# Supervolcano eruptions driven by melt buoyancy in large silicic magma chambers

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The geological record shows abundant evidence for rare, but extremely large caldera-forming eruptions of siliceous magmas that dwarf all historical volcanic episodes in erupted volume and environmental impact. Because of the large size of the magma chambers that feed these eruptions, the overpressure generated by magma recharge is insufficient to fracture the cap rock and trigger an eruption. For these thick magma chambers, the buoyancy of the magma potentially creates a sufficient overpressure capable of fracturing the cap rock, but the lack of data on the density of rhyolite melts precludes the appropriate estimation of the overpressure and the role of buoyancy in initiating supervolcano eruptions. The density of rhyolite melts has not been determined at super-liquidus temperatures or elevated pressures because traditional techniques, including Archimedean methods, sink/float experiments and acoustic measurements, are limited by the high melt viscosity.

In this study, we measured the density of rhyolitic/granitic melts with 0, 4.5 and 7.7 wt. pct. of dissolved water at geologically relevant conditions, generated in a Paris-Edinburgh large volume press: 0.9 to 3.6 GPa, 1270 to 1950 K. Before and after each density measurement, the molten state of the sample was verified by X-ray diffraction. The density of the melt was determined in situ from the X-ray attenuation coefficient of the sample. The acquired data were combined with available ambient pressure data on super-cooled liquids to derive a third order Birch-Murnaghan equation of state that accurately predicts the partial molar volume of dissolved water and the density of rhyolite melts as a function of pressure, temperature and water content.

Application of the melt equation of state to calculate the overpressure at the roof of supervolcano magma chambers for a range of conditions/configurations indicates that magma buoyancy provides a significant background overpressure, which in many cases may suffice to initiate an eruption. Thus, although magma recharge and mush rejuvenation, volatile saturation or tectonic stress may be important triggers for specific eruptive episodes, the initiation of a supereruption does not a priori require such a trigger.

# A laboratory model for melting erosion of a magma chamber roof and the generation of a rhythmic layering

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A hot magma chamber can ascend by melting the roof rock, a process which in turn affects the magma composition. The disaggregated mineral particles which consisted the roof rock will descend in the magma chamber to form a sedimentary cumulate. However the fluid dynamics leading to the formation of the sediment, and how we can decipher them is unknown. Here we extend the work by Shibano et al (2012) and conducted a series of experiments modeling melting erosion of the roof with particle size consisting the roof rock as the parameter. We find that there is a critical particle size below which the melting erosion occurs cyclically. Melting erosion stops because the disaggregated particles are suspended in the magma chamber, and suppress the vertical heat transfer. The suspension then separates into an upper clear layer and a lower suspension layer. Eventually, the heated stratified layers become unstable. An overturn occurs, and melting erosion resumes. When the particles consist of 2 sizes such that at least one of them is smaller than the critical size, a cyclic erosion occurs. Particles are sorted during each melting cycle, and a size-graded rhythmic layering is spontaneously generated. We estimate that rhythmic layering can be generated from melting erosion in a basaltic magma chamber when the grain size of the roof rock is <0.6 mm, assuming a vertical temperature difference of 10 ℃. We suggest that cyclic roof melting coupled with particle settling is one possible mechanism for generating the rhythmic layering which is commonly observed in solidified magma chambers.

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# Volatile/melt equilibrium in subvolcanic reservoirs: the partitioning of sulfur and chlorine

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Understanding volatile/melt equilibria is essential for the use of gas chemistry in volcanic monitoring as well as for the prediction of the likelihood of magmatic-hydrothermal ore deposit formation. The abundance of various S and Cl species in magmatic volatiles may provide information on magma chamber processes and also determines the efficiency of the extraction of economically important metals from the magma.

We conducted experiments in rapid-quench MHC pressure vessels and piston cylinder apparatus at 150 to 500 MPa and 800-1240 $^{o}$C to identify the most important controls on the volatile/melt partition coefficients of S and Cl. Most experiments employed relatively high fluid/melt mass ratios of 0.33 to 16, which allowed precise estimation of the volatile phase composition at run conditions by mass balance calculations. The results show that the volatile/melt partition coefficients of Cl and both reduced and oxidized S strongly increase with increasing degree of melt polymerization, i.e. with melt composition evolving from mafic to felsic. At $fO_2$ less than 0.5 log units above the Ni-NiO buffer, S is primarily dissolved as FeS species in the silicate melt and its volatile/melt partition coefficients are mostly determined by the activity of FeO in the melt and the activity coefficients of dissolved FeS species. At 200 MPa confining pressure, pyrrhotite saturation limits the maximum $H_2S$ concentration in the volatile phase to a few mol% in equilibrium with a wide range of melt compositions from basalt to rhyolites. At the sulfide/sulfate transition, the volatile/melt partition coefficients of S drop nearly an order of magnitude due to a remarkable change in the dissolution mechanism of S in the silicate melt. Oxidized S is present as sulfate species in melt, which is more easily accommodated by depolymerized melt structure resulting in exponentially increasing volatile/melt partition coefficients with increasing melt polymerization. It has also been shown, that alkali metal rich silicate melts are much more efficient at dissolving oxidized sulfur species than Ca-rich ones, which are in turn significantly more favorable to Mg-rich ones. Therefore, degassing of oxidized sulfur is the least efficient from alkaline mafic magmas and peralkaline rhyolites.

Volatile/melt partition coefficients of Cl decrease nearly 2 orders of magnitude from rhyolite to basalt melt compositions; therefore Cl degassing is rather inefficient from intermediate and mafic magmas. In the subvolcanic P-T regime, the chloride fraction of the volatile phase exsolving from typical calc-alkaline melts is composed of sub equal amounts of alkali metal- and Fe chlorides and HCl.

Decompression induced degassing may allow the extraction of most reduced S even from mafic magmas; whereas crystallization induced degassing will play an increasingly important role in the extraction of oxidized S and Cl at subvolcanic P-T conditions.

# Laboratory geyser; Insights into predictability of mass and style of eruptions

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The time predictability of geysers implies that the mechanism of mass and energy conservation works in the simplest manner. Even in such a simplest case, the mass predictability is quite difficult. Thus, in the present study, in order to obtain insights into factors controlling mass and style of geyser and volcanic eruptions, we conducted laboratory experiments of geysers in which the time-predictability is reproduced. In the series of experiments, we measured pressure and temperature in a hot water chamber, flux from a cold water reservoir, and mass erupted by events (total number of eruptions are up to 100), varying experimental conditions such as the heating rate, water quality, and system geometry. We observed two styles of eruptions, "jet" and "flow" depending on the maximum height of erupted water reached. Based on the statistical analysis of the erupted mass, an experiment setup that produces only jet events exhibits a narrower frequency distribution of the erupted mass with a relatively large average. In the experimental setup in which flow events occupied increasing proportions, the frequency distribution of the erupted mass widens with relatively small average mass. The temperature measurements indicated that jet-dominated experimental setups had smaller temperature fluctuations than flow-dominated setup. In order to understand these correlation among temperature fluctuation, mass and style of eruptions, we propose a model including a triggering condition and eruption condition using a Monte Carlo simulation consisting of 256x256 parcels with temperature as a stochastic variable by a Gaussian probability density function (PDF). The triggering condition (the gas volume in chamber under hydrostatically over-pressured state exceed the volume of the vacant conduit) gives a constraint on the average and variance of PDF by an inverse manner. The eruption condition defines two types of parcels with two thresholds of eruption potential according to hydrodynamic energetics; explosive parcel and eruptive parcels. The results showed that when the PDF has a larger average and smaller variance, the event tends to be explosive and large fraction of water is evacuated, as in jet events. Decreasing the average temperature or increasing the variance of the PDF shifts the events to an explosive style followed by an effusive event and to an event that produces only effusive flow. This transition of eruption styles from explosive to effusive and the relationship with the erupted mass is consistent with results of the laboratory experiments. Applying this results to volcanic systems, we speculate that an uniformly supersaturated chamber produces a large plinian eruption whereas a chamber with a highly heterogeneous supersaturation produces the lava flow remaining a large un-erupted mass in chamber. Intermediate heterogeneity of chamber supersaturation produces a plinian followed by equivalent mass of lava flow event like in typical andesitic volcanoes.

# Cyclicity in slug driven basaltic eruptions: insights from large-scale analogue experiments

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Basaltic eruptions commonly exhibit cyclical or pulsatory behaviour. Strombolian eruptions are typically discrete and rhythmic, with return interval of minutes-to-hours; lava fountains may fluctuate over similar, or shorter, timescales. In both cases the cyclicity results from the separation of gas from the magma, and its localization into discrete gas slugs or gas-rich packets. We report analogue experiments which model the fluid dynamics of slug-driven basaltic eruptions. Experiments were conducted in liquid-filled vertical pipes at a range of scales, from 0.02 to 0.2 m in diameter, and 2 to 13 m in height, allowing us to investigate Reynolds numbers $10^{-3} < Re < 10^{5}$, encompassing the natural range for volcanoes. The dynamics of both discrete gas slugs (Taylor bubbles) and continuous sluggy flow were quantified. A significant novelty of this study is that we explore the role played by the boundary conditions at the top and bottom of the conduit, which may be either closed (zero flux) or held at constant pressure. This allows us to mimic plugged or open vent, and the influence of a magma chamber. Our study combines direct observation of in-conduit fluid dynamic processes with measured pressure variations in the conduit.

Our results demonstrate that, when discrete gas slugs are injected, plugging the vent has a strong influence on the development of overpressure in the system, and on the potential for the system to manifest cyclic behaviour. When gas is injected continuously, with constant pressure boundaries at the top and bottom of the conduit, the system spontaneously self-organizes into rhythmic sluggy flow when the injection rate exceeds a critical value. In both cases we find that the capacity of the system to sustain well-formed, discrete slugs depends strongly on the Reynolds number of the flow. Well-formed Taylor bubbles - which have a smooth cap, occupy the width of the conduit, and ascend relatively slowly - only form when the liquid column is stagnant, or is flowing in the laminar regime. Slugs that rise through turbulent liquid are poorly-formed and, at the extreme, ascend as turbulent gas-rich packets which ascend more rapidly than true Taylor bubbles. A major factor influencing the turbulence in the liquid is the separation between slugs; when slugs are closely spaced, the wake of one slug tends to disrupt the next. At the onset of eruption, therefore, poorly-formed, fast-moving slugs tend to catch up with the well-formed, slow-moving lead slug, increasing the potential for an impulsive, explosive onset. During sustained eruption, lower gas fluxes lead to lower frequency, higher amplitude fluctuations in eruption rates, whilst higher gas fluxes lead to higher frequency, lower amplitude fluctuations. The spectrum of natural activity, from discrete Strombolian eruptions to sustained, pulsatory lava fountaining can, therefore, be characterized as a change in the behaviour of the separated gas phase in the conduit.

# Periodic lava fountaining on basaltic volcanoes: dynamic behavior and experimental model

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Since 1983 we have been conducting volcanological and geophysical studying of lava fountains at the Klyuchevskoy volcano. Analysis of continuously registered volcanic tremor, processed by means of statistical analysis, allowed us for the first time to identify steady periodicities in the dynamics of fountaining which are manifested in a wide time range: from tens of minutes – to tens of hours. When studying the eruptions of 1984, 1993 and 2007 it has been established that at steady increase of magma discharge in crater three regimes of fountaining are sequentially manifested: steady low-intensity, periodic and steady high-intensity. Two intervals of change of the regime (ICR) – ICR-1 of "entry" to the periodic regime and ICR-2 of "exit" from it have been identified. The obtained results laid the basis for laboratory experiments.

Analysis of descriptions of eruptions and seismograms at other basalt volcanoes has allowed to establish periodic fountaining at Etna, Karkar, Kilauea, Manam, Niragongo, Tolbachik and at an underwater volcano NW Rota-1.

Processes determining periodic lava fountaining were studied through the use of constructed by us in 2003-07 Complex Apparatus for Modeling Basaltic Eruptions – CAMBE. It is 18 m high and consists of modeling and recording systems. When creating the Complex, the geometric parameters of the actual feeding system of the Klyuchevskoy volcano have been considered; the ratio of CAMBE's channel diameter to its height is $\sim$ 1:1000. There is no analogue to CAMBE in the world.

Our goal was to reveal the causes of periodicities in the dynamics of lava fountaining at basalt volcanoes. Experimental studies included studying of behavior of gas bubbles during their barbotage in vertical pipes through model liquids of various densities with subsequent comparison of the obtained data to real volcanic events. The majority of experiments have been conducted with the bubbles of one size that relates to the internal diameter of the hose as $\sim$ 1:20 which excludes a possibility of locking the internal section of the hose by a large bubble.

In the course of experiments, a new earlier unknown morphologically steady gas-hydrodynamic structure – an open bubbly cluster has been identified. It represents a volume of liquid with high concentration of bubbles, separated with a liquid containing no free gas phase from above and from below. A set of open bubbly clusters (following one another at a fixed distance), divided by liquid without bubbles, represents a periodic regime of open clusters.

Comparison of CAMBE acoustic records with diagrams of Klyuchevskoy volcanic tremor showed good correlation between the modeled and natural data. The results obtained allowed us to suggest a new pattern for gas-hydrodynamic migration of magmatic melt in the feeding channel, where the regime of open gas clusters accounts for periodic lava fountaining during basaltic volcanic eruptions.

# The slug buster: an analogue experiment for the study of Strombolian explosions

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Strombolian explosive activity is often described as the simple bursting of individual, large gas bubbles (slugs) at the surface of a stagnant magma column. However, individual explosions may often last up to several tens of seconds and produce complex geophysical signals. High-speed imaging revealed complex patterns within individual explosions, with large velocity and mass fluctuations in the ejected pyroclasts flux, and the presence of multiple ejection pulses characterized by exponential decay of pyroclast velocity throughout each pulse (Taddeucci et al., 2012a). Shock-tube experiments successfully reproduced such pulses by the impulsive release of pressurized gas-particles mixtures, allowing modeling the maximum velocity and velocity decay in the jets as a function of pressure, volume, and depth of the pressurized mixture (Taddeucci 2012b). However, these shock-tube experiments that used solid particles and gas could not investigate the dynamic response of slugs in magma to rapid decompression.

Here we present a new experimental setup specifically designed to investigate the response of slugs in a liquid when subjected to rapid decompression. Gas and liquid are provided by air and water, respectively. A pressurized gas slug is attained by suddenly releasing a controlled volume of pressurized air into a 3m long pressurized water column. The water column plus slug system is kept pressurized until the slug reaches a given burst distance (typically a few cm) from the top of the water column. Then the top of the column is suddenly exposed to ambient pressure and the slug expands explosively, ejecting a mixture of air and water droplets into the atmosphere. Monitored parameters currently include slug volume, pressure, and burst distance, with the possibility also to investigate the effect of liquid rheology, conduit diameter, and vent geometry. Mixture ejection velocity and mass histories are recorded by two high-speed cameras. Also, acoustic to infrasonic signals generated by the experiment are recorded by two microphones.

Preliminary experiments yield the same trend of ejection velocity decay observed in shock-tube experiments, as well as during Strombolian explosions. Specific features in this trend are related to slug volume and pressure, also controlling the resulting signal recorded by the microphones.

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# See-through experiments of volcanic eruption for outreach program

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Analog experiments are useful for outreach program. We cannot see the inside of a volcano directly, though an eruption is caused by underground magma. We develop the see-through experiments of volcanic eruption to observe a process from magma system to eruption. After experimental eruption, audience can learn hazard areas for various eruption types, and the time sequence of typical eruption. (1) The first experiment is to observe the effect of bubble. This experiment has an advantage to prepare easily. A plastic transparent sheet is covered on a plastic transparent bottle to build an artificial volcano. Bicarbonate and citric acid with detergent for kitchen (BCD liquid) are put in the bottom of the bottle. Next, just after the bottle is filled up to the middle level with colored juice (or water), the cap with a hole is closed. Eruption will occur with a 1m high explosive column, and change into effusive flow. We can observe the process of eruption and the hazard area controlled by the topography. (2) The second is to see the effect of both buoyancy and bubble. The system is installed in a plastic bag, and put in water container. Only a juice-filled plastic bag without bubble sinks in the container, if the liquid in the bag such as a colored juice is denser than water. However, with bubble, the liquid begins to erupt. (3) The third is the mixed effect among bubble, buoyancy, and stress of the host material. The liquid with bubble such as BSD liquid or carbonate drink is injected into gelatin as the host material. We can cause an explosive eruption to form a funnel -shaped crater like diatreme. If the liquid injection is slow, the liquid accumulate bubble in it upper part. After bubble escapes like de-gassing, the liquid injects laterally like dike injection. (1), (2) and (3) were carried out at elementary schools, junior high schools, science museums (Takada, 2012), the open house in AIST (Yamasaki et al., 2013), training course for school teachers in YIES (Takada, 2012), and lectures of Tsukuba University. Questionnaire from audience after each experiment are introduced.

# Mechanism of delayed fragmentation of vesicular magma by decompression

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The fragmentation of vesicular magma is a key phenomenon to determine the style of volcanic eruption. To understand the magma fragmentation, we performed a rapid decompression experiment using bubbly syrup as an analogous material of vesicular magma. We classify the onset of fragmentation using a measure of brittleness ("critical brittleness") at the bubble surface at the time when the differential stress at the surface reaches the critical fracture stress. In our case, the brittleness is unity when the response of material is brittle. It is 0.5 when the material response is completely ductile. We find a delayed fragmentation which occurs when the differential stress sufficiently exceeds the critical stress, even if the critical brittleness indicates the ductile response of the material. The delayed fragmentation occurs within the characteristic time of bubble expansion in viscous liquid, while its onset is after the relaxation time of viscoelastic material. This means that the delayed fragmentation is "brittle-like" (solid-like) fragmentation. Magma fragmentation may be viewed as sequential brittle-like fragmentation.

To understand the cause of the delayed fragmentation, we tested the response of a large number of samples and experimental conditions, which vary in critical brittleness, volume, void fraction, and porosity distribution. The volume of samples is selected from 25 ml (small) or 100 ml (large). The void fraction is in the range of 3 to 28

From the experiments with small volume of samples, we observed some of the samples exhibit no fragmentation even if their critical brittleness was about 0.9. All the samples with large volumes fragment when the critical brittleness was 0.9. The pore distribution of the small samples is more uniform than that of large samples. Therefore, stress concentration in the small samples is weaker than that in the large samples.

We find that fragmentation does not occur in the sample with the void fraction less than 8

The critical brittleness was calculated using the differential stress on the bubble surface under the assumption of uniform pore distribution. Our experiments indicate that this calculated value may inadequate to evaluate the fragmentation. The "true" value of brittleness required to the onset of brittle fragmentation should be closer to unity. Our experiments also suggest that the delayed fragmentation observed with lower value of the critical brittleness is caused by non-uniform pore distribution, which leads to increase the local differential stress and brittleness in the sample.

# The lifetime of bubbles

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A process that is of fundamental importance for bubbly suspensions is bubble coalescence, the process whereby the liquid film that separates adjacent bubbles ruptures, transforming two or more individual bubbles into a single bubble of larger size. We present new experimental results of film drainage caused by liquid expulsion due to gravitational forces, associated with the density difference between bubbles and surrounding liquid, as well as capillary forces arising due to changes in curvature of the interface between a bubble and surrounding liquid. In our experiments the liquid film is not stabilized by surfactants or impurities, rendering the boundaries of the liquid film fully mobile. Air bubbles were suspended beneath the free surface of a layer of PDMS. We measured the time for the liquid film surrounding the bubbles to drain until the time of rupture. To ensure the dynamic similarity to magmatic systems, our experiments are at small Reynolds number (Re < 1), so that inertial forces are negligible during film drainage. Consequently, film drainage is solely driven by gravitational and capillary forces, and balanced by viscous forces. The relative dynamics of film drainage is determined by the relative importance of gravitational to capillary forces, quantified by the Bond number, which spans five orders of magnitude in our experiments from Bo $\sim 10^{-3}$ to Bo $\sim 10^{2}$, with a transition between capillary and gravitationally dominated drainage at $Bo = 0.25$. We derive a scaling relation for the drainage time $t \sim C ln \delta_o / \delta_f \, \tau$, where C is an empirical constant (C $\sim$10), $\delta_o$ is initial film thickness and $\delta_f$ is final thickness. At Bo < 0.25 the characteristic time is given by $\tau = \eta R/\sigma$, whereas it is $\tau = \eta / \Delta \rho g R$ for Bo > 0.25, where R is bubble radius, $\eta$ is fluid viscosity, $\sigma$ is surface tension and $\Delta \rho$ is density contrast between bubble and liquid. We find that our results are consistent with previously published empirical drainage times of bubbles in silicate melts. In contrast, prior formulations for film drainage, based on the assumption of immobile film boundaries, result in over-predictions of film drainage times by at least several orders of magnitude.

# Experimental constraints on the effects of shear and displacement on vesicle coalescence

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Vesiculation processes in magmas control whether eruptions result in explosive magma fragmentation or effusive eruption of lava. A better understanding of the effects of viscosity, shear, and time on the development of permeability (vesicle nucleation, growth, and coalescence) allows for better prediction of eruptive styles or changes in eruptive style. We present vesiculation experiments on natural, non-vesicular, high-silica rhyolite obsidian cores loaded into graphite cylinders that allow only uniaxial (upward) expansion. Experiments were performed at 800-1300℃, 1 atm, and for durations of 25 s to 4 hrs. Preliminary results show clear trends in vesiculation as a function of time and temperature (for example, reaching about 50% vesicles after 50 s at 1300℃, about 80% vesicles after 200 s, and collapsing back down to about 70% vesicles after 2000 s), reflecting vesicle growth, coalescence, and gas escape through ruptured vesicles. Portions of foamed samples that expanded past the end of their confining cylinders expanded in an unconfined manner, but later shrank back on themselves and retreated into the cylinder. Vesicle textures in the experiments are anisotropic; for example, samples run for about 900 s at 1300℃ contain large vesicles at the base, and smaller vesicles near the unconfined top, whereas samples run for about 2 hrs have a single vesicle running the length of the sample and very small, spherical vesicles in the dense, glassy exterior sample walls. Along axis gradients in expansion, displacement, and shear affect bubble coalescence rates and generate the observed textures. Darcian permeability measurements show that the bases of foamed samples increase in permeability from $1.2 \times 10^{-13}$ to $1.1 \times 10^{-12}$ $m^2$ between run times of 500 and 900 s, respectively, at 1300℃, while the permeability near the unconfined tops of samples is significantly lower. X-ray Computed Tomography (XRCT) imaging allows reconstruction of the internal structures of foamed samples, and reconstructions are used to estimate permeability independent of physical measurements. Our experiments demonstrate that shear and displacement affect vesicle coalescence rates, and suggest an inverse relationship between shear and coalescence rates.

# Experimental study on textural relaxation of deformed melt foam

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The surface tension of melt is a primary force for textural development of vesiculated magmas such as bubble coalescence and textural relaxation, but its effect on the microstructure and permeability development of magmas is not well constrained. In flowing viscous magmas, shear stress overwhelms surface tension (e.g., Okumura et al., 2006), whereas textural relaxation driven by surface tension becomes the dominant process, once the magma stops flowing. In this study, we examined the textural relaxation of deformed melt foam driven by surface tension. We carried out heating experiments of andesitic pumice cubes of the 1914 Plinian eruption of the Sakurajima volcano by assuming that the pumice approximates conduit magma in terms of bubble microstructure and water content just after the explosion. The sample size was ca. 3 mm on a side. Two series of experiments have been conducted: evacuated experiments ($P_{H2O}$ < 0.1 MPa) and high water vapor pressure experiments (2.0–6.0 MPa). The experimental temperature was set to be 800 to 1000℃. The run duration ranges from 3 minutes to 32 hours. After the runs, the microstructure of pores and bubbles was analyzed on the BSE images of polished cross sections. At a temperature of 1000℃ and $P_{H2O}$< 0.1 MPa, the vesicularity and bubble connectivity decreased and the circularity increased within 3 minutes. The decrease in the vesicularity occurred via disappearance of open pores connected to sample surface due to the surface tension, resulting in "self-compaction." The decrease in the pore connectivity and the increase in the circularity in the initial stage reflect the breakup of tortuous pore networks. Bubble size increased with time owing to bubble coalescence. At temperatures of 800℃ and $P_{H2O}$< 0.1 MPa, however, no significant textural change was observed until 32 hours. At a temperature of 1000℃ and higher vapor pressures, the degree of the decrease in the vesicularity was smaller than that of the experiments at $P_{H2O}$< 0.1 MPa. The circularity increased and connectivity decreased first, and then oscillated with time owing to bubble coalescence and relaxation. These results suggest that melt viscosity is the primary controls the degree of relaxation. Our experiments shows that the relaxation of melt foam decreases small-scale bubble connectivity and hence decreases local gas permeability. The effects of sample size (i.e., specific surface area) should be considered for the larger scale permeability.

# Bubble morphologies, gas escape and fragmentation of crystal-rich magma

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Hydrous intermediate and mafic magmas commonly erupt with abundant microlites that crystallized as volatiles exsolved during ascent. Both natural and experimental samples show that crystal-rich groundmasses are associated with substantially thicker bubble walls and more complex bubble morphologies than crystal-poor melts. The physical and chemical relationships between co-evolving bubbles and crystals are complicated. Here we combine observations from three-phase (gas, viscous liquid, solid particle) analogue experiments and textures of scoria from Fuego Volcano (Guatemala; October 14 and 17, 1974) to examine the effects of crystals on bubble morphologies, and their role in gas escape and fragmentation of crystal-rich magma.

The Fuego samples are extremely crystal-rich: in a typical basaltic scoria erupted Oct.14 1974, we find a matrix of 61 vol% microlites, which together with the phenocrysts gives a total crystallinity of 70 vol% on a vesicle-free basis. As is common for crystal-rich scoria, the bubbles are non-spherical and often polylobate. Similar bubble morphologies have been ascribed to extensive bubble coalescence, with implications for interpretations of bubble number densities and ascent conditions. However, our analogue experiments and analysis of bubble textures in rims and cores of lapilli, indicate that bubble expansion is sufficient to generate polylobate bubbles in crystal-rich suspensions (which can be further modified by bubble coalescence).

High crystal contents and thick bubble walls resist bubble expansion, promoting bubble overpressure. Analogue experiments indicate that if there is sufficient gas pressure, there is a transition from lobate bubbles to fracturing as the crystal content approaches maximum packing, and if crystal distribution is inhomogeneous, the fractures tend to propagate through regions of relatively high crystallinity. Such inter-crystal fracture networks would aid degassing as magma ascends and could play a role in the fragmentation of magma to ash and lapilli.

Fragmentation of crystal-poor silicic magma occurs if gas is unable to escape sufficiently quickly to prevent overpressured bubbles breaking the magma apart. For this reason, deposits from silicic Plinian eruptions contain abundant fine ash composed of bubble wall remnants, and the total deposit ash size distribution is closely related to the bubble-size distribution determined from co-erupting pumice. In contrast, the size distribution of fine ash from the well-characterized Oct. 14 1974 subplinian/vulcanian Fuego fallout deposit correlates with the crystal- rather than bubble-size distribution measured in scoria, suggesting a strong control of crystals on the production of the fine ash. The groundmass crystals are both smaller and much more abundant (by number) than the bubbles. There is a substantially larger median grain size (mm-scale) on a volume (mass) basis, which may be related to phenocrysts as well as bubble textures.

# Dissolved $H_2O$ distribution in vesicular magmatic glass records bubble resorption

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Volcanic eruptions are driven by the nucleation and growth of bubbles in magma. Bubbles grow as volatile species in the melt, of which water is volumetrically the most important, diffuse down a concentration gradient towards and across the bubble wall. On cooling, the melt quenches to glass, preserving the spatial distribution of water concentration around the bubbles (now vesicles). We use Backscatter Scanning Electron Microscopy (BSEM), Secondary Ion Mass Spectrometry (SIMS) and Fourier Transform Infra-Red spectroscopy (FTIR) to measure the spatial distribution of water around vesicles in both experimentally-vesiculated and naturally erupted samples, with unprecedented spatial resolution. We find that, contrary to expectation, the water concentration increases (by up to 3wt.%) in the ~30 microns closest to the vesicle wall.

Our samples record significant resorption of water back into the melt around bubbles during the quench process. We propose that the observed resorption profiles result from the increase in the equilibrium solubility of water as temperature decreases during the quench to glass, and that the resorption locally overprints the pre-existing concentration profile resulting from bubble growth during decompression. Our experimental samples demonstrate that the bulk of the resorption occurs above the glass transition, while the melt is still plastic; consequently, resorption may reduce bubble volumes and sample porosities by as much as a factor of two. Experimental samples are quenched too rapidly (1-5 seconds) for observed resorption profiles to be generated by diffusion of 'total' water ($H_2O_t$). Speciation data showing molecular ($H_2O_m$) and hydroxyl (OH) water concentrations around vesicles in these samples reveal that quench resorption is driven by rapid, disequilibrium diffusion of ($H_2O_m$).

Failure of previous experimental studies of bubble growth to account for quench resorption may have led to incorrect conclusions. We present here a methodology, using BSEM and SIMS, for a first order correction of such datasets. Our work lays the foundations for a new tool for the interpretation of the pressure-temperature history of natural pyroclasts, and challenges the conclusions of two recent studies which interpret similar features as evidence of repressurization of magma in the shallow subsurface, prior to eruption. Bubble resorption can cause significant rehydration of surrounding melt and may therefore be an important mechanism controlling melt viscosity and the glass transition. Our data also demonstrate that the diffusion of water in magmatic glass can, under disequilibrium speciation conditions, be substantially faster than is usually assumed. In dynamic volcanic systems such conditions may occur in a variety of situations; hence our findings are relevant to a broad range of studies.

# Effects of gas escape and crystallization on the complexity of conduit flow dynamics during lava dome eruptions

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During lava dome eruptions, the degree of gas escape and that of crystallization strongly affect the dynamics of conduit flow. Generally, the dynamics of conduit flow is determined by the relationship between chamber pressure (p) and mass flow rate (q) for steady conduit flow (the p-q relationship). When the slope of the p-q relationship (dp/dq) has a positive value (positive differential resistance), the steady flow is stable. When dp/dq has a negative value (negative differential resistance), on the other hand, complex dynamics such as abrupt change and/or cyclic change of magma discharge rate can result. In this study, on the basis of a 1-dimensional conduit flow model, we investigated how the coupled effects of gas escape and crystallization control the features of the p-q relationship and transitional process of conduit flow induced by the negative differential resistance.

For conduit flow involving gas escape and crystallization, two positive-feedback mechanisms that result in the negative differential resistance are identified. First, effective magma viscosity decreases with increasing q because of delay of crystallization, leading to the reduction of viscous wall friction (feedback 1). Second, magma porosity increases with increasing q because of less efficient gas escape, leading to the reduction of gravitational load of magma (feedback 2). These two feedback mechanisms induce a sigmoid p-q relationship for some realistic conditions; the positive differential resistance in the low-q and high-q regimes, and the negative differential resistance in the intermediate regime. The analyses of time-dependent conduit flows indicate that, because of the sigmoid p-q relationship, magma discharge rate abruptly increases from the low-q to high-q regimes as magma supply at depth gradually increases from the low-q regime to the intermediate regime. This abrupt increase in magma discharge rate accounts for the transition from a lava-dome eruption to an explosive eruption.

We found that the governing mechanism for the transition from a lava-dome eruption to an explosive eruption changes depending on phenocryst content of magma. For high phenocryst content (volume fraction >0.5), the feedback 1 is the main mechanism that forms the negative differential resistance. In this case, the transition from lava-dome to explosive eruption occurs when the magma supply rate at depth exceeds a fixed critical value. On the other hand, for low phenocryst content (volume fraction <0.5), the feedback 2 plays a key role so that the transition is controlled by the permeability of the surrounding rocks; the critical magma supply rate remarkably decreases with decreasing permeability. The transition due to the feedback 2 is associated with a change in chemical composition of volcanic gas, a drastic increase in magma porosity from nearly 0 to greater than 0.8, and overpressure at a shallower level, which can be detected from geochemical and geophysical observations.

# Outgassing dynamics along dikes and fractures

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Two–phase flow dynamics of magmas in volcanic conduits is controlled by several factors, including magma rheology, gas content, flow rate and geometry. Most of the existing models are based on the assumption of a cylindrical conduit, which is realistic only for the very shallow portion of the magmatic system, and never applicable to fissure eruptions, which are very common for basaltic activity in several tectonic settings (Stothers et al., 1986; Wright et al., 2006). It has been proven that magma cooling and solidification along the fissure determines viscosity gradients, which contribute to flow localization and the evolution towards central eruptions (Wylie et al., 1999, Wylie and Lister, 2006). However, even when the effects of magma cooling and solidification are negligible, as in the case of long–lived systems, the elongated geometry of the conduit has primary influence in the distribution of shearing in the flow and can have strong control in the flow pattern and phase distribution. We have investigated the dynamics and flow pattern of the outgassing of basaltic magmas along a dike coupling experimental activity and 2D numerical modeling. Experiments were performed on a 1.5x0.75x0.03 m rectangular bubble column, using glucose syrup at variable concentration (viscosity ranging from 0.1 to 70 Pa s) and compressed air. Gas was inserted through a set of equally spaced nozzles, whose configuration and number was changed to test the effect of the initial gas distribution. The effect of the orientation of the fracture on the flow pattern has also been investigated running experiments with the rig inclined up to 30 degrees. We collected data on the average vesicularity, lateral and vertical gas distribution, pressure gradient and oscillations within the flow. With increasing gas superficial velocities or liquid viscosity, the average properties of the flow varied with trends similar to cylindrical columns, but the geometrical distribution of the phases displayed peculiar features. We observed two main patterns: bubbly flow (for low gas superficial velocities), with non–interacting multiple bubble streets developing form each nozzle, and bubble plume patterns, where all the bubbles were rapidly converging toward the centre of the tank. Plume geometry was controlled by large–scale, gas–driven liquid circulation, developing into circular to elongated patterns. Increasing liquid viscosity increased the size of the gas bubbles, subjected to repeated coalescence and breakup during rise and eventually converging into a single flattened bubble with dm–scale length. Numerical modeling, validated with specific experiments, allowed for the analysis of the time–dependent behavior of the flow and was extended to magmatic conditions to explore the applicability of our experimental results.

# Thermomechanical milling of lithics in volcanic conduits

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Accessory lithic clasts recovered from pyroclastic fallout deposits are an underutilized resource for understanding the processes operating in volcanic conduits. Lithic clasts result from syn-eruptive fragmentation of conduit wall rocks and are entrained into the rapidly ascending stream of erupting material. Here, we use the size, morphological and textural properties of accessory lithic clasts to elucidate processes operating in volcanic conduits during explosive eruptions.

The pyroclastic fallout deposits of the 2360 BP eruption of the Mount Meager Volcanic Complex in British Columbia, Canada, contain two main types of accessory lithic clasts: i) rough and subangular dacite clasts, and ii) smooth and rounded monzogranite clasts. We have quantified and described the morphological properties of these two clast types using a variety of techniques, including 2-D image analysis, 3-D laser scanning, and SEM-based textural analysis. We identified three main processes that contributed to shaping lithic clast morphology and surfaces: 1) ash-blasting of clasts suspended within the volcanic flux, 2) high-energy impacts between clasts or between clasts and conduit walls, and 3) thermal spalling of exterior surfaces due to heating of clasts. The extent to which these processes affect a given clast depends on the total time an individual clast resides in the conduit prior to its evacuation. The residence time of a clast is, in turn, controlled by its size and depth of incorporation. Here, we use previously established eruption parameters for the 2360 BP eruption (e.g. column height) to compute transit times of accessory lithics within the volcanic conduit.

By combining field data of lithic sizes with our modelled residence times we have constrained the diameter of the eruption conduit to 40-45 m – a parameter that is normally quite difficult to quantify. Furthermore, we establish a qualitative understanding of the relative roundness of the two types of accessory lithic clasts. The dacite source rocks are so shallow (0 to 550 m) that entrained dacite clasts have very short (<2 minutes) residence times regardless of their size. Conversely, monzogranite lithic clasts are sourced from depths of at least 700 m, and perhaps even deeper than 2 km, so the highly smoothed and rounded nature of many of the observed monzogranite lithics is the result of a prolonged residence time within the dynamic conduit environment. For example, a 30 cm diameter dacite clast incorporated at a depth of 0.5 km would have had a residence time of $\sim$ 30 seconds, while the residence time of a monzogranite clast of equivalent size entrained at 2 km depth would have been $\sim$ 10 minutes.

Ultimately, we suggest that the size, shape and surface properties of accessory lithics should find increasing use in constraining many different parameters related to volcanic eruptions, such as conduit diameter, eruption duration and depth of fragmentation.

# Radio wave emission phenomenon due to rock fracture and its application to volcano research and hazard mitigation

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Volcanic activity is associated with rock fracture in a crater and inside a mountain. Fumes eruption, where radio wave at low frequency was observed (1), is an assembly of small-scale rock crashes. On the other hand, the microwave emission due to rock fracture was formerly found at the higher frequencies of 300 MHz to 22 GHz (2). Recently, we have studied the phenomenon experimentally in various fracture modes. Rocks of quartzite, gabbro, granite, and basalt were used as a specimine.

This paper describes the measurement system and experimental results. Then, we discuss the availability of the obtained results to the research of volcanoes.

The measuring system handles 1 MHz-, 300 MHz-, 2GHz- and 18 GHz-bands. We calibtae the measuring system beforehand so that we can estimate the received power from the received waveform. In the modes of fast fracture, signals at all bands were recorded in pulse shapes. The radio wave component is included inside the pulse. There is hardy difference of the signal power level among gabbro, granite, and basalt. In the modes of slow fracture and with moisture existence, the waveform was almost the same as the fast fracture mode.

Application of radio wave measurement on a volcano offers the following advantages:

(a) Remote sensing is safer and more stable than mechanical means of measuement,

(b) Frequency- sensitive features can be extracted through a particular frequency,

(c) Modern technologies can be diverted.

Our measurement showed radio wave emission from basalt which is popular in volcanic areas, and which contains no piezo-electric material.

In volcanic activities, we can conceive several cases of radio wave emission. The radio wave due to collapse of crater cliff was confirmed in the field experiment on Miyake-jima (3). Eruption of fumes can be observed at higher fequncies with grater advantages than a low fequency, because interferences can be eliminated by virtue of a sharp directivity of an antenna.

Rock fracture due to undergraound magma is not verified through radio waves yet, but has a lot of capability. Even if a rock coexists with underground water, we can obtain the same signal power, as indicated experimentally. It was revealed that a radio wave can propagate underground in a gap of several wavelengths (4). Therefore, a shorter wavelength or a higher frequency is preferred for this application.

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# Simulating discrete volcanic explosions: bench-scale and field-scale detonation experiments

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Discrete volcanic eruptions - those exhibiting non-steady state conditions - are relatively poorly understood volcanological phenomena [Zimanowski et al., 1991; Taddeucci et al., 2009; White and Ross, 2011]. Whereas the nature of the fragmentation zone in steady state, open vent volcanic eruptions has been extensively assessed through the use of both fieldwork and analogue experimentation over the last few decades, the natures of explosion-generating zones in various types of discrete eruptions are open to a wide range of interpretations [e.g. White and Ross, 2011]. The initial mobilisation and entrainment of particles is a process affecting both discrete jets and inception of subsequently sustained ones that has rarely been addressed. A recent set of analogue experiments, both involving bench-scale and field-scale detonations, demonstrate that this initial mobilisation and entrainment may be complex. Our experiments show that different ejected particle populations may take very different trajectories, with movement beginning at very different times, in response to a single driving explosion source. The timing and physical nature of the initial coupling that drives movement may lead to a dynamic segregation of the surrounding, entrained material, with rapid, uneven distribution of momentum during the initial blast generating multiple, upwards-thrusting jets. The implications of these analogue experiments apply not only to discrete volcanic eruptions known to occur in monogenetic volcanic fields, but in any subterranean, discrete explosion within a granular material host.

# Heat transfer during large-scale lava-ice/snow experiments

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One of the most basic requirements for understanding interactions between lava flows and their emplacement environments is knowledge of heat transfer. This is particularly important when lava flows are emplaced into environments with liquid/solid H2O. Although recent eruptions have provided new insights into heat transfer between lava and snow/ice (e.g. Fimmvorduhals 2010), quantitative measurements of interactions between lava and ice/snow are rare. To address these difficulties, we conducted a series of pilot experiments designed to allow close observation, measurements, and textural documentation of interactions between basaltic melt and ice. Here we discuss the results of the several experiments designed to investigate heat transfer directly between lava and snow/ice, as well as experiments designed to have a boundary layer (silica sand) separating the lava and snow/ice. The experiments involve controlled pours of up to 300 kg of basaltic melt on top of ice. The design of the experiments allows for monitoring of temperatures on the lava surface using FLIR cameras, as well as continuous measurements of temperatures at several critical boundaries (lava-snow/ice, lava-boundary layer-snow/ice) within the experimental vessel. Our experiments provide: 1) estimates for rates of heat transfer through boundary layers and for ice melting; 2) constraints on controls for rates of lava advance over ice/snow; 3) documentation of lava bubbles (Limu o Pele) formed by steam from vaporization of underlying ice/water; and 4) new insights on the role of within-ice discontinuities to facilitate lava migration beneath and within ice. The results of our experiments confirm and provide better constraints for field observations about the rates at which lava can melt snow/ice, the efficiency of heat transfer across a boundary layer, and morphologies/textures indicative of direct lava-ice interaction. We also show that the generation of steam from meltwater can buffer temperatures at the boundary layer interface, and can create bubbles and even large cavities within the overlying lava flow.

# Experimental Generation of Volcanic Lightning

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The large explosive volcanic eruptions that are responsible for injecting large quantities of gas and pyroclasts into our atmosphere, are often associated with intense electrical activity. Their explosive nature means that direct measurement of the electric field close to the vent, (where initial electric activity in the volcanic plume is typically observed), is severely impeded, limiting progress in its investigation. We have achieved volcanic lightning in the laboratory during rapid decompression experiments of gas-particle mixtures under controlled conditions. We have recorded the lightning phenomenon with the observation of electrical discharges using a) a high-speed camera and b) two antennas.

Lightning at the volcanic vent is controlled by the dynamics of the particle-laden jet and by the grain size of the particles. Two main conditions are required to generate the lightning: 1) electrification of particles and 2) clustering of particles driven by the jet fluid dynamics. The relative movement of clusters of charged particles within the plume generates the gradient in electrical potential which is necessary for lightning. In this manner it is the gas-particle dynamics together with the evolving particle-density distribution within different regions of the plume that emerge as the key variables in volcanic lightning. A proportionality between fine ash content of the jet and number of lightning strikes is also evident in our experiments. This first recorded experimental generation of volcanic lightning means that rapid progress can now be expected (under controlled laboratory conditions) in understanding electrical phenomena produced during explosive volcanic eruptions. This in turn may aid the development of lightning monitoring systems for the forecasting of volcanic ash emissions into our atmosphere.

# Rheology of bubble- and crystal-bearing magma: an analogue dataset

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Magma is commonly a complex mixture of three phases: a viscous silicate melt, crystals, and a gas phase. The degree of interaction between bubbles and crystals, and the relative proportions of these phases, exert a major control on the bulk flow behaviour of the magma or lava. Generally, the addition of solid particles increases the viscosity of a suspension and potentially causes non-Newtonian effects such as shear thinning or yield strength, whereas bubbles can either increase or decrease viscosity, depending on the flow regime. Whilst numerous studies exist on the rheology of two-phase suspensions, the bubble-particle interactions in three-phase systems and their effect on rheology to date remain largely unexplored.

Here we present, for the first time, a comprehensive rheometric dataset of analogue three-phase experiments. More than 40 experiments were performed, covering a broad parameter space with 0 to 45 vol% solid glass spheres, and 0 to 28 vol% bubbles mixed into a Newtonian magma-analogue liquid (Golden Syrup). Rheometric tests were carried out on a ThermoHaake MARS II Rheometer, and include steady (stress-strainrate flow curves) and transient (oscillatory) experiments.

The resulting flow curves were modeled to obtain the three Herschel-Bulkey parameters (consistency, shear tinning index, and yield strength) of the suspension as a function of particle and bubble content. The oscillation tests delivered complex viscosity values as function of strain rate and strain rate change, under consideration of the suspension's bubble size distribution. Results suggest that the role of the solid and gaseous phase, respectively, varies considerably with the dynamic properties of the flow: in steady flow conditions, the solid particles exert a major influence on the bulk rheology of the system, whilst under transient flow conditions the effect of bubbles becomes increasingly important.

# Experimental investigations on rheology and microstructure of the 1946 andesitic lava from Sakurajima volcano, Japan

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In this study, high-temperature viscosity measurements and microstructural analyses were done for the andesitic lava effused at 1946 from Sakurajima volcano, the Showa lava, to examine the effects of suspended crystals on rheology of highly crystalline magma. In historic times, lava flows effused at least five times in Sakurajime volcano, and the Showa lava is the latest one. Whole rock composition of the lava is representative of lavas from the volcano. The lava contains ca. 30 vol. % of phenocrysts of plagioclase and pyroxenes and its groundmass is composed of microlites and silicate glass; total crystallinity of the lava is ca. 60 vol. %. Uniaxial compression experiments were done for the lava to determine apparent viscosity using the uniaxial deformation apparatus at Earthquake Research Institute, the University of Tokyo, under conditions of temperature from 1297 to 886 K, strain rate from $10^{-2.4}$ to $10^{-5.5}$ $s^{-1}$, and atmospheric pressure. The run samples were processed to polished thin sections and their microstructures were analyzed using EPMA and FESEM.

Under the experimental conditions, apparent viscosity of the lava varies from ca. $10^{7.3}$ to $10^{11.3}$ Pa $s^{-1}$. The lava behaves as shear thinning fluid at each temperature; log apparent viscosity linearly correlates with log strain rate with the slope of -0.434 (1sigma = 0.05). In addition, apparent viscosity systematically increases as temperature decreases. At constant strain rate, log apparent viscosity shows almost linear relation with reciprocal temperature; apparent activation energy is estimated to be ca. 206 kJ, which is similar to that of silicate melt in groundmass of the lava. This suggests that the observed temperature-dependence of apparent viscosity is chiefly attributed to that of silicate melt in groundmass. At strain rate of $10^{-4}$ $s^{-1}$, relative viscosity, the ratio of apparent viscosity to melt viscosity, increases from ca. 2 to 10 as temperature decreases from 1297 to 1275 K although it is almost constant at ca. 10 below 1273 K if silicate melts in run samples were assumed to be dry.

Total crystallinities of run samples vary from ca. 0.49 at 1297 K to 0.7 at 1183 K. Relative viscosity was almost constant when crystallinity is above ca. 0.54. In contrast, it increased with crystallinity when crystallinity is below 0.54. This indicates that threshold value of crystallinity for rheological transition is around 0.52, which is lower than that for spherical particle-bearing suspensions. In addition, the plateau value of relative viscosity at crystallinity above 0.54 was several orders of magnitude lower than those of previous studies whereas apparent viscosity values seems to be reasonable compared to those of andesitic lavas measured in previous studies. We will discuss about the cause of low relative viscosity of the lava based on the results of microstructural analyses.

# Viscosity measurements of crystal-bearing natural lava samples from Unzen volcano, Japan

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Goto (1999) pointed out the apparent viscosity of Unzen lobe lava from field observation, 0.9-4.2$\times10^{10}$ Pa s by Fukui et al. (1991) and Suto et al. (1993), is much lower than predicted from matrix melt viscosity (8$\times10^{12}$ Pa s at 800 ℃) and about 50 vol.% lava crystallinity. This implies the mechanism of lobe lava displacement may be different from the Newtonian flow.

To the contrary Cordonnier et al. (2009) measured the viscosity of Unzen dome lava samples and concluded that their experimental results is in harmony with the observation if, based on the viscosity model by Hess and Dingwell (1997), the viscosity decrease by ≈0.2 wt.% water is considered. However, their experimental temperature ranges between 940 and 1010 ℃. If we linearly extrapolate their data down to 800 ℃ lava viscosity should be over $10^{16}$ Pa s, which is difficult to be lowered to observed viscosity range by water effect. Thus far the viscosity of crystal-bearing lava is still under debate.

We have started viscosity measurement of natural lava sample from Unzen 1991-1995 activity. The rock sample used in our preliminary experiment was collected from 1991 Sep. 15 pyroclasitc flow deposit. The test piece was cored to 14.95 mm diameter and 30.55 mm high for parallel plate viscometry. The core bulk density was 2.24 g/cm$^3$. The core was loaded 10 N (57 kPa) during the heating for 3 hours to desired temperature (980 ℃) and additionally held for 30 minutes, then loaded up to 1800 N (10 MPa) within a minute and kept at this load for 30 minutes. The total deformation was 47 %. Except the last 10 minutes viscosity was almost constant at each loads, 2$\times10^{10}$ Pa s at 57 kPa and 6$\times10^{9}$ Pa s at 10 MPa.

At the same temperature (980 ℃) Cordonnier et al. (2009) obtained the apparent viscosity to be 2$\times10^{11}$ Pa s at 2.8 MPa and 3$\times10^{10}$ Pa s at 10 MPa. Our experimental result is in harmony with them in that shear thinning occurred and time weakening did not occur at stresses less than 10 MPa, but differs in that the viscosity is lower at the same stress (10MPa) and the shear thinning is less prominent.

Avard and Whittington (2012) pointed out most laboratory studies are typically conducted at higher stresses and strain rates than experienced by lava moving as surface flows, and showed their experiments at low stress (0.085 to 0.42 MPa) yielded apparent viscosities more than one order of magnitude lower than predicted by models based on experiments at higher stress. Our experiment at 57 kPa actually yielded one order lower viscosity than at 2.8 MPa by Cordonnier et al. (2009), but the conclusion by Avard and Whittington (2012) conflicts with shear thinning. We have to explore the rheological property of crystal-bearing lava more.

# Deformation and failure of single- and multi-phase silicate liquids: seismic precursors and mechanical work

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Along with many other material failure phenomena, volcanic explosion is regarded as a catastrophic one and is often preceded by diverse precursory signals. Although a volcanic system intrinsically behaves in a non-linear and stochastic way, these precursors sometimes display systematic trends leading to eruptions. During dome growth, the seismic activity displays a (supra-)exponential acceleration prior to an explosive eruption – a precursory signal similarly observed prior to failure of magma under controlled laboratory experiments. In laboratory experiments, acoustic emissions (AE) are commonly used to monitor fracture initiation and propagation at a decimetric sample scale. Here, we investigate the mechanical work involved in the failure of magma and assess the ability of AE to be used as a failure forecast proxy. The method has been applied to high-temperature (around the glass transition temperature of the material) deformation experiments in compression with synthesised glass samples (0 to 30% porosity). The technique has also been applied to samples from the dome of Volcán de Colima, Mexico, with a similar porosity range. We observe that the failure of more dense (porosity below 10%) glasses is achieved at large compressive stress (greater than 200 MPa) and thus requires a significant accumulation of strain, suggesting the importance of pervasive microfracturing. Less dense glasses as well as volcanic samples (porosity above 10%) need much lower applied stress (less than 100 MPa) and deformation to fail, as fractures are nucleating, propagating and coalescing into localized large-scale cracks, taking the advantage of the existence of numerous defects (pores in glasses, pores and crystals in volcanic rocks). These observations demonstrate that the mechanical work done through cracking is efficiently distributed inside more homogeneous samples, as underlined by the overall larger AE energy released during experiments. In contrast, the quicker AE energy released during the loading of heterogeneous samples shows that the mechanical work tends to rapidly concentrate in specific weak zones facilitating dynamical failure of the material through dissipation of the accumulated strain energy. Applying a statistical Global Linearization Method (GLM) in multi-phase silicate liquids samples leads to a maximum likelihood power-law fit of the accelerating rate of released AEs. The calculated $\alpha$ exponent of the famous empirical Failure Forecast Method (FFM) tends to decrease from 2 towards 1 with increasing porosity, suggesting a shift towards an idealized exponential-like acceleration. Single-phase silicate liquids behave more elastically during deformation without much cracking and suddenly releasing their accumulated strain energy at failure, implying less clear trends in monitored AEs. In a predictive prospective, these results support the fact that failure forecasting power is enhanced by the presence of heterogeneities inside a material.

# In situ observation of brittle fracturing of rhyolite magma by X-ray radiography

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Brittle fracturing of silicic magma during its ascent in a volcanic conduit is thought to trigger seismicity (e.g. Tuffen et al., 2008). The brittle fracturing of dense highly crystalline lava has been studied well on the basis of laboratory experiments (e.g. the crystallinity >50 vol % in Lavallee et al., 2008). In the lava, the crystals can form network; hence, the fracturing is probably controlled by the interaction between crystals. On the other hand, the relationship between fracturing and seismicity in crystal-free melt and the effect of gas bubbles are unclear. Tuffen et al. (2008) demonstrated that glassy obsidian shows seismogenic fracturing at high temperature (645 ℃); however, the temperature is very close to its glass transition and low to simulate magma fracturing. In this study, we observed the fracturing of rhyolitic melts (0.4-0.5 wt % water) under torsional deformation at temperatures of 700-820 ℃ by using X-ray radiography at SPring-8 (BL20B2) in Japan. Sample size is 3-4 mm long and 5 mm in diameter and the rotational rates were set to be 0.05 and 0.5 rpm, which correspond to shear strain rates of $3\text{-}4\times10^{-3}$ to $3\text{-}4\times10^{-2}$ $s^{-1}$. The confining pressure was controlled to be 4-5 MPa. The acoustic emission (AE) and the pressure change during the fracturing were also monitored. The brittle fracturing of rhyolitic melts was observed in runs at temperatures of 800-820 ℃ under the rotational rate of 0.5 rpm and at temperatures of 700 ℃. The deformation and fracturing processes are summarized below: (1) shear stress increased with deformation (elastic manner), (2) shear stress started to decrease and large AE was monitored, and this AE corresponds to the formation of cracks, (3) the crack formation localized to a horizontal plane around a piston, (4) AE increased again, which probably corresponds to the pulverization of fragments, and (5) finally stable sliding along the fractured zone occurred. In some experiments, the effect of annealing of the fractured zone was investigated by holding melt at the same temperature. After 15 minutes, deformation started again. In this stage, the deformation showed the sliding along the fractured zone and large AE such as that found in (2) was not monitored. The experimental results indicate that brittle fracturing of crystal-free magma releases the AE before the weakening of magma and then the large AE is not released from the fractured zone as long as it is perfectly welded. This may indicate that the acceleration of magma ascent involving brittle fracturing is accompanied with seismicity, if the AE is directly linked to the seismic observation although it has still been under debate (e.g. Chouet and Matoza, 2013).

# Fluid flow and degassing in high temperature magma

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Dacitic volcanoes such as Mount St Helens can erupt magma as lava domes that, in addition to simple effusion, frequently pass through episodes of major collapse and can also explode in vulcanian eruptions under suitable increases in gas pressure. Both dome collapse and vulcanian events can propagate pyroclastic flows and so extend the hazardous range of a dome far beyond the radius of the dome itself.

As magma rises in the conduit it becomes supersaturated with dissolved volatiles and, during decompression, exsolution occurs creating gas bubbles within the melt. The ability of gases to escape the rising magma depends strongly on its permeability. It is common in highly viscous magma for gas pressure to build up until, under a sufficient amount of depressurisation, the tensile strength of the magma is exceeded and fragmentation occurs. However effusion of lava domes requires magma to reach the surface in a relatively volatile free state and the processes that control this gas escape in high temperature magma are still poorly understood.

To investigate the controls on degassing processes, we have measured how permeability varies progressively with increasing temperature and deformation on samples from the 2004 to 2008 lava dome at Mount St Helens. Permeability was measured on cylindrical samples 25 mm in diameter in a high temperature triaxial deformation apparatus and a hydrostatic permeameter at temperatures up to 900℃, confining pressures of 10 MPa and pore fluid pressures of 5 MPa. Samples of intact dacite from the interior of Spine 4 were used to test temperature effects on fluid flow.

Our results show that fluid flow in the dacite lava at the core of the lava dome is reduced by up to four orders of magnitude when the temperature is increased from 20℃ to 900℃, with no apparent discontinuity when the pore fluid water flashes to steam at 264℃. During ascent in the conduit the magma is cooled from around 850℃ and depressurisation causes thermal and mechanical micro-cracks. We therefore suggest that thermal expansion of the mineral grains when heated during the experiment progressively closes the pre-existing cracks causing a decrease in permeability. When applied to degassing processes, our results suggest that, as the magma rises in the conduit, it becomes progressively more permeable and so gases can more readily escape.

# Experimental study of liquefaction and fluid transport: implication for triggered eruptions

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Liquefaction is a phenomenon in which the inter-particle contact of a liquid-saturated granular matter is loosened by vibration and as a result, the bulk behaves like a fluid. It is widely known that earthquakes can cause soil liquefaction which can manifest in the form of sand boils and mud volcanoes. Liquefaction can also occur in a more viscous fluid (e.g, Sumita and Manga, 2008, EPSL), one example of which is a magma chamber. Magmatic liquefaction may also be caused by earthquakes, and may even trigger a volcanic eruption. There have been a number of experimental studies using water saturated soil and sand in the field of soil mechanics or civil engineering. However the details of the critical condition to cause the liquefaction, and how the consequences of the liquefaction differ with the changeable parameters, are still insufficiently known. Here we conduct an experimental study of liquefaction under a vertical vibration to understand the elementary process of liquefaction and fluid transport. We aim to explore the variety of phenomena which may occur, and to better constrain the conditions which cause these results.

An experimental cell (cross section 22.0mm x 99.4mm, height 107.6mm) is filled with a granular matter and liquid (water or glycerin solution). The lower 33.7mm is a two-layered granular medium; the upper layer and lower layer consist of packed glass beads with a size of 0.05 and 0.2 mm, respectively, such that the upper layer becomes a low-permeability layer. The cell is placed on a vertical shaker which vibrates sinusoidally with an acceleration of 2.0-41.1m/s$^2$ and a frequency of 10-40 Hz.

Here we describe the results for a water-saturated case. From a series of experiments, we find that as we increase the acceleration there are 4 styles of pore water discharge; No-change, Percolation, Transitional, and Flame (i.e., Rayleigh-Taylor type instability). Under a small acceleration, there is no apparent change in the thickness of the granular medium and the two-layer boundary (No-change). As we increase the acceleration, the two-layered granular medium compacts by expelling the pore-water. First there is no apparent change in the form of the two-layer boundary (Percolation), but as acceleration increases, an instability appears (Transition) whose amplitude grows and a flame structure forms (Flame).

In a two-layered water-saturated granular medium, we find that the pore water which originated from the bottom layer temporary accumulates at the interface of the two layers, and then ascend through the upper layer in the form of vertical channels. We find that the critical acceleration for the formation of the flame structure is of the order of $(\Delta\rho/\rho)$g, where $\Delta\rho$ is the particle-water density difference, $\rho$ is the particle density, and g is the gravitational acceleration.

# Flowers, snowflakes and crystalline magmas - insight into gas migration regimes in crystalline viscous melts

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Magmatic volatiles affect eruption processes, and are therefore widely studied. However, the physical effects of crystals on degassing processes are often disregarded, except for considerations of their role on the bulk viscosity of the magma. Here we address this issue by asking the fundamental question: How do crystalline magmas degas?

We have started to answer this question by running a set of experiments in a Hele-Shaw cell to map gas flow regimes in 3-phase systems (sugar syrup, air, and $\sim$ 100$\mu$m polydisperse glass beads). The experimental apparatus consists of two glass plates separated by a 0.48mm gap. During an individual experiment, air is injected into the mixture at a steady rate using a syringe attached to a mechanical pump. Air influx, viscosity and particle volume fraction are varied between experiments.

We consider three main regimes, as identified by patterns of gas distribution: (1) fingering, characterized by long, irregular, smooth intrusions of air into the mixture at a relatively steady rate; (2) fracturing, whereby the gas penetrates the mixture in bursts, and forms a trail of thin cracks; and (3) gas filter pressing (or capillary fingering) which is the advance of gas between the particles, pushing out the liquid without disrupting the particle network. We therefore expect distinctive air pressure profiles for each regime. These will support the interpretation of 3D experiments, for which bubble shapes will no longer be visible.

Preliminary results suggest that transitions between regimes do not depend on the liquid viscosity (for $\mu \leq$ 100 Pas) but are strongly dependent on crystal volume fraction. Specifically, gas flow transitions from fingering to fracturing $\sim$54% crystals, which is close to, but not at, the maximum packing fraction. When the maximum packing is reached, the gas flow regime changes from fracturing to gas filter pressing. These observations have important implications for gas escape from crystal mush zones. Other interesting results include (1) a transition from fracturing to fingering when the gas front approaches the edge of the experimental set-up; (2) local variations in crystal volume fractions due to the advancing gas fronts, which can cause a change in regime; (3) the development of preferential flow paths towards zones of higher or lower crystal fractions (depending on the regime), therefore shifting the location of degassing; and (4) the development of new degassing pathways, replacing the existing primary channel, in a manner reminiscent of the irregular degassing observed at some volcanoes.

# Intermittent and efficient outgassing by upward propagation of film ruptures

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We simulate the ascent of bubbly magma in a volcanic conduit by slow decompression experiments of syrup foam as a magma analogue. During the decompression, some large voids appear in the foam. The expansion of a specific void at a depth leads to another void expansion, and the void expansions then propagate upward. The void expansion finally reaches the surface of the foam, which rises and falls locally by outgassing. The velocity of the upward propagation of void expansions agrees with the rupture velocity of a bubble film, suggesting that the rupture of films separating each void propagates upward to create a pathway for outgassing. This mechanism may cause gas emission, such as Strombolian eruption, in which the upward traveling of decompression triggers the explosive gas emission originated at a depth. The calculated apparent permeability of decompressed foam can become higher than that measured for natural pumices/scoriae. The upward propagation of film ruptures can cause efficient outgassing.

# Buoyant bubble rise through concentrated particulate suspensions with potential application to crystallizing magmas

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Buoyant rise of bubbles through magmas containing a large fraction of crystals, of similar or smaller size than the bubbles themselves, are of importance in some magmatic processes· One example is bubbles rising through a crystallizing mafic magma, intruded beneath a silicic magma body, and potentially of importance for the rejuvination of the silicic host· The presence of crystals will significantly increase magma viscosity and reduce bubble rise speed· In addition, nonNewtonian rheological effects ⟨e·g·, strain rate dependence, strain dependence, yield stress⟩ may also affect how the ascending bubbles interact with one another· For example, the presence of crystals has the potential to affect bubble coalescence, thereby modulating the overall behavior of the system, because it may affect the density distribution, as well as the rheology of the three−phase suspension· Here we report preliminary results on the relationship between crystal size and content, bubble size and content, as well as rheology on the bubble rise speed and dynamics, using analog laboratory experiments·

# Nucleation and growth of bubbles using smooth interface models

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Modelling the nucleation and the growth of bubbles in a dense fluid is a difficult task due to the complex coupling between thermodynamics (nucleation) fluid mechanics (growth and detachment) and thermal transport. Moreover the numerical solution of such problem is usually difficult due to its free-boundary nature. Quite recently Phase-Field approaches based on smooth interface models have been used to tackle this last difficulty, allowing bubbles to be nucleated, to grow, collapse or coalesce spontaneously. We present here such a model coupling thermodynamics, fluid mechanics and thermal transport applied to the problem of heterogeneous nucleation of bubbles and growth in various thermal or pressure conditions.

# Experimental model of a volcanic conduit: Acoustic and seismic signals associated with an overpressure release

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Bubble bursting at the top of a volcanic conduit – and, more generally, any overpressure release, generate acoustic and seismic signals, whose characteristics can be linked to the source properties. However, the relation between the amplitude and frequency of both signals and the source parameters (e.g. bubble length, conduit diameter, initial overpressure) has not yet been demonstrated. In order to quantify which information can be obtained from these signals, we performed laboratory experiments. An overpressurized gas cavity is initially closed either by a thin liquid film, or an elastic membrane. We measure the acoustic signal produced when the film or membrane bursts, as well as the pressure variations inside the cavity. This well-controlled experiment makes it possible to tune all the parameters of the system: cavity length, diameter, overpressure and film/membrane properties.

In a first series of experiments (thin liquid film), we show that the rupture time is the key parameter for the generation of an acoustic wave. The amplitude of the signal depends on the film opening dynamics, and drastically decreases when the rupture time increases. Therefore, the measurement of the amplitude of the acoustic wave, alone, cannot provide any information on the overpressure inside the bubble before explosion. This could explain the low energy partitioning between infrasound, seismic and explosive dynamics often observed on volcanoes. Experiments performed with liquid films of different viscosities put forward not only the role of the rupture time, but also of the opening dynamics, from a single hole growth to filaments breaking.

In a second series of experiment (elastic membrane), we explore the acoustic limit by increasing the overpressure initially loaded in the cavity, up to values above the atmospheric pressure. We point out a regime for which the acoustic amplitude after bursting reaches a plateau. The membrane opening dynamics is monitored by a fast camera, up to 14000 img/sec. We analyze the pressure signals inside and outside the cavity, depending on the initial membrane position, either at the open end or inside the conduit. Accelerometers at the surface, far from the cavity aperture, monitor the 'seismic' signal associated with the membrane opening. The characteristics of this signal are analyzed in regards to the acoustic signal and the initial overpressure in the cavity.

# Influence of decompression path in the shallow conduit on eruption dynamics: first insights from laboratory experiments

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Volcanoes are moody creatures. They are well known for their ability to display a wide spectrum of eruptive styles, ranging from effusive phenomena, as lava flows or dome growth, to violent explosive eruptions, generating vast amounts of ash eruption plumes and pyroclastic flows. Rapid changes in the eruptive style can occur during an ongoing eruption, and are, amongst others, likely to be related to variations in the magma ascent rate. Indeed, the rate at which magma reaches the surface, i.e. its speed of decompression, is a key parameter affecting the eruptive style. This ascent rate depends on several factors like the pressure in the magma chamber, the physical properties of the magma, and the rate at which these properties change. Laboratory decompression experiments can give quantitative information about the interplay of those factors, the dynamics of nucleation, growth and coalescence of bubbles in a volatile-bearing magma and the related impact on the eruption style. We carried out decompression experiments at varying decompression rates, using silicon oil as analogue of the magmatic melt which allows encompassing a range of viscosity values. Additionally, for a set of experiments we added particles to simulate the presence of crystals in the magma. The pure liquid or suspension was mounted into a transparent autoclave and pressurized to 10 MPa. Then the sample was saturated with a noble gas (Argon or Helium) for a fixed amount of time (i.e. 24, 48, 72 h for Argon). The samples' decompression path consists of three main parts mimicking magma ascent in the shallow conduit: (1) a slow decompression, (2) a phase of stable pressure and finally (3) rapid decompression to atmospheric condition. We were able to reproduce different ascent rates, accordingly to values reported in literature for different magma chemistry and type of eruptions. In phase (3), the fluid goes through a fast decompression, which causes the exsolution of the volatile phase and eventually its fragmentation. The entire decompression path was monitored with pressure sensors as well as regular and high-speed video cameras; Image analysis of the videos allowed for a qualitative analysis of the fluid dynamics inside our samples and above. Indeed, until now the relationship between the history of magma ascent and the eruptive dynamics has been investigated mostly by looking petrological studies, i.e. on degassing related reactions or melt inclusions. Our approach is complimentary to these studies and focus on the physical aspects during decompression.

## Why does Fuji volcano release only basalt? Experimental study of deep magma chamber

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Fuji volcano, the largest in volume and eruption rate in Japan, is located at the center of Honshu, where North America, Eurasia and Philippine Sea plates meets. Because of the significance of Fuji volcano both in tectonic settings and potential of volcanic hazard, precise knowledge on its magma plumbing system is essentially important. Very frequent LF-earthquakes occur at about 15 km beneath Fuji volcano (Ukawa 2007). Seismic tomography beneath Fuji volcano suggests the existence of large magma chamber below 20 km (Nakamichi., 2007). Fuji volcano has released only basalt (>750 $km^3$) which has narrow range of $SiO_2$ compositions ($SiO_2$ = 49-53 wt.%) in the last 100,000 years. Some incompatible elements show more than a factor of 2 variations (Takahashi et al., 2003). Variation in incompatible elements may be due to some kind of magma fractionation process. Fujii (2007) proposed that the silica-non enrichment trend of Fuji volcano is explained by pyroxene dominate fractionation in the deep magma chamber. Primary purpose of this study is to reproduce the silica non-enrichment trend by high-P experiment and reveal PT conditions and water content of magma in the deep magma chamber.

Basalt scoria Tr-1 which represents the final ejecta of Hoei eruption in AD1707, was adopted as a starting material. This is because 1) 0.7 $km^3$ of magma was discharged by subplinian eruption within 2 weeks, 2) Basaltic Hoei scoria is homogeneous, apyric and representing melt composition. Internally heated Ar-gas pressure vessels (IHPV-5000 and IHPV-8600) at the Magma Factory, Tokyo Institute of Technology were used. The $f_{O_2}$ was controlled at NNO buffer. Experiments were carried out at 4 kbar (equivalent to the depth of LF earthquakes) and 7 kbar (equivalent to the inferred depth of Fuji magma chamber by seismic tomography; $\sim$25 km depth).

Quenched run products were analyzed with EPMA. Run products from 4 kbar experiments always include magnetite and melt composition shows silica enrichment trend. In the phase diagram at 7 kbar, multiple saturation point of opx+cpx+pl+melt exists on the liquidus at around 1120℃, 3.5 wt.% H2O, which is the likely condition of the top of the Fuji magma chamber at the time of Hoei eruption. Melt compositions at 7kbar shows silica non-enrichment trend until magnetite starts crystallization. Vanadium partitions strongly into magnetite (Toplis et al., 2002) and therefore it is a good indicator of magnetite crystallization. Judging from high vanadium content in Fuji basalts, magnetite does not crystallize in the deeper magma chamber. Origin of the monotonous basalt magma production in Fuji volcano may be due to the absence of shallow level magma chamber. Because plate boundary exists at 3-5km beneath Fuji volcano, shallow level magma chamber may be short-lived due to high-stress and large crustal deformation.

# Analogue study of bomb sag formation: effects of substrate properties and impact velocity

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We performed analogue experiments to determine the relationship between the wetness of the substrate and the velocity and density of impacting clasts and 1) the formation (or not) of bomb sags, 2) the morphology of the impact crater, and 3) the penetration depth of the clast. Downward deflection of layering only occurs for water-saturated substrates. Collision angles < 20 degrees from vertical are needed to produce bomb sags in which the bomb is retained in its crater. Penetration depth is proportional to impact velocity squared and hence the impact energy.

To illustrate the potential usefulness of the experiments, we apply scaling laws obtained from the experiments to interpret the observation by the Mars Exploration Rover Spirit of a bomb sag at Home Plate, Mars. The downward deflection of beds seen on Mars is consistent with water-saturated sediment in the laboratory experiments. From the experiments we infer an impact velocity up to 40 m/s, lower than ejection velocities during phreatic and phreatomagmatic eruptions on Earth. If this velocity represents the terminal subaerial impact velocity, atmospheric density exceeded 0.4 kg/m3 at the time of eruption, much higher than at present.