# Phreatic & hydrothermal eruptions: Insights into energy budget and eruption dynamics based on laboratory experiments.

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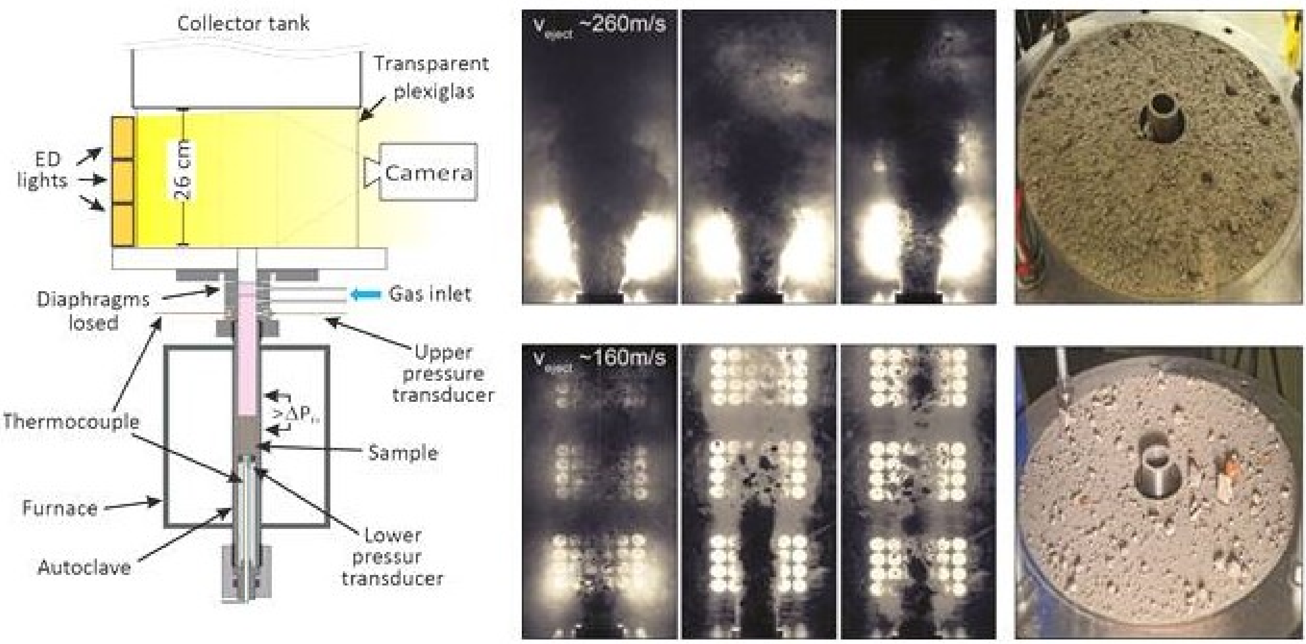
Phreatic and hydrothermal eruptions are amongst the most common and most diverse eruption types on earth. Heating and/or decompression leads groundwater or hydrothermal fluids to rapidly flash to steam triggering these types of eruptions. Their diversity arises from the variety of (1) rock types and host rocks that can be involved, (2) ways to seal possible degassing pathways, (3) alteration type and degree of depending on the composition of volcanic gases and the hydrothermal fluids, and finally (4) P-T conditions possible. In addition phreatic and hydrothermal eruptions are very difficult to predict in terms of timing and magnitude bearing important consequences, especially in densely populated regions or popular hiking / recreation destinations. Despite of their hazard potential, phreatic and hydrothermal eruptions have been understudied in volcanology compared to their magmatic counterparts. Recent violent eruptions as for instance the 2012 Upper TeMaari eruption (NZ) and especially the 2014 Ontake eruption (Japan) spotlighted this eruption type and triggered various studies, combining for instance field and experimental approaches.

Here we present conclusions from several case-studies, representing weak and violent eruption behavior. Further we give insights into the effect of host rock lithology and alteration on the eruption likelihood and dynamics.

Field studies revealed insights into the eruption dynamics, for instance based on detailed mapping of the deposits and or the ballistic strew field of a hydrothermal eruption. The main lithology types identified for an eruption were characterized for their petrophysical properties and degree of alteration. Then these lithology types were used for rapid decompression experiments mimicking hydrothermal explosions under realistic P-T conditions (from 110 ˚C & 0.3 MPa up to 400˚C & 25 MPa). Experimental studies of this kind facilitate better constraints on the eruption dynamics as for instance the ejection of ballistics or amount of ash produced and their associated hazard. Furthermore they shed light on the energy conversion and partitioning during hydrothermal explosions.

Keywords: phreatic , hydrothermal , energy budget, eruption dynamics, experimental volcanology



Left: Experimental Setup used to investigate phreatic eruptions under controlled laboratory conditions. Right: Still frames showing the plume and ejection created in the lab. Fragmentation and ejection behavior is different comparing energetic steam-flashing (above) to pure steam expansion (below).

# Automated seismic event location combining waveform stacking and relative location techniques: An application to geothermal and volcanic environments

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Microseismic monitoring became a common operation in many applications, including monitoring of volcanic areas and underground industrial operations (i.e. induced seismicity). The analysis of microseismicity is challenging, because of the large number of recorded events often characterized by low signal-to-noise ratio. Such seismic datasets are often characterized by multiple events with short inter-event times or overlapping events; in this case, correct phase identification and event association are challenging, and errors can lead to missed detections and/or reduced location resolution. In the last years, to improve the performance of the current data analysis procedure various waveform-based methods for the detection and location of microseismicity have been proposed. These methods exploits the coherence of the waveforms recorded at different stations and do not require the automated picking and phase association procedures. When the recorded waveforms are very noisy, waveform based methods appear to be more robust than the traditional ones (based on phase picking). However, like any other absolute location method, the accuracy of locations strongly depends on the knowledge of the velocity model. Volcanic areas are generally characterized by complex 3D velocity and by a pronounced topography, for these reasons the use of simplified 1D velocity models may strongly affect the locations accuracy. In general, the largest source of error in the seismic event location process is related with the use of inaccurate velocity models (a condition which often occurs in volcanic areas). In this work we apply a location method which combines some features of relative location techniques (such as the source specific station correction term [Richards-Dinger and Shearer 2000]) with the waveform based location methods [Grigoli et al 2016]. This location approach inherits all the advantages of the full waveform location methods without the main drawback which characterizes all the absolute location procedures. In fact, this method is less dependent on the knowledge of the velocity model and presents several benefits, which improve the location accuracy: 1) it accounts for phase delays due to local site effects, e.g. surface topography or variable sediment thickness 2) theoretical velocity model are only used to estimate travel time within the source volume, and not along the entire source-sensor path. We tested this location approach with different datasets, including: a seismic swarm associated with magmatic fluid migrations in NW-Bohemia (Czech Republic) and to seismic swarms in volcanic environments (Piton de la Fournaise Volcano (La Reunion) and Masaya Volcano (Nicaragua)).

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Grigoli, F. et al. Automated microseismic event location using Master-Event Waveform Stacking. Sci. Rep.

6, 25744; doi: 10.1038/srep25744 (2016).

Keywords: Fluid Induced Seismicity, Microseismic data analysis, Earthquake location

# Trapped bubbles keep pumice afloat and gas diffusion makes pumice sink

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Pumice can float on water for months to years –long enough for pumice to travel across oceans and facilitate the spread of species. Long-lived pumice floatation is unexpected, however, because pumice pores are highly connected and water wets volcanic glass. As a result, observations of long floating times have not been reconciled with predictions of rapid sinking. We propose a mechanism to resolve this paradox - the trapping of gas bubbles by water within the pumice. Gas trapping refers to the isolation of gas by water within pore throats such that the gas becomes disconnected from the atmosphere and unable to escape. We use X-ray microtomography to image partially saturated pumice and demonstrate that non-condensable gas trapping occurs in both ambient temperature and hot (500°C) pumice. Furthermore, we show that the size distribution of trapped gas clusters matches predictions of percolation theory. Finally, we propose that diffusion of trapped gas determines pumice floatation time. Experimental measurements of pumice floatation support a diffusion control on pumice buoyancy and we find that floatation time scales as $L^2/DF^2$ where L is the characteristic length of the pumice, D is the gas-water diffusion coefficient, and F is pumice water saturation. A mechanistic understanding of pumice floatation is a step towards understanding how pumice is partitioned into floating and sinking components and provides an upper bound on the lifetime of pumice rafts in the ocean.

# Shallow submarine silicic eruptions at Oomurodashi Volcano, northern Izu-Bonin Arc, and their potential hazards

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Oomurodashi is a large bathymetric high located at the northern end of the Izu-Bonin Arc. Using the 200 m bathymetric contour to define its summit dimensions, the diameter of Oomurodashi is ~20 km, making it one of the biggest edifices among the Izu-Bonin Arc volcanoes. Oomurodashi has been regarded as inactive, largely because it has a vast flat-topped summit at ~100 meters below sea level (mbsl).
During cruise NT07-15 of R/V Natsushima in 2007, we conducted a dive survey in a small crater, Oomuro Hole, located in the center of the flat-topped summit, using a remotely-operated vehicle (ROV). The heat flow measurement conducted on the floor of Oomuro Hole during this dive recorded an anomalously high value of 4,200 $mW/m^2$. Furthermore, ROV observations revealed that the southwestern wall of Oomuro Hole consists of fresh rhyolitic lavas.
These findings suggest that Oomurodashi is an active silicic submarine volcano. To confirm this hypothesis, we conducted detailed ROV and geophysical surveys of Oomurodashi in 2012 and 2016 (cruises NT12-19 of R/V Natsushima and KS-16-6 of R/V Shinseimaru).
The ROV surveys revealed numerous active hydrothermal vents on the floor of Oomuro Hole, at ~200 mbsl, with maximum water temperature measured at the hydrothermal vents reaching 202°C. We also conducted a much more detailed set of heat flow measurements across the floor of Oomuro Hole, detecting very high heat flows of up to 29,000 $mW/m^2$. ROV observations revealed that the area surrounding Oomuro Hole on the flat-topped summit of Oomurodashi is covered by extensive fresh rhyolitic lava and pumice clasts with minimal biogenetic or manganese cover, suggesting recent explosive eruption(s) from the Hole. Furthermore, several small (~50 m in diameter) domes were discovered on the flat-topped summit of Oomurodashi, and an ROV survey recovered fresh rhyolite lava from one of these domes, suggesting that more effusive, lava dome-building eruptions also occurred recently.
These findings strongly indicate that Oomurodashi is an active silicic submarine volcano, with recent eruption(s) occurring from Oomuro Hole. Since the summit of Oomurodashi is in shallow water, it is possible that eruption columns are likely to breach the sea surface and generate subaerial plumes. A ~10 ka pumiceous tephra layer with identical geochemical characteristics to the rhyolites recovered during the dives has been discovered in the subaerial outcrops of the neighboring islands of Izu-Oshima and Toshima, strongly suggesting that these tephra deposits originated from Oomuro Hole.
The deeper slopes of Oomurodashi are composed of effusive and intrusive rocks that are bimodal in composition, with basaltic dikes and lavas on the northern flank and dacite volcaniclastics on the eastern flank. This suggests that Oomurodashi is a complex of smaller edifices of various magma types, similar to what has been observed at silicic submarine calderas in the southern part of the Izu-Bonin Arc (e.g. Sumisu Caldera; Tani et al., 2008, Bull. Vol.).
We will provide a geological overview of Oomurodashi Volcano and edifice growth history based on the ROV observations, and discuss its potential hazards from shallow submarine silicic eruptions.

Keywords: Shallow submarine silicic eruption, Oomurodashi, Izu-Bonin Arc

# Investigating submarine eruptions using $H_2O$ contents of volcanic glasses: application of a new FTIR spectroscopy method

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Volatile degassing during magma ascent plays a fundamental role in determining eruption style and pyroclast formation, and the analysis of the dissolved volatile contents preserved in volcanic glasses (both melt inclusions and matrix glasses) is therefore an important tool for investigating eruption processes. Given its strong control on parameters such as melt viscosity, $H_2O$ is one of the most important magmatic volatiles, especially for felsic magmas where it is often the most volumetrically abundant volatile. In addition, the well-constrained pressure-dependence of $H_2O$ solubility means that the $H_2O$ contents of pyroclast glasses can provide a record of the pressure at which pyroclasts quenched. For submarine eruptions, where vent depth and pyroclast formation are rarely observed directly, this is particularly valuable information. Unfortunately, silicate glasses are vulnerable to secondary hydration (i.e. the addition of $H_2O$ from the surrounding environment at low temperature in the time following deposition), and thus volcanic glasses deposited in the submarine environment are often hydrated. To obtain meaningful $H_2O$ data from these hydrated glasses it is therefore necessary to distinguish between the original final dissolved $H_2O$ content and the $H_2O$ added subsequently during hydration. Since $H_2O$ added during hydration is added as molecular $H_2O$ ($H_2O_m$), and the species interconversion between $H_2O_m$ and hydroxyl (OH) species is negligible at ambient temperature, the final OH content of the glass remains unaltered during hydration. By using $H_2O$ speciation models to find the original $H_2O_m$ content that would correspond to the measured OH content of the glass, the original total $H_2O$ ($H_2O_t$) content of the glass prior to hydration can be reconstructed. These $H_2O$ speciation data are obtained using Fourier Transform Infra-red (FTIR) spectroscopy. In many cases OH cannot be measured directly and instead is calculated indirectly as $OH = H_2O_t - H_2O_m$. Here we demonstrate the importance of using a species-dependent $H_2O_t$ molar absorptivity coefficient to obtain accurate $H_2O_t$ and $H_2O$ speciation data and outline a methodology for calculating such a coefficient for both hydrated and unhydrated rhyolite and andesite glasses. Using this method we present reconstructed final $H_2O_t$ contents of hydrated felsic pyroclasts from submarine volcanoes in the Japanese Izu-Bonin Arc and use these data to investigate submarine felsic eruptions and the processes that produce submarine pyroclasts, in order to understand their associated hazards.

Keywords: FTIR spectroscopy, hydration, submarine volcanology

# Rootless cones as Martian cone analogues and miniature volcanoes

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Rootless cones are a type of volcanic pyroclastic cones formed through lava-water interaction. When hot lava flows onto a region of waterlogged sediments secondary explosion is induced triggered by intense vesiculation of water and forms a pyroclastic cone. They are peculiar in that they are formed at remote places from lava emanation site. On Mars even at distal part of long lava flow such as 1000 km from the source rootless cones are found. Until recently much attentions have not been paid on rootless cones and they have been regarded as a minor existence so that even the basic information such as the morphology of the cones and the pyroclastic constituents is lacking. But in the recent 10 years significant meanings have been gradually recognized in planetology and terrestrial volcanology.

Although the formation of terrestrial rootless cones is regionally restricted to several areas such as Iceland and Hawaii high-resolution imaging has revealed the pervasive existence on Mars (e.g., Greeley and Fagents, 2001). Martian rootless cones are located in very young volcanic regions which were thought to be active in 2 Ma at the latest (e.g., Burr *et al.*, 2002). The existence of these young rootless cones is an evidence of 1) the distribution of subsurface water ice on recent Mars and 2) hot interior of recent Mars enough to generate amount of flood lava (e.g., 5000-7500 km$^3$ in Athabasca Valles; Jaeger *et al.*, 2010). Thus, rootless cones show recent environment and thermal state of Mars, and terrestrial ones should contribute to this field.

Rootless cones would be nature analogues of huge terrestrial volcanoes. There are several good points to focusing rootless cones in point of volcanology; 1) they are formed as groups (more than 1000 cones), i.e., they can be a target of statistical analysis which is difficult for limited numbers of huge volcanoes, 2) they help simple understanding of volcanic explosions because of their simpler formation system, and 3) easier field working thanks to their small edifices.

In the presentation at first we show typical examples of rootless cones in Iceland and on Mars; their distributions and the cone morphometry in comparison with other pyroclastic cones based on our surveys of 5 years. Then we will discuss the relative position of the rootless eruption among cone-forming eruptions by magmatic and phreatomagmatic.

Keywords: rootless cone, Mars, miniature volcano

# Statistical classification of tephra from rootless eruptions

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Rootless cones (RCs) are classified into a peculiar type of pyroclastic cones formed by lava-water interaction (Thordarson and Hoskuldsson, 2002). Different from other cone-forming eruptions the size is generally small so that they can be used as a miniature of volcanic eruptions which unite between large scale natural eruptions and laboratory scale experiments. In this context, the data about the morphology of the edifice as well as physical characteristics of eruption products (hereafter called as rootless tephra) are important in the comparison although the available data are quite limited until recently. In the recent decade there appear several researches on the RCs in Iceland mainly from planetological interests (Reynolds *et al.*, 2015; Noguchi *et al.*, 2016; Hamilton *et al.*, 2017; Fitch *et al.*, 2017). Fitch *et al.*, 2017 investigated detailed grain morphology of rootless tephra and found correlation among mean grain size and tephra morphologies; blocky, mossy, fluidal, shard, and aggregate. The study is based on the analysis of morphological classification for about 100 hand-picked grains. The results seem interesting but always associated with morphological investigations the limited numbers of specimens and the sampling uniformity are controversial.

In this study we investigated morphology of rootless tephra by using automated particle-morphology analyzer. Thanks to the recent advances of the device, we can obtain information of morphology for thousands of grains in a short time. By using this device we try to overcome the above-mentioned problems. The target samples were collected in three fields of RCs in Iceland (Myvatn, Landbrot and Thjorsardalur). We used seven parameters to characterize the morphology: aspect ratio, circularities (circularity and high-sensitivity one), convexity, solidity, intensities (mean and standard deviation) which are measured on Morphologi G3S$^{TM}$ (an automated particle analyzer, Malvern Instrument$^{TM}$) in AIST. The target of this investigation is to explore the magnitude of lava-water interaction of rootless eruptions in comparison with other phreatomagmatic/phreatic eruptions based on the morphology of tephra.

In the analysis we seek possible correlations between morphological parameters and the magnitude of rootless eruptions (volume and average slope of the cone). We found that transparent elongated-irregular shaped grains are notable in the samples which were collected from the lower layer of RCs. Looking at the images of specimen, these grains include bubbles and/or bubble walls. This might indicate the lava which was still at the degassing stage was quenched and fragmented at the beginning of rootless eruptions. To verify this idea, the bubble and crystal size and density analyses are necessary.

Keywords: rootless tephra, grain shape, cluster analysis

# Constraints on the chemical evolution of magma at Fuji volcano from plagioclase phenocrysts.

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Volcanic eruption brings materials from inside the Earth to the surface. Studying such volcanic materials is important to know how magma is evolved and how eruption is triggered. Chemical evolution of magma is considered to proceed through various processes such as fractional crystallization, degassing, assimilation and mixing. In this study, we have conducted petrology, geochemistry and Sr isotopic study of plagioclase phenocrysts to constrain the chemical evolution at Fuji volcano in Japan.

The studied samples are basaltic lavas, gabbros, pumices, and scoriae from Fuji volcano. All the samples except the lavas are products of the latest eruption, the Hoei eruption in 1707. Pumices and scoriae of the Hoei eruption were collected from three outcrops and scoria cone in the first crater of the Hoei eruption. Gabbroic xenoliths brought by Hoei eruption were also collected near the second crater. In addition, two lava samples which belong to Kofuji group were collected by drilling into the northwestern flank of Fuji volcano (Yoshimoto et al., 2010).

Major element compositions of plagioclase phenocrysts from the samples were determined by EPMA, whereas their trace element abundances and Sr isotopic composition were measured by LA-ICPMS at the University of Tokyo. In addition, water contents in some plagioclase phenocrysts were investigated by FTIR at JAMSTEC.

The results revealed that there are two distinctive trends for the chemical evolution of magma at Fuji volcano ( Fig.a). One is characterized by the decrease of anorthite content (An) with the increases of La abundance and Eu-anomaly in plagioclase crystals. The other trend is characterized by the decrease of An with the increase of Mg abundance and with insignificant changes of La abundance. The former evolutionary trend was observed mainly in the gabbro xenoliths and Hoei pumices, whereas the latter was identified in the basaltic lavas and Hoei scoriae. The finding suggests that the source magmas of the gabbros and Hoei pumices evolved under similar conditions and those of the lavas and Hoei scoriae did so as well. This is consistent with the inference that the dacitic and basaltic source magmas of the Hoei pumices and scoriae existed in different magma chambers(e.g. Yoshimoto et al., 2004).

The negative correlation between An and Eu-anomaly observed in the gabbro and pumice plagioclase indicates that their source magmas became more reductive so that the proportion $Eu^{2+}$ relative to $Eu^{3+}$ increased as crystallization proceeds. Such reduction of magma can be caused by assimilation of sediments enriched in organic materials or by sulfur degassing (Moussallam et al., 2016). Our Sr isotopic analyses indicate that the core and rim of the plagioclase have identical Sr isotopic ratios within analytical uncertainty, precluding significant sediment assimilation. Thus, we envisage that the source magmas of the gabbros and Hoei pumices experienced degassing during the chemical evolution.

Our FTIR analyses revealed that plagioclase crystals in the Hoei pumices and scoriae have water under the detection limit (sample thickness: 100 micro-meter). The IR spectra of plagioclase crystals exhibit flat spectra between 3000 and 4000 $cm^{-1}$. This is somewhat enigmatic, given that the studied pumices and scoriae contain many vesicles and also that glass-inclusions of the Hoei scoriae contain 1~4 wt % $H_2O$ (Iida et al., 2004). There is no clear explanation for this at present.

Keywords: volcano, Hoei eruption, plagioclase, water

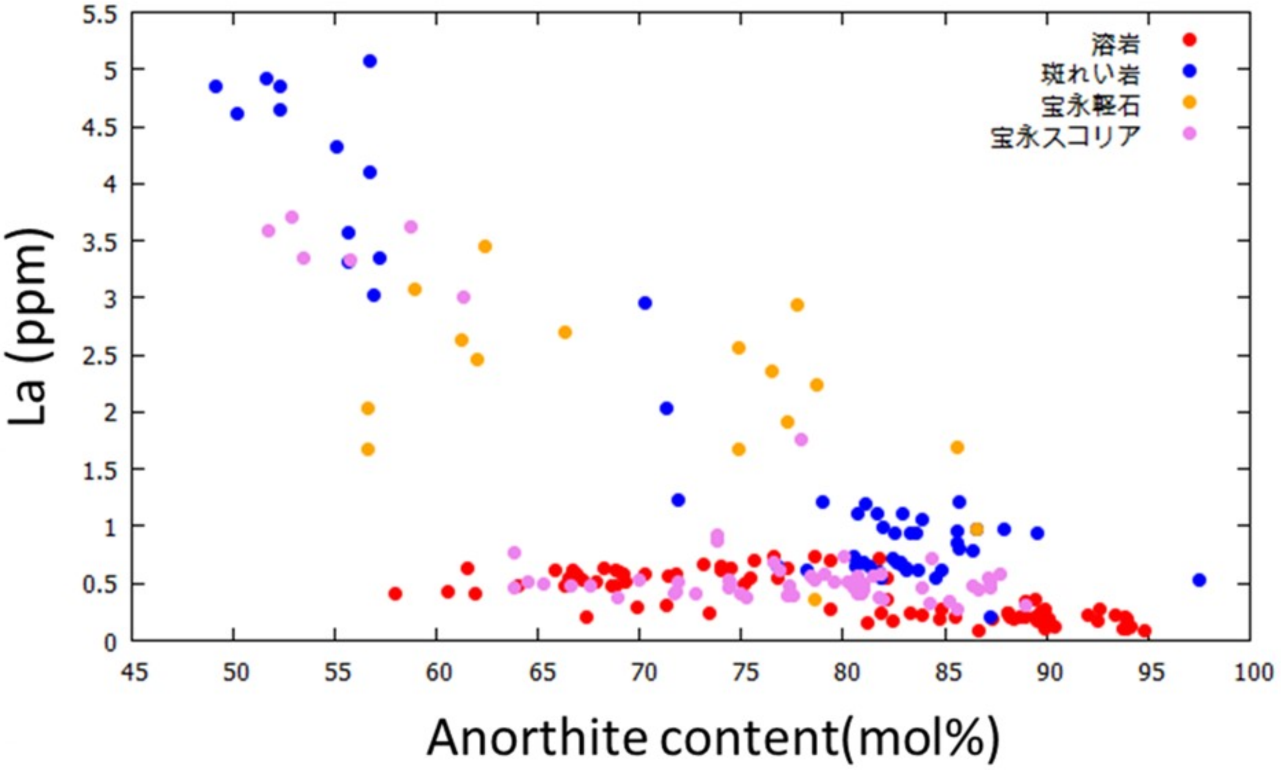

Fig. a

# Model experiments of degassing process in a crystal bearing magma

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Degassing from an ascending volatile-rich magma affects the style of volcanic eruption. Eruption is considered to become explosive when the magma viscosity is high because degassing is difficult. However as solidification progresses, cracks may form in the pathway of the bubbles such that the degassing is promoted. Then the eruption may become effusive. Magma contains crystals and becomes non-Newtonian such that the viscosity decreases with the strain rate (a shear-thinning property). Divoux *et al.* (2011) conducted degassing experiments using a non-Newtonian fluid (a diluted solution of a commercial hair-dressing gel), and showed that several distinct styles of degassing styles exist. However, there have been no degassing experiments in which ascending bubbles are directly observed in a fluid containing liquid and particles. In this study we inject bubbles into a transparent mixture of liquid and particles which models a crystal-bearing magma. We vary the particle volumetric fraction *phi* to understand how the degassing regimes transition as *phi* increases.

A transparent model fluids are made by mixing a silicone powder (particles) and a silicone oil which has the same refractive index. The volumetric fraction *phi* of the particles range from 0 to 0.5. From the rheology measurements, we find that the viscosity and the yield stress increases with phi. In addition the fluid becomes increasingly shear thinning with *phi*.

In this study, we conduct two types of experiments. Experiment 1 is conducted to study how the bubble ascent velocity ($U$) depend on its volume ($V$). Experiment 2 is conducted to observe the pattern of the bubbly flow and the fluctuations of differential air pressure at several flow rates $Q$. From experiment 1 (*phi* = 0-0.4), we find that $U$ decreases with *phi*. We fit the data to a power-law relation ($U$ *proportional to* $V^n$) and obtain the power-law exponents $n$, for each fluids with different *phi*. From the Stokes' law, $n$ in a Newtonian fluid is $n = 2/3 \sim 0.67$. At *phi* = 0, 0.1 we find that $U$ is smaller than the Stokes' velocity and that $n < 0.67$. Reynolds number ($Re$) in these experiments are $Re \sim 100$ which is much larger than 1, and we consider that the turbulent drag is the cause of this deviation. On the other hand for *phi* = 0.3-0.4, $U$ becomes sufficiently small such that $Re < 1$. The value of the exponent $n$ is $n > 0.67$ and the measured $U$ agree well with the Stokes' velocity calculated using the shear-thinning viscosity. Here we note that $n$ increasing with *phi* implies that the coalescence of bubbles with different sizes are enhanced, which we confirmed in our experiments. For fluid with *phi* = 0.5, we find that the bubble ascent is strongly inhibited because the yield stress becomes comparable to the bubble buoyancy. From experiment 2 (*phi* = 0.4-0.5), we observe that the generation and coalescence of the bubbles occur continuously. As $Q$ increases, the bubbles become larger and vertically elongated (slugs). Furthermore, at *phi* = 0.5, narrow cracks form near the orifice where the bubbles form. The style of the differential pressure fluctuations also change with *phi*. At *phi* = 0.4, the pressure fluctuates regularly having a short period. However at *phi* = 0.5, the fluctuation becomes irregular with a longer period.

Our experiments suggest that as the magma cools and *phi* increases, the bubble ascent velocity becomes slower, such that the bubbles may even become trapped. However if the bubble size exceeds a critical value such that they can ascend, at large *phi* coalescence of bubbles with different sizes are enhanced which promotes degassing. Our experiments also show that whenever a bubbly flow occurs, an increase in *phi* results in an irregular, long period pressure fluctuations, which may excite volcanic tremors having similar temporal features.

Keywords: magma, degassing, shear-thinning, model experiment, volumetric fraction, bubble

# Visualization of the rapid crack propagation driven by a pressurized air in viscoelastic gels

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Sudden expansion of the external water heated by a magma source sometimes fractures the country rocks so that causes explosive eruption, known as a phreatic eruption. If the steam expansion fractures the juvenile magma and erupts it out, the eruption is called as a phreatomagmatic eruption. Fine ash generated by phreatic/phreatomagmatic eruptions has smaller grain size than those generated by dry (without external water) eruptions.

Experiments of buoyancy-driven fluid-filled cracks as a model of a dike propagation by a magma ascent have revealed that the importance of the pressure inside the cracks. In contrast, the stress perturbation propagates at the shear wave velocity, which may become an upper limit of a fracture propagation. A sudden expansion of a steam from a point source may cause phreatic/preatomagmatic explosive eruptions, but the fracture mechanism has not yet understood well.

In this study, we visually observe a rapid crack propagation using the expansion of a pressurized air from a point source in transparent gels. We use three types of gels: (gel1) a hard quasi-Maxwell fluid with a shear modulus of $10^4$-$10^5$ Pa, (gel2) a soft quasi-Maxwell fluid with a shear modulus of $10^3$ Pa, and (gel3) a quasi-Voigt solid with a shear modulus of $10^2$ Pa. We introduce a pressurized air from the bottom of the gel, visually observed the pressure perturbation and the crack propagation by using polarized sheets, and record it by a high-speed video camera.

In gel1 and gel3, a thin air sheet with a sharp tip, usually recognized as a crack, propagates into the gel. On the other hand, in gel2, the air becomes a thick sheet with a round tip, which is more like a slug rather than a crack. In all experiments, the pressurized air erupts out the ash-like small particles generated by the friction between the pressurized air and the clack walls. The propagation velocity of the crack does not exceed the calculated shear wave velocity in gel1, but does in gel3. These results suggest that the combinations of the rheology and the gas pressure inside the cracks generate a variety in the shape of crack/slug and the fracture mechanism. The various shapes of the crack/slug may be observed as the difference of the resonance frequency by seismic signals.

Keywords: crack, phreatic eruption, gel

# An experimental study of the role of subsurface plumbing on geothermal discharge

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In order to better understand the diverse discharge styles and eruption intervals observed at geothermal features, we performed three series of laboratory experiments with differing plumbing geometries. A single, straight conduit that connects a hot water bath (flask) to a vent (funnel) can originate geyser-like periodic eruptions, continuous discharge like a boiling spring, and fumarole-like steam discharge, depending on the conduit length and radius. The balance between the heat loss from the conduit walls and the heat supplied from the bottom determines whether and where water can condense which in turn controls discharge style. Next, we connected the conduit to a cold water reservoir through a branch, simulating the inflow from an external water source. Colder water located at a higher elevation than a branching point can flow into the conduit to stop the boiling in the flask, controlling the periodicity of the eruption. When an additional branch is connected to a second cold water reservoir, the two cold reservoirs can interact. Our experiments show that branching allows new processes to occur, such as recharge of colder water and escape of steam from side channels, leading to greater variation in discharge styles and eruption intervals. This model is consistent with the fact that eruption duration is not controlled by emptying reservoirs. We show how differences in plumbing geometries can explain various discharge styles and eruption intervals observed in El Tatio, Chile, and Yellowstone, USA.

Keywords: Geyser, plumbing system

# Experimental study on precursory pressure oscillation in the experimental geyser system

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Geysers exhibit characteristic behaviors such as precursory seismic events, time-predictability, and periodicity. They have similarities to volcanos in seismicity, so understanding the seismic events of geysers may provide potential insights into volcanic tremor. It is known that pressure pulses inside the water column of geysers trigger the tremor. However, the origin of the pressure pulses is still unclear. The phenomena of natural geysers are complicated and difficult to observe directly, so laboratory experiments may be useful to understand natural geyser system. In this study, we try to reveal the origin of the pressure oscillation inside the geysers using laboratory experiments.

We conducted two experiments: experiment 1 and experiment 2. In experiment 1, we used an analog experiment (basically same one documented by Toramaru and Maeda (2013)), which reproduces the natural geyser; the flask corresponds to the hot water chamber, the glass tube to the geyser conduit, the cooler water reservoir to the inflow of ground water and the hot plate to the geothermal heat.We measured pressure and temperature in the flask and took normal speed and high speed videos of the flask interior and the surface of water in a glass tube, thereby we examined the relationship between the phenomena taking place in the flask and the conduit, and the fluctuation of pressure. In experiment 2, in order to reproduce bubble formation caused by boiling, we designed an experimental setup which is capable of injecting air into the flask filled with water. Using this experimental setup, we measured pressure in the flask and took videos of behavior in the flask and at the surface of water to observe the pressure fluctuation like tremor, with varying experimental conditions such as injection amount (the amount of air injected into the flask), the injection rate (the amount of injected air par unit time), and initial water level (the level of water head in the conduit).

From the results of the experiment 1, it is found that (a) a bubble formation in the flask cause a pressure pulse and a subsequent damped pressure oscillation, (b) the amplitudes of the pressure pulses have positive correlation with the diameters of bubbles. From the results of the experiment 2, we find that (c) an air injection into the flask causes a pressure pulse and a damped pressure oscillation similar to result (a), (d) the pressure oscillations in the flask attenuate by the coupling with the fluctuation of water level in an opposite phase, (e) the amplitudes of pressure oscillations have positive correlations with the injection rate and initial water level, (f) the frequency of damped pressure oscillation has negative correlation with initial water level and no correlation with injection rate. Considering the result (a) and (c), it is suggested that the pressure oscillations are induced by additions of fluid (in this study, they are bubble formations by boiling and air injections) to the flask interior, and from the result (d), it seems that subsequent damped pressure oscillations are caused by the vertical movement of upper water column.

In conclusion, the pressure oscillations in the flask are induced by additions of fluid to the flask interior, and then attenuate by the coupling with the fluctuation of water level. Their amplitudes have positive correlation with the bubble diameters, injection rate and initial water level, and their frequencies has negative correlation with initial water level.

# Recent uplift of Iwo-yama volcano, Kirishima Volcanic Complex, southwest Japan, derived from ALOS-2 images

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Phreatic eruptions are usually smaller than magmatic eruptions, but they are sometimes a source of major hazards if infrastructures are close by. Here we report on rapid ground uplift in Iwo-yama volcano, one of vents in Kirishima Volcanic Complex, southwest Japan, potentiallly leading to a phreatic eruption.

Kirishima Volcanic Complex is a collection of volcanic vents striking northwest-southeast. Shinmoe-dake, one of the vents in the volcanic complex, had sub-Plinian and Vulcanian eruptions in early 2011. Iwo-yama is located about 6 km to the northwest of Shinmoe-dake. In Iwo-yama, elevated surface temperature has been observed since December 2015 and volcanic earthquakes and tremors have been observed in January and February 2016. With this background, we investigated the temporal evolution of the deformation in Iwo-yama volcano inferred from Synthetic Aperture Radar images taken from the ALOS-2 satellite.

We first generated interferograms all possible pairs of SAR images. Then we applied a time-series analysis to extract the temporal evolution of deformation of volcanic origin by removing errors due to the uncertainty of Digital Elevation Model and atmospheric disturbance. The time-series analysis reveals an uplift of a region with a diameter of about 500 meters. We found that the uplift started in late 2015 and amounts up to approximately 60 mm as of June 2016. The deformation pattern looks like almost a mirror of the subsidence observed in 1990s by JERS-1 images. These observations by JERS-1 and ALOS-2 suggest a depressurization in 1990s and a recent pressurization of the same aquifer located a few hundred meters beneath the surface. Electromagnetic observations also endorse the existence of the shallow acquire at the same depth level as we suggest. We need to note that the recent uplift continues even after a cessation of the volcanic earthquakes and tremors in late February 2016. This indicates that the observation of ground deformation adds insights into the current activity of a hydrothermal system that could lead to a phreatic eruption.

Keywords: Synthetic Aperture Radar, Volcano deformation, Phreatic eruption