding allows us to decode each crystal and track its history of circulation up and down the magmatic conduit.

Tracking the hydraulic connection between Kilauea's summit and rift zones using lava level

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A magmatic connection between Kilauea Volcano's summit and rift zones has been inferred for decades, even centuries, based on the temporal relationship of changes during discrete events in these two areas of the volcano, but continuous tracking of the fluid connection has not been possible in modern times until just recently. We track the fluid lava levels at Halema'uma'u and Pu'u 'O'o craters and demonstrate that a state of dynamic hydraulic equilibrium exists between Kilauea's summit and east rift zone. The hydraulic head loss in the system was used with the Darcy-Weisbach equation to infer that the conduit feeding the east rift zone eruption is <5 m in diameter, and the rate of draining of the summit lava lake in March 2011 was modeled with the Poiseuille equation to infer that the conduit supplying lava to Halema'uma'u is also <5 m wide. During 2011, rising lava levels at both Halema'uma'u and Pu'u 'O'o, inflation of the summit and east rift zone and increasing numbers of earthquakes along the upper east rift zone presaged several rift zone eruptive events, consistent with rising hydraulic head pressure in the summit-rift magmatic system that triggered the rift activity and draining of the summit magma reservoir. The summit lava level closely tracked tiltmeter and GPS measurements of summit deformation (during both inflation and deflation), indicating that the lava level within Halema'uma'u Crater is a reasonable proxy for pressurization of the magmatic system. The Halema'uma'u lava lake level therefore serves as a convenient gauge for judging the likelihood of future eruptive or intrusive events along the rift zones. Historical summit lava level data from the 1800s and early 1900s confirms that rift eruptions were usually preceded by rising, elevated lava levels in the summit. The patterns from 2011 reaffirm the usefulness of lava level in forecasting rift activity and provide an improved picture of how lava level relates to precursory trends observed in modern geophysical data. Forecasting eruptive potential from lava level likely has value at other open-vent basaltic volcanoes around the world.

Estimating the location and volume of shallow magma storage at Kīlauea Volcano from observations of episodic ground deformation

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A variety of geophysical observations suggest the presence of at least two long-lived magma reservoirs beneath the summit of Kīlauea Volcano. Although the locations of the reservoirs are known generally, their volumes are poorly constrained. Episodic pressure perturbations in the shallow magmatic system, however, generate cycles of ground deformation that provide valuable constraint on the location and volume of the more shallow of the two reservoirs. These cycles of ground deformation, divided into three different classes based on their temporal histories, have been labeled deflation-inflation (DI) events. Recorded by tilt, GPS, InSAR, and strain data, a typical DI cycle consists of deflation of the summit region over a period of roughly 8 hours to 3 days, in many cases at a quasi-exponentially decaying rate, followed by a recovery over hours to a few days to roughly the original level. Since the opening of Kīlauea's summit vent in 2008, the rate of DI event occurrence has increased, and DI-related ground deformation has also closely tracked the level of the summit lava lake. Cyclic deformation at the summit is also often reflected, after a pause of roughly one-half to three hours, at the Pu‘u ‘Ō‘ō eruptive vent 20 km from the summit, suggesting that DI events reflect perturbations of magma flow and pressure conditions throughout much of Kilauea's interconnected shallow plumbing system.

We invert deformation data recorded during more than 400 individual DI events to estimate the location of Kīlauea's shallow magma reservoir (the Halema‘uma‘u reservoir) and look for changes associated with eruptive activity. We find that the three classes of DI events share a common source region, located near the east margin of Halema‘uma‘u Crater, which has moved little if at all in more than ten years (the time span of the most accurate deformation records). The depth of this source is shallow but poorly resolved from the tilt data alone; however, GPS, InSAR, and strain data can provide additional constraint. The volume change associated with individual DI events is probably less than one million cubic meters, although the estimate is correlated with source depth. While the deformation data cannot constrain the total volume of the Halema‘uma‘u reservoir, we are able to estimate volume by assuming that the summit lava lake is in magmastatic equilibrium with the reservoir such that its surface height may be used as a manometer. Using probabilistic estimates of host rock rigidity and magma density together with volume change obtained from inversion of the deformation data, we estimate that the Halema‘uma‘u reservoir has a volume of several cubic kilometers.

Componentry of pyroclastic fall deposits from September and October 2008 weak explosions at Kilauea summit crater: insights into the dynamics of an open basaltic magma column

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On 19 March 2008 a small explosive event at Kilauea's volcano summit opened a 35-m-wide vent on the south wall of Halema'uma'u crater, initiating an eruptive period that extends to the time of writing. The activity of the open basaltic magma column has been characterized by a vigorous outgassing and an unevenly intense spattering at the free surface (permanent or background activity), and the occurrence of small explosive events consistently triggered by conduit-wall and/or rim collapses. The componentry analyses of samples collected daily near the vent during different sequences of events (including transitions from background activity to explosions and vice versa) in September and October 2008 allow us to distinguish three main classes of juvenile particles by their vesicularity and bubble size distributions. The abundances of these classes vary from background- to explosion-samples, revealing consistently contrasts in degassing and fragmentation processes before the disruption of the lava free surface by the rockfalls, and during and soon after the explosive events. Textural and chemical analyses of particles from different componentry classes revealed mixing features and crystallinity variations. These results give insights into the dynamics of the open lava column and particularly into the behavior of the top of the column during outgassing and external disruption of the free surface-equilibrium state.

An analysis of volcano inflation prior to an eruption at Stromboli volcano based on slug flow and rising gas bubble models

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Stromboli volcano is a small volcanic island located in the south of Italy, and its eruption is characterized by repeated Strombolian type which is considered to be generated by a sudden release of a large gas slug at the crater bottom. In this study, we examine the mechanism of magma flow in the conduit by comparing the tilt record reported in Genco and Ripepe (2010) with two models: slug model and rising gas bubble model.

The tilt records associated with eruptions at Stromboli are observed at five stations located at about 300 -1100 m distances from the vent. The observed tilt change prior to each eruption show volcano inflations with accelerated rate from about 200 s before eruption and same temporal changes at the five stations.

We use slug flow model presented by James et al. (2008). Rising gas bubble model assume that plural gas bubbles rise in melt without interaction of surrounding gas bubbles. Each bubble rise according to Stokes' law. Model parameters of the slug flow are the initial depth and size of slug, viscosity of melt. Model parameters of rising gas bubbles are the initial radius and depth of gas bubbles. Number of the gas bubbles is also a model parameter. Length and radius of the conduit and initial magma head depth are model parameters for both of the two models. We compare spatio-temporal changes of tilt caused by two models with the observed data. We use a 3-D boundary element method that can take into account the effects of topography of Stromboli volcano to calculate volcano deformation.

First, we compare the changes of magma pressure in the conduit from the initial condition to just before an eruption for the two models with the tilt changes observed at five stations. We estimate the model parameters that can fit the observed tilt by using grid search methods. Subsequently, we compare temporal changes of tilt at each station using the estimated model parameters with the observations. The results show that both models can explain the spatial changes of tilt at five stations with a variance reduction more than 98%. The pressure sources for the both models are located at a shallow part (about a few hundred meter depths). Slug flow model, which are often used to explain Strombolian eruptions, cannot explain the volcano inflation at a station located at 1000 m far from the vent. This is because the tilt changes at such stations show down lift toward the vent due to depressurization of magma where a slug locates at. On the other hand, the gas bubbles rise model can produce uplift toward the vent even at stations far from the vent. We obtain model parameters of the rising gas bubble model: conduit length of 550 m and radius of 5 m, initial gas bubbles radius of 0.6 m, the number of gas bubbles of 100, and initial magma head depth of 170 m.

Can passive degassing induce volcanic crisis?

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Openly-degassing volcanoes (e.g. Asama, Japan; Mayon, Philippines; Etna, Italy) usually erupt every few months or years. During quiescence, they passively emit several thousands of tonnes of gas per day (mainly water vapour). Such gas mass withdrawal leads to a volume change of melt because the volatiles were previously dissolved in it. On the other hand, there are evidences showing that openly-degassing volcanoes have well developed conduits with the head of the magma column close to the summit. Thus, a volume decrease of magma could decrease the mean liquid level in the conduit and may, in turn, decrease significantly the pressure at depth. This reasoning suggests that passive degassing may play an important role in the pressure evolution of magma plumbing systems. However, the problem is much more complex when we consider a response of the host-rock to pressure changes and hydraulic connection between deeper sources and shallow reservoirs. In such a case, there is a feedback between degassing-induced underpressure, closure of the conduit and reservoir, and magma replenishment. We have modelled these processes and we have found that underpressures up to some tens of MPa may easily occur during the observed repose timescales. Continuous magma intrusions through permanent hydraulic connections are induced by passive degassing without the need of a pressurized magma source. Intermittent replenishment can also be explained via passive degassing and successive openings and closures of the feeding dykes. These pressure decreases may also cause physical destabilizations of the chamber wall-rock and massive bubble nucleation and growth in the reservoir. The imbalance created by the large amount of gas released during repose may incite the frequent volcanic unrest and eruptions of openly-degassing volcanoes. This "top-down" process contrasts with the commonly proposed "bottom-up" processes of magma intrusions in shallow reservoirs driven by unspecified mechanisms occurring at depth. Coupling of top-down models with real time monitoring of total gas fluxes may open new doors for anticipating volcanic crisis.

The opening of vents like decompression valves of the hydrothermal system at Turrialba volcano, Costa Rica

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Between 1996 and 2009, Turrialba volcano, Costa Rica, reactivated, with the culmination on January 5th, 2010 with a phreatic (hydrothermal) explosion that opened a large vent. This vent has allowed since then to passively decompress the volcanic system as suggested by the large increase in the SO2 flux observed between January 2010 and May 2011, followed afterwards by a marked decrease on the SO2 flux, even when a small but noticeable second vent opened in early 2011. The opening of the 2010 vent has been attributed to movement of fluids from deep to shallow levels through cracks which allowed the migration of a hot magmatic volatile phase. On January 12th, 2012, a new vent opened possibly in response to the pressurization of a shallow hydrothermal system, as suggested by the absence of changes in the seismic patterns and the short-lived enhancement in the flux of heat, CO2 and H2S that diffused through the soil. This event may have triggered a deeper decompression later on January 18th which produced seismic tremor accompanied with the release of hot gases, water vapor, and non juvenile ash through a confined conduit and with absence of CO2 and H2S diffuse flux anomaly. The near magmatic temperature of gas (around 800°C) suggests that this second degassing event opened the system further.

These three vents are visually assumed to be the main contributors to the plume of Turrialba volcano even if numerous low-temperature (<130°C) sulfur-rich fumarolic fields exist inside and outside the Central and West Craters (about 25,000m^2) in 2012, less than 5% of the summital area). Considering the stability and the range of temperature of the vents (around 600, 600 and 800°C for the 2010, 2011, and 2012 vents, respectively), it is proposed that the 3 vents are an opening through the shallowest hydrothermal system of the volcano, while the low temperature fumarolic fields are the surface manifestation of purely shallow-level hydrothermal activity.

The existence of these vents most likely combined with a decrease in the magmatic input prevented any compression of the edifice in 2012 as suggested by the low seismic activity composed of mostly LPs, few screw shape signals characteristic of gas-rich fluids motion and shallow VTs. Altogether, the decrease of seismicity, SO2 flux, and of the acidity of the total deposition observed since mid 2011 support the hypothesis of the cooling down of the magma body that probably intruded sometime in 2007-2008 or before. Thus, the opening of vents in 2011 and 2012 while the system has been considered opened since the opening of the 2010 vent suggests that they are the manifestation of a saturation of the hydrothermal system capacity to transfer heat and volatiles to the atmosphere. Testimonies prior to the 1864-66 eruption of Turrialba and prior to the 1963-65 eruption of Irazu support this idea as many vents opened for both volcanoes prior to their magmatic eruptions.

Open-system submarine volcanoes: dynamics and phase state

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The discovery and subsequent exploration of active submarine volcanoes along convergent plate margins (de Ronde et al., 2001) raises questions of the persistence of their eruptive activity and the phase state of gaseous discharges from them. Several have been shown to host molten sulfur lakes (e.g. Macauley cone, Kermadec Arc, Diakoku, Mariana Arc) while NW Rota-1 (Mariana Arc) has maintained Strombolian eruption activity for at least six years. Some are known to discharge significant quantities of hydrothermal fluid (e.g., Brothers volcano, Kermadec arc), while others have sustained hydrothermal activity for up to 18,000 years, (e.g., Clark volcano, Kermadec arc) while others, such as Giggenbach volcano (Kermadec arc), persistently discharge gases (especially CO2) more vigorously than others.

However, based on observations from spreading volcanic environments, it has been suggested that that drilling into submarine arc volcanoes could not penetrate beneath a two-phase fluid regime. Here, we show from first principles that the normal state of magmatic gas discharge through an active volcanic system, whether submarine or subaerial, is single phase, forming a low density, high enthalpy core regime Two phase conditions are constrained to flank regimes with only surficial mixing and cooling in vent areas.

de Ronde, C.E.J.,et al., 2001, Intra-oceanic subduction-related hydrothermal venting, Kermadec volcanic arc, New Zealand:Earth Planet. Sci. Lett.193, 359-369.

SO2 camera measurements at Popocatepetl Volcano (Mexico). Insights into the dynamics of an atypical open vent volcano

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Popocatepetl Volcano (Mexico) has been, since its reawakening in 1994, one of the strongest permanent emitters of sulfur dioxide in the world (e.g. Delgado, 2008). Its activity poses also a direct threat to the most populated area of Mexico including its capital city. Activity has so far consisted of cycles of dome building and destruction by vulcanian explosions, alternating with periods of quiescent degassing. Average SO_2 emission rate over the whole eruption is about 50 kg/s but peaks of activity have released up to >1000 kg/s. Popocatepetl volcano is atypical because other volcanoes capped by an active lava dome usually exhibit SO_2 emission rates one or two orders of magnitude lower. Volcanoes hosting lava domes and plugs are known to be subject to sealing processes that precludes them from sustaining high SO_2 emission for long periods.

We have used a UV camera to obtain high temporal resolution measurements of SO_2 emission rates at Popocatepetl volcano. The state-of-the-art UV camera technique was coupled with a coaligned mini-DOAS, and often backed by ground-based DOAS traverses, in order to ensure the maximal accuracy of the results. Frequent field campaigns, with durations of up to several weeks, were conducted during various states of volcanic activity. This has allowed us to build a detailed picture of the sort-timescale variations of the degassing. Spikes of SO_2 emissions are superimposed over a long term, slowly varying trend of 50-100 kg/s. We propose a model of gas slugs bursting beneath a highly fractured dome to explain this degassing pattern. Strong fluxing of gas, provided by unerupted mafic-intermediate magma, is suggested to hamper sealing processes from plugging the conduit.

Open and closed system eruptive dynamics at Tungurahua volcano constrained by SO2 emission rate and seismo-acoustic intensity measurements

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The current eruptive period of Tungurahua volcano (Ecuador) began in 1999 with multiple episodes of explosive activity that have threatened the local population. The monitoring network has been continuously improved in order to better understand the eruptive behavior of Tungurahua and eventually provide early warning to the population. We obtain SO2 gas emission measurements from a network of four permanent NOVAC stations located between 7 and 11 km from the volcano, covering the preferential directions of winds in the area. Seismic and acoustic energies were calculated for explosions using a seismo-acoustic network composed of five broad band seismic stations coupled to infrasonic sensors installed at distances between 5-7 km from the vent. Furthermore, we derive tremor amplitudes from a short period seismic station, situated at about 2 km from the crater.

Since December 2009, five well-defined eruptive phases lasting from 21 to 70 days and following 82 to 181 days of quiescence have been recognized. Besides, between November 2011 and September 2012 a succession of short explosive and/or ash emission phases also took place. Activity is characterized by strombolian and vulcanian eruptive styles. In five occasions, pyroclastic flows were generated by sustained lava fountains or triggered by discrete explosive events. Ash fallouts were common to these eruptions and had low to significant impact on the nearby populations, depending on the duration and intensity of the eruptions.

During the eruptive phases no clear correlations were found between observed SO2 mass emission rates, seismic and acoustic energy of the explosions and the tremor amplitude. However, in a few cases some patterns related to different eruptive dynamics can be identified. We identify and characterize two end-members, which correspond to open and closed system degassing. In the first case, observed SO2 emission rates increase a few days before any significant change in tremor amplitude and any explosive activity appear. A clear example of this behavior is the eruptive period between December 2009 and March 2010, where the SO2 measurements increased 4 days before a change was evident in the seismic amplitude of tremor and 9 days before the occurrence of the first explosions. This suggests open system dynamics where gases are easily released throughout the entire eruptive phase. In the closed-system end member, the increase in SO2 degassing occurs simultaneously with the increase of tremor and/or explosive activity. An example of this activity took place in May 2010, when almost no SO2 was detected by the DOAS stations before a vulcanian explosion, with associated pyroclastic flows, partially opened the system allowing gas escape.

In this work, we present observational evidence of these mechanisms which are used to identify possible patterns of evolution of the activity, contributing to a more effective volcanic hazard assessment.

Degassing of Erebus lava lake, Antarctica

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Open system degassing was first observed at Erebus volcano, Antarctica, over a century ago, in the form of a lava lake in its summit crater. The persistent activity of the lava lake provides an opportunity for continuous measurements and observations of changes on a range of timescales. Gas emissions from Erebus lava lake have been measured using open–path Fourier transform infrared spectroscopy, during each austral summer field season from 2004 to 2012. The technique works particularly well at Erebus, thanks to the aridity of the Antarctic atmosphere, and the availability of a permanent 'infrared lamp' in the form of the lava lake itself. At Erebus, it is straightforward to measure both water and CO_2 in the gas emissions, something that is challenging at most volcanoes by OP–FTIR spectroscopy.

The sustained passive degassing and turnover of the lava lake is sporadically punctuated by Strombolian explosions. Both types of activity have been captured in the gas measurements. The measurements also identify longer–term changes to plume composition during and between field seasons (i.e. time scales of a few weeks to interannual variability). While the connection between surface observations of the lake behaviour and the plume composition is fairly clear, measured gas ratios have also been used with the thermodynamic model 'D–Compress' to investigate deeper processes. The model simulates the equilibrium composition of melt and gas as a function of pressure (depth). We report here on the application of 'D–Compress' in investigating magmatic source conditions likely to generate the observed plume gas composition.

Gas-driven lava lake fluctuations at Erta ’Ale volcano (Ethiopia) revealed by MODIS measurements

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The permanent lava lake of Erta ’Ale volcano (Ethiopia) is remotely monitored by MODerate resolution Imaging Spectroradiometers (MODIS) installed on satellites. The Normalised Thermal Index (NTI) is shown to be proportional to the volume of the lava lake based on visual observations. The lava lake’s variable level can be related to a stable foam trapped at the top of the magma reservoir, whose thickness changes in response to the gas flux feeding the foam being successively turned on and off.

The temporal evolution of the foam thickness, and the resulting variation of the volume of the lava lake, is calculated numerically by assuming that the gas flux feeding the foam, initially constant and homogeneous since December 9, 2002, is suddenly stopped on December 13, 2002 and not restarted before May 2003. The best fit between the theoretical foam thickness and the level of the lava lake deduced from the NTI provides an estimate of both the reservoir radius, 150-190 m, and the gas flux feeding the foam, 5.5x10-3-7.2x10-3 m3/s when existing. This is in agreement with previous estimates from acoustic measurements. The very good agreement between the theoretical foam thickness and that deduced from MODIS data shows for the first time the existence of a regime based on the behaviour of a stable foam, whose spreading towards the conduit can explain the permanent activity. The lava lake, when high, often shows regular rise and fall of its level. We have recognised a minimum of 26 very well marked cycles between January 2001 and December 13, 2002, corresponding to a typical return time of 10.8 +- 2.3 days and a gas volume of 8.3x105 +- 2.0x105 m3. This corresponds to a gas volume fraction in the reservoir equal to 0.03–0.12 pourcent. The yearly gas flux, estimated between December 13, 2002 and September 27, 2004, varies between 2.3x10-6 m3/s and 5.9x10-6 m3/s at the depth of the reservoir.

What infrasound tells us about open-vent volcanic systems

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Open-vent volcanoes produce prodigious and intense infrasound that can be reliably recorded with arrays and networks of broadband microphones. The infrasound signals produced by volcanoes are as diverse as their eruptive processes and reflect both a wide range of conduit processes and degassing styles. This presentation focuses on observations of volcanic activity made with cameras, thermal imagers, seismic, and tiltmeters, in conjunction with infrasound recordings. We highlight the relationship between sound intensity and explosive degassing, which exists for a subset of volcano behaviors. We also explain the very energetic sounds produced by some open-vent volcanoes with relatively minor levels of explosive activity. We conclude that while eruptive vigor does not always scale well with radiated infrasound power, infrasound spectral content and envelope shape can help to constrain eruptive and degassing style.

We present comparative results from open-vent volcanoes with activity ranging from bubble bursts at lava lakes (e.g., Erebus) to open-vent lava lakes (Halemaumau, Villarrica), to episodically erupting stratovolcanoes (e.g., Tungurahua, Karymksy, Santiaguito, and Sakurajima). We show how explosive gas outflux relates to the bimodal, or N-shaped, pulses that commonly accompany explosions. The various types of infrasonic tremors that are routinely observed at open-vent systems will also be compared and contrasted. Responsible source processes for tremor ranging from pulsating gas flow to crater/ vent resonances. In many cases these tremor signals rival explosions pulses in terms of acoustic power, highlighting the diverse range of acoustic efficiencies capable of open vent systems.

Effects of the atmospheric structure and topography on infrasound propagation around Sakurajima

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Detailed observations and numerical studies on infrasonic propagation reveal that effects of the atmosphere layers and of the topography are more significant than it was thought. The topographic effect is more significant in near-source (less than 10 km) while the atmospheric structure has a strong effect at the regional scale (>100-1000 kilometers).

We use a dataset of infrasound generated by Vulcanian activity at Sakurajima and recorded by a dense network of well-calibrated infrasound sensors deployed around Sakurajima and at different distances <60 km from the crater. The effect on wave propagation of atmosphere and topography with the distance is numerically investigated by a 2.5D finite difference (FDTD) method while a pure 3D FDTD modelling is used to analyse the azimuth distribution around the crater.

We show how the amplitude ratio of individual stations with the reference station at 3 km from Sakurajima shows remarkable seasonal differences. Amplitude ratio can vary 2 times at the same distance but different azimuth due to topography and/or 5 times at the same station within one day by atmospheric changes.

Numerical results indicate that topography and atmospheric variations are the main factors affecting the acoustic wave propagation. Our work provide evidence that a detailed knowledge of the topography and of the meteorological conditions are needed for accurate analysis of the acoustic source.

Seismic and geodetic precursors of small vulcanian eruptions at Suwanose-jima volcano, Japan

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Suwanosejima is a small volcano island south of Kyushu on the Pacific Ocean. The volcanic eruption of the island is characterized by small vulcanian explosions that repeatedly occur within a short interval of a few tens of minutes every a few months. We deploy 4 broad-band seismometers, 3 short-period seismometers and 5 borehole tilt meters at distances of 0.4-1.5 km. In the present study, we summarize precursor signals that are caused by magma behavior beneath active crater before explosions to understand the mechanism of vulcanian eruptions at Suwanosejima volcano for the period from September 2009 to 2011. Vulcanian explosions often occur during successive ash emissions for a few hours to days that generate continuous tremor. The explosions follow a sudden stop for about one or two minutes of continuous tremor. Uplift toward the crater also start at the same time when continuous tremor amplitude stop. Such coincidence suggests that the pressurization in the shallow magma is caused by accumulation of volcanic gas or ash due to a formation of a cap just beneath the active crater. It is noted that the inflations and explosions are also observed during a quiet period when no ash emission is observed. The cap is considered to be formed in a short time because the continuous tremor amplitude generally decreases for a few tens of seconds. Amplitude and duration of the inflation signals tend to become larger and longer, respectively, for explosion earthquakes with large maximum amplitude. The tilt signals are about a few tens of nano radian, which are detected at only station located close the active crater. The inflation amplitude is attributed to the pressurization at a depth of a few hundred kilometers beneath the active crater, and the maximum amplitude of explosion earthquakes are also explained by a release of the pressure stored before explosion. About 0.5 to 1 s before the onset of explosions, a tiny deflation with duration of about 0.6 s is observed in the seismogram of explosion earthquake. Our seismic waveform inversion shows that the tiny deflations are explained by contraction of volcanic conduit at a few hundred meter depth beneath the active crater. Pressure decreases are estimated to be about 0.03-1 MPa for a cylindrical source with a length of 500 m and a radius of 10 m. The pressure decrease may be a small leakage of gas, but no significant signal is detected by the acoustic sensors at stations: acoustic signal gradually and slightly sometimes increase its amplitude just before an onset of explosion, but the duration is not matched with that of the contraction seismic source. Although the mechanism of the contraction is still under investigation, it is noteworthy to mention that the maximum amplitude of explosion increases with the amplitude of contraction source.

Long lived effusive activity on Arenal Volcano: Insight from a volcano-tectonic study

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Interactions between tectonic and volcanic systems are not well understood. Here we present the initial results of a joint study combining several dozen UNAVCOs permanent GPS stations, a gravimetric campaign and geological field results at Arenal volcano which showed more than four decades of relatively low-level continuous effusive activity since its reawakening in 1968. Our results indicate that the magmatic system of Arenal volcano is being built in an active extensional area, which may have promoted the low-level yet persistent activity.

Costa Rica is located in the western part of Caribbean Plate; the Cocos Plate subducts along the Middle America Trench (MAT). Oblic subduction has generated a trench-parallel motion up to 10 mm yr-1 toward the North-West, which creates shear stresses between the MAT and the volcanic arc. Located in the volcanic arc, Arenal volcano, a basaltic-andesitic stratovolcano, grew within a comparable short timescale of a 7ka. The tectonic setting is complex and active seismogenic faults surround the Arenal volcanic edifice. After 440 years of dormancy, Arenal erupted in July 1968. The eruptive period lasted until 2010, during which approximately 0.55 km3 (2 m3 s-1 in 1968 to 0.086 m3 s-1 between 2000 and 2004) of lava and pyroclasts have been erupted.

Gravimetric measurements detect an E-W negative anomaly with 10 mgal amplitude while the GPS velocities shows a centimetric shear strain located within the volcanic arc. These geophysical techniques plus geological field observations suggest the settlement of the volcanic complex on a pull-apart basin. We propose a hypothesis in which the reported long-lived low effusion rate volcanic activity would be a consequence of local extensional tectonics and relatively high heat fluxes typical of active volcanic arcs.

Syneruptive deep magma transfer and shallow magma remobilization during the 2011 eruption of Shinmoe-dake, Japan-Constraints from melt inclusions and phase equilibria experiments-

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The 2011 Shinmoe–dake eruption started with a phreatomagmatic eruption (Jan 19), followed by climax sub-Plinian events and subsequent explosions (Jan 26–28), lava accumulation in the crater (end of January), and vulcanian eruptions (February–April). In Suzuki et al. (resubmitted after revision, as of January 2013; JVGR), we have studied a suite of ejecta to investigate the magmatic system beneath the volcano and remobilization processes in the silicic magma mush. Most of the ejecta, including colored pumice blocks (Jan 26–28), ballistically ejected lava (Feb 1), and juvenile particles in ash from the phreatomagmatic and vulcanian events are magma mixing products (SiO2 57–58 wt.%; 960–980C). Mixing occurred between silicic andesite (SA) and basaltic andesite (BA) magmas at a fixed ratio (40%–30% SA and 60%–70% BA). The SA magma had SiO2 62–63 wt.% and a temperature of 870C, and contains 43 vol.% phenocrysts of pyroxene, plagioclase, and Fe–Ti oxide. The BA magma had SiO2 55 wt.% and a temperature of 1030C, and contains 9 vol.% phenocrysts of olivine and plagioclase. The SA magma partly erupted without mixing as white parts of pumices and juvenile particles. The two magmatic end-members crystallized at different depths, requiring the presence of two separate magma reservoirs; shallower SA reservoir and deeper BA reservoir. An experimental study reveals that the SA magma had been stored at a pressure of 125 MPa, corresponding to a depth of 5 km. The textures and forms of phenocrysts from the BA magma indicate rapid crystallization directly related to the 2011 eruptive activity. The wide range of H2O contents of olivine melt inclusions (5.5–1.6 wt.%) indicates that rapid crystallization was induced by decompression, with olivine crystallization first ($\leq$ 250 MPa), followed by plagioclase addition. The limited occurrence of olivine melt inclusions trapped at depths of <5 km is consistent with the proposed magma system model, because olivine crystallization ceased after magma mixing. Our petrological model is consistent with a geophysical model that explains whole crustal deformation as being due to a single source located 7–8 km northwest of the Shinmoe-dake summit. However, even the shallowest estimated source of this deformation (7.5–6.2 km) is deeper than the SA reservoir, which thus requires a contribution of deeper BA magmas to the observed deformation. Remobilization of mush-like SA magma occurred in two stages before the early sub-Plinian event. Firstly, precursor mixing with BA magma and associated heating occurred (925–871C; stage-1 of $\geq$ 350h), followed by final mixing with BA magma (stage–2). MgO profiles of magnetite phenocrysts define timescales of 0.7–15.2h from this final mixing to eruption. The mixed and heated magmas, and stagnant mush that existed in the SA reservoir in the precursor stage, were finally erupted together.

Magma mixing and degassing processes of the 2011 eruption series of Shinmoedake, Kirishima volcano, based on petrological monitoring and melt inclusion analyses

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The 2011 eruption activity of Shinmoedake, Kirishima volcanic group, Japan, began with phreatomagmatic eruptions on 19 January. The activity was culminated with the sub-Plinian eruptions on 26-27 January, followed by lava effusion within the summit crater. Vulcanian explosions and minor ash discharges occurred intermittently from February to September. Open system behavior was observed by geophysical, geological and geochemical monitoring; (1) Continuous inflation of the magma chamber in a year before the eruption (Kawamoto et al., 2011), (2) All tephra samples of the 2011 eruptions observed contained essential material (Oishi et al., 2012), (3) Continuous degassing activity since January (Mori and Kagoshima Local Meteorological Observatory, 2012), (4) Inflation of the magma chamber from 2 February to November 2011 (Imakiire and Nishimura, 2012; Nakao et al., 2012). In this study, petrological and melt inclusion studies of the 2011 eruption series in order to investigate the eruption and degassing processes. The bimodal plagioclase core composition, relatively small rims of olivines and pyroxenes, and diffusion profiles of the olivines in the eruptive products of the sub-Plinian eruptions indicate the mixing of mafic magma and felsic magma in several days before the sub-Plinian eruption. The short time scale is consistent with estimation by diffusion profiles of the magnetite (Tomiya et al., 2012). Melt inclusion analyses indicated that the end members of the magma mixing were basaltic andesite and dacite magmas and its mixing ratio was estimated to be 0.4 of the basaltic andesite. The eruptive products of the Vulcanian explosions and minor ash discharges in February to August have similar mode composition, chemical compositions of phenocrysts, groundmass minerals and groundmass and zoning profiles of olivines to those of the sub-Plinian eruptions. These results suggest that the same mixing process also occurred before each eruption. The amount of the degassed magma was estimated based on sulfur content of melt inclusions of the end member magmas and SO2 flux observation during January 2011 to September 2012. The amount of the degassed magma was larger than that of eruptive products in 2011, indicating the degassing of the magma in the chamber due to magma convection in a conduit. The amount of the degassed magma during 2 February 2011 to September 2012 (31 Mm^3) is larger than inflation of the chamber observed by GPS after 2 February 2011 (10 Mm^3). However, assuming that the mixing ratio of the magmas (0.4), the amount of the degassed mafic magma was calculated to 12 Mm^3. This amount is similar to the inflation, suggesting that injection of the mafic magma from a deeper part into the chamber continued after February and caused the eruptions and degassing activity.

Characteristics of magma accumulation process of a basaltic volcano Izu-Oshima, Japan as revealed from integrated monitoring of deep low-frequency earthquakes, volcano deformation and CO2 out-gassing

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In order to make successful mid-term eruption predictions, we need to detect particular precursory processes operating in magma-plumbing system. Since 1989, Izu-Oshima volcano has continued its re-inflation, after the last eruption in 1986, and further repeated deflation-inflation cycles, resulting a net inflation of the volcano. The rate of secular inflation decreased exponentially until 2006, while the amplitudes of the deflation-inflation cycles increased. Since 2007, the rate of secular inflation has kept a constant speed and has also increased the activity of deep low-frequency (LF) earthquakes occurring at the depth range of 30-40 km beneath the volcano. Each episodic LF earthquake activity was preceded by the volcano deflation and accompanied by the inflation. Based on these evidences, we may suppose that the volcano inflation is caused by the supply of magma from a source region at the depth range of 30-40 km beneath the volcano, and that an episodic out-gassing from the shallow magma reservoir triggers each deflation-inflation cycle. To demonstrate the proposed mechanism, we need to combine the data on magma accumulation and out-gassing processes. To monitor the out-gassing of basaltic magma accumulating beneath the volcano, CO_2 is most helpful. In September 2005, we started continuous monitoring of soil CO_2 concentration at the summit of Izu-Oshima volcano, and obtained an evidence for the out-gassing process; the correlated increase of soil CO_2 concentration during the periods of not only accelerated inflation but also deflation of the volcano. Integrating the observational data, we suppose that the rate of magma supply from the upper mantle has increased since 2007 and that the increase in amplitude of deflation-inflation cycles might indicate a volume increase of CO_2 over-saturated region at the upper part of the magma reservoir beneath the volcano.

Dissecting the August 2012 Paroxysmal Eruption: Advances and Challenges in Monitoring Open System Activity at Tungurahua Volcano, Ecuador

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Tungurahua volcano (5023 m) is an andesitic stratovolcano that looms more than 3 km above the surrounding population centers. Since reactivation in 1999, Tungurahua has been in a relatively open system state characterized by low-level strombolian and vulcanian activity, short periods of repose (days to months), and more violent paroxysmal eruptions capable of producing hazardous pyroclastic flows, subplinian columns, and voluminous ash falls. Transitions from low-level to more hazardous activity can be abrupt and make monitoring challenging. Tungurahua is actively monitored by the Instituto Geofisico (IG) in Quito, in collaboration with national and international partners, using data from broadband seismoacoustic stations, DOAS gas spectrometers, tiltmeters, an ash fallout quantification network, satellite thermal and gas data, and reports from local observers.

Here, we highlight an example of the current open system activity with a multi-parameter analysis of the short-lived paroxysmal eruption that occurred during August 2012. Based on ash fallout and seismoacoustic data, the duration of the eruption was ~20 days, with just 11 days of continuous, elevated energy release. The gas (SO_2), ash, and thermal emissions of the eruption were clearly seen from space, and although the estimated fallout volume (0.3-0.45 x 10^6 m^3) and explosive intensity (VEI=1) is low the ash fall significantly affected local air quality and agricultural production. The seismoacoustic data and observations of the eruption indicate that the eruption began with intermittent gas jetting and tremor that became strong and nearly continuous from 13-21 August, and was associated with strong ash fallouts and the highest SO_2 emissions observed since a DOAS network was installed in 2007. We compare correlation patterns between co-located seismic and infrasound sensors with gas emission and ash fallout data, and identify the patterns indicative of continuous emissions. Tremor and ash emissions abruptly declined on the 21st and strong explosions began to occur, generating small pyroclastic flows and ash columns to 4 km above the vent. The strongest explosive infrasound (>1000 Pa at 5.3 km from the vent) recorded since 2006 was generated on 21 August. Hundreds of explosions were recorded over 21-23 August, prior to a rapid decline in seismic and acoustic output and return to background activity within several days. This eruption sequence provides an example of the current open system activity at Tungurahua volcano, highlights the methods and efforts currently in use to monitor and analyze the activity, and emphasizes the challenges and scientific opportunities provided by open system volcanoes.

Precursors to explosive eruptions at the persistently restless Telica Volcano, Nicaragua.

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Persistently restless volcanoes (PRVs) are characterised by consistently high levels of geophysical activity, such as a high or variable seismicity rate, strong degassing and sporadic explosions. PRVs do not exhibit typical distinct 'background' and 'unrest' states, but do experience non-eruptive and eruptive episodes. Traditional methods of forecasting volcanic activity based on seismicity patterns are not applicable to PRVs and the physical processes behind the transition between non-eruptive and eruptive episodes are not well understood. Telica Volcano, Nicaragua, is a PRV that has experienced numerous VEI 1-2 eruptions over the last century, as well as historic VEI 4 eruptions. We present geophysical data from the two most recent VEI 2 eruptions, in 1999 and in 2011. The 1999 eruptive episode started in May 1999 and consisted of ash emissions and discrete explosive activity, including explosions in August and October 1999 and the most energetic explosions in December 1999. We observe a sudden short-lived swarm of high-frequency (HF) (> 5 Hz) seismic events in September 1999, between the August and October 1999 explosions, coincident with the onset of many (22) short-lived long-period (LP) (< 5 Hz) seismic event multiplets. This is followed by a reduction in the seismic event rate between the October 1999 explosions and the large December 1999 explosions. In May 2011 an eruptive episode occurred at Telica with a five-week-long series of explosions. Nine months before the eruption we observe a swarm of HF events followed one month later by a significant drop in both LP and HF events. The event rate continued to decline until it reached a minimum six weeks before the eruption. Seismic event locations between September 2010 and May 2011 suggest that all events are shallow (< 2 km) and clustered beneath the active vent. Continuous GPS observations of the 2011 eruption of Telica show no deformation that can be related to volcanic activity and precludes a large influx of magma. Both the 1999 and 2011 eruptions show similar characteristics of a HF swarm followed by decreased seismicity before the most energetic explosive episodes. We suggest that these patterns of seismicity relate to the sealing of the magmatic/hydrothermal system. This transition from open-system degassing to a closed system may have lead to pressurisation of the system, resulting in explosions.

Volcano deformation caused by magma recession during a vulcanian explosion at Showa-crater of Sakurajima, Japan

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It is necessary to investigate spatio-temporal changes of pressure source during the eruptions to understand the dynamics of magma in volcanic conduit. In this study, we present a simple moving pressure source during a vulcanian eruption and calculate volcano deformation. We compare the results with the observed data at Showa crater of Sakurajima to understand the spatio-temporal change of magma recession.

We simplify the vulcanian eruption as follows. The explosion is triggered by a removal of a "cap" that pressurizes magma in the conduit beforehand. The magma head propagates downward as volcanic ash ejects. During the magma head falls down, the normal stress that works on the conduit wall weaken. At the same time, the drag force generated by magma flow is applied on the conduit wall, and its reaction force works on the bottom of conduit.

We calculate volcano deformation by using a 3-D boundary element method. We duplicate topography of Sakurajima by 10 m meshed DEM (GSI) and make a cylindrical conduit with a radius of 15 m under Showa crater. Radial tilt and strain changes caused by the magma depression and drag force at the ground surfaces are calculated at Arimura and Harutayama stations which are located at distances of 2.1 km and 3.2 km, respectively, from the Showa crater. The initial position of the magma head is set at 650 m altitude. We firstly explain deformation at Arimura caused by the normal stress. The tilt does not change remarkably during the magma head is dropped from 650 m to 0 m. The tilt starts to subside toward the crater at about 0 m and turns to uplift at about -1300 m. The radial strain shows extension at the beginning and turns to contract when the magma head reaches at about -950 m. The tilt caused by the drag force and its reaction force shows uplift toward the crater, and then turns to subside when the magma head reaches at about -1300 m. The strain shows contraction at the beginning, and then turns to show extension at about -950 m. Similar changes are shown at Harutayama station. These calculations indicate that recession process of magma in the conduit can be quantified by the tilt and the strain data.

We compare the calculation results with observation records of a Showa crater eruption on Feb 6, 2008, which is reported in Iguchi (2008). The observed radial strain shows a change from extension to contraction about 10 min after the start of eruption. The calculation indicates that the magma head downs to -950 to -1150 m at that time.

When the magma head becomes deeper than -2000 m, the tilt caused by normal stress shows uplift toward the crater, while such a change is not observed. This fact suggests that the eruption stopped at the depth shallower than -2000 m or that another deep deflation source exist.

The observed uplift toward the recorded just after the start of the eruption may be explained by upward drag force due to magma ascent at shallower part of the conduit.

Characteristics of precursory volcanic earthquakes to eruptions at the Showa crater of Sakurajima volcano, Japan

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Sakurajima is a post-caldera cone situated on the southern rim of Aira caldera, south Kyushu, Japan. Vulcanian eruptions have occurred at the Minamidake crater at the summit since 1955. Principal eruptive activity shifted to the Showa crater at the eastern flank of the summit in 2006. The eruptions at the crater become active and minor vulcanian eruptions occurred about 1,000 times per year in 2010-2012. Inflationary strain changes are observed by extensometers a few tens of minutes to several hours prior to the eruptions and are caused by pressure sources located at depths of 0-1.5 km (Iguchi et al., 2013). The inflation rates decrease or sometimes suspend about 30 minutes before the eruptions. Small earthquakes dominated by high frequency components (5-6 Hz) swarm when duration of inflation is longer than 1 hour. The earthquakes begin to occur a half hour to 1 hour after the start of the inflation. The amplitudes and number of the earthquakes further increase when the inflation rates decrease or suspend. And, the occurrences of the earthquakes suddenly stop at the start of the eruptions. The occurrences of the earthquake swarms are related to the decrease of inflation rate and the long inflation. The hypocenters of the earthquakes are located at a depth of 0.5 km beneath the crater and are close to depth of the pressure source. The precursory earthquakes may be generated by release of excess pressure accumulated by inflation of the pressure source. The earthquakes are similar to BH-type earthquakes during the eruptive activity of the Minamidake crater in waveforms and relation of the inflationary deformation, however the earthquakes are different in amplitude, patter of occurrence and direct precursor of eruptions.

Petrological monitoring of volcanic ash and evaluation of on-going eruptive activity of Sakurajima volcano, Japan: Characterization of juvenile magma and its evolution since 2006

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Sakurajima volcano restarted vulcanian eruptions in 2006 after a quiet period of nearly ten years. Recently, our petrological examination of juvenile materials of major eruptions during 20th century indicated that basaltic magma had repeatedly input in silicic mixed magma and that the level of eruptive activity had corresponded to the scale of basaltic injection (Ebihara et al., in this meeting). Here, we reveal the relationship between eruptive activity and erupted magma since 2006 to clarify whether magma plumbing system has changed or not. Based on the temporal change of the magmatic system, we also evaluate the geophysical monitoring to forecast future activity. Collected eruptive materials since 2006 consist mainly of volcanic ash, and sometimes lapilli. Lapilli usually have pyroxene phenocrysts with reverse zoning, and sometimes olivine ones with normal zoning. Its whole-rock chemistry shows the most mafic (SiO_2 = 58.5-59.8 wt.%), being consistent with the compositional trends of the 20th century's juveniles. These features suggest that the 20th century's magma plumbing system accompanied with basalt input has continued until now. Based on microscopic and BEI observation, juveniles in ash samples can be identified and are subdivided into two types: Juvenile-A and -B. Juvenile-A are magmatic, essential materials with fresh matrix in each eruption. On the other hand, Juvenile-B are similar to Juvenile-A, but usually contains dull colored matrix. Thus, we recognized that Juvenile-B are slightly altered materials which were related to the previous eruptions since 2006. We focus on Juvenile-A materials to investigate temporal change of magmatic materials. Juvenile-B are occurred in all the samples since 2006, whereas juvenile-A has occurred since September, 2009. The matrix glass compositions of Juvenile-A are wide (SiO_2 = 65-73 wt.%) and become more mafic from Sep. 2009 to Apr. 2010. Then, those have become more silicic again until Sep. 2010. Although such compositional fluctuation has repeated four times until now, those have gradually changed to be silicic as a whole.

If matrix glass compositions of juveniles could reflect the increase of the basaltic input, we can recognize four periods with the increase of basaltic magma (Sep. 2009-Apr. 2010; Nov. 2010-Feb. 2011; Aug-Sep. 2011; Dec. 2011-Feb. 2012). In these periods, the weight of volcanic ash as well as the volume of expansion of possible pressure source beneath the volcano became larger. Thus, we conclude that the scale of the basalt input correlates to the level of eruptive activity as in the case of activity during 20th century. Petrological and geophysical monitoring suggests that the eruptive activity since 2006 reached maximum in the period from Sep. 2009 to Apr. 2010. Although eruptive activity has continued since then, the temporal change of petrological features of volcanic ash suggests that there exists no evidence indicating the increase of the level of eruptive activity.

Seismic and tilt observation of vulcanian explosions at Lokon-Empung volcano, Northern Sulawesi, Indonesia

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Lokon-Empung located in the northern Sulawesi is one of the most active volcanoes in Indonesia. Vulcanian eruption activity is considerably high, so we began temporal seismic and tilt observation around the volcano since September 2012, to understand the mechanism of vulcanian eruptions at Lokon-Empung.

Four broadband seismometers, Trillium 40, are deployed around the volcano in the distance range of 1.6 - 6.8 km from active Tompaluan crater. At the closest station WAILAN, a tilt meter (Pinnacle Denali) is also installed. Each seismometer is connected to a data logger (HKS-9550) to record seismic data in a CF card with an A/D resolution of 24 bit and a sampling rate 100 Hz with GPS time stamps. Tilt data digitized every 1 second within the tilt meter are transmitted to a laptop PC at Kakaskasen Volcano Observatory (KKVO) through wireless LAN. Seismic data of WAILAN is sent to Japan through the wireless network and global internet on a trial basis.

Explosion earthquakes on October 5 and November 11 have obvious onset with compressional P phase. Ground velocity of the event on October 5 is in the order of 0.001 m/s at the station WAILAN. Visual report on the height of ash column was about 1500 m above the crater.Before the eruption, small inflation phase (-80 nanoradian) around crater can be seen in tilt record. Duration of the inflation phase is about 40 minutes, which is almost same order to those found in Semeru volcano (3 - 30 minutes). The height of ash column of the explosion on November 11 is about 600 m. The velocity amplitude of the event on November 11 is about half of that on October 5. Although the seismograms of these two explosions seem different in non-filtered traces, we can find very similar waveforms in the lower frequency band below around 1 Hz. This similarity indicates that explosion mechanism of these two events have common physical process. In the low-pass filtered seismograms, large dilatational phase is identified after the compressional P wave and then clear retrograde motion representing Rayleigh wave appears. These waveform characteristics are similar to the explosion earthquakes at Sakurajima, Suwanosejima which often explode with Vulcanian styles. While small deflation phases appearing about a few seconds before the initial compressional phase that are reported for the explosion of Suwanosejima and Semeru volcanoes are not well recognized.

Although we have analyzed only a few events, several remarkable features have found in the obtained data, comparable to the other vulcanian eruptions. To analyze more events and compare them to the other eruptions are effective ways to understand also the mechanism of vulcanian eruption itself, not only at Lokon-Empung.

Variations in eruptive style and depositional processes of Neoproterozoic terrestrial volcano-sedimentary successions in the Hamid area, North Eastern Desert, Egypt

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Two contrasting Neoproterozoic volcano-sedimentary successions of ca. 600 m thickness were recognised in the Hamid area, Northeastern Desert, Egypt. A lower Hamid succession consists of alluvial sediments, coherent lava flows, pyroclastic fall and flow deposits. An upper Hamid succession includes deposits from pyroclastic density currents, sills, and dykes. Sedimentological studies at different scales in the Hamid area show a very complex interaction of fluvial, eruptive, and gravitational processes in time and space and thus provided meaningful insights into the evolution of the rift sedimentary environments and the identification of different stages of effusive activity, explosive activity, and relative quiescence, determining syn-eruptive and inter-eruptive rock units.

The volcano-sedimentary deposits of the study area can be ascribed to fourten facies and seven facies associations: (1) basin-border alluvial fan, (2) mixed sandy fluvial braid plain, (3) bed-load-dominated ephemeral lake, (4)lava flows and volcaniclastics,(5)pyroclastic fall deposits,(6) phreatomagmatic volcanic deposits, and (7)pyroclastic density current deposits. These systems are in part coeval and in part succeed each other, forming five phases of basin evolution: (i) an opening phase including alluvial fan and valley flooding together with a lacustrine period, (ii) a phase of effusive and explosive volcanism (pulsatory phase), (iii) a phase of predominant explosive and deposition from base surges (collapsing phase), and (iv) a phase of caldera eruption and ignimbrite-forming processes (climactic phase). The facies architectures record a change in volcanic activity from mainly phreatomagmatic eruptions, producing large volumes of lava flows and pyroclastics (pulsatory and collapsing phase), to highly explosive, pumice-rich plinian-type pyroclastic density current deposits (climactic phase). Hamid area is a small-volume volcano, however, its magma compositions, eruption styles, and inter-eruptive breaks suggest, that it closely resembles a volcanic architecture commonly associated with large, composite volcanoes.

Lava dome structures and their significance

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Lava domes form by a combination of viscous, plastic and brittle deformation modes. During magma ascent, the competition between these deformation mechanisms controls the construction of the damage structure across the domes and thus the degassing network with important repercussions on the eruptive style.

Here, we present an overview of signature structures developed during magma ascent, with a focus on crystal-bearing lava domes (including Unzen, Santiaguito, Tarawera, Ceboruco, Colima, Soufriere Hills, and Mount St. Helens). Our observations encompass features such as foam bands, tuffisites, thermal-stressing fractures, unloading fractures, shear fractures, pseudotachylytes and cataclasites. We describe the relationships between these structures and ultimately question the conditions underlying their origins as well as their influence on lava dome eruption dynamics.

Frictional processes in glass and ash gouge

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The ascent of high-viscosity magma in upper conduits proceeds via the development of shear zones, which commonly fracture, producing fault surfaces that control the last hundreds of meters of ascent by frictional slip. Frictional slip in conduits may occur along magma-rock, rock-rock and magma-magma interfaces, with or without the presence of gouge material. During slip, frictional work is converted to heat, which may result in strong geochemical disequilibria as well as rheological variations, with important consequences on the dynamics of magma ascent.

Here, we present a thermo-mechanical study on the ability of glass and ash gouge (with different fractions of glass and crystals) to sustain friction, and in some cases to melt, using a high-velocity rotary apparatus. The friction experiments were conducted at a range of slip velocities (1.3 mm/s to 1.3 m/s) along a (fault) plane subjected to different normal stresses (0.5-5 MPa). We observe that the behaviour of volcanic rocks during slip events varies remarkably, and unlike rocks which undergo comminution during slip, the inability of glass asperities to comminute induces thermal stressing and commonly results in catastrophic failure within the elastic regime or upon the glass transition. Notably, samples heated at more than 400 K/s fully liquefied but subsequently failed nonetheless. Thermo-mechanical analysis illustrates that beyond the calorimetric glass transition, slip continued in the elastic regime before the samples relaxed and underwent viscous remobilization. We conclude that during slip events, comminution, volumetric fluctuations and the viscous remobilisation temperature distinguish the frictional behaviour of glass from that of crystalline rocks. Increasing damage along the slip zone contributes to the development of a cataclasite.

Slip in cataclastic ash gouge generally obeys Byerlee's rule at low velocity, but shows an exponential decrease of the friction coefficient with increasing slip velocity. An increase in slip velocity further increase the localisation of deformation and development of shallow C/S fabrics in the gouge. The experiments do not produce significant heat compared to glass-on-glass friction, and brings into question the capability for frictional melting when cataclasite is present along the fault zone. We discuss the implications of our findings to case studies of lava dome eruptions.