Applying exhaustive crustal xenolith petrology to test fluid dynamic simulations in the magma conduit

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The importance of the interactions of thermal and mechanical processes during silicic magma ascent, and the relationships between wall-rock and magma within the conduit, are explored through the integration of (i) crustal xenolith petrology (foliation, equilibrium mineral assemblages and thermodynamic modelling, the size, abundance, distribution and age of minerals), and (ii) fluid dynamics.

We examine two-dimensional thermal models of dacitic magma injection and flow in a 200 m wide magma conduit - that caused their wall-rock to undergo partial melting. The case study selected is the Neogene Volcanic Province (SE Spain), where rapidly erupted crustal xenoliths had been previously incorporated into dacitic lava by rooting up from the wall-rock and/or dropping into the magma conduit at 13-18 km depth. These partial melt zones record the thermal history of magma flow in the conduit and, consequently, both the emplacement behaviour of the flow it fed, and the xenolith history before (and during?) the eruption event.

The results reveal important information on (i) the circulation and transport of xenoliths at depth by relating the textures and pressure-temperature conditions of the xenoliths to their position in a transient thermal regime in the wall-rock of the magma conduit; (ii) the time spent as a xenolith immersed in magma; and (iii) the magma ascent process by their interactive integration to fluid dynamics models and vesicles evolution within the magma conduit. They may also help to link observations on xenoliths and xenocysts to eruption style and intensity.

Magma chambre paradox: decompression upon replenishment

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The invasion of active magma chambers by fresh magma of deeper provenance is invariably assumed to cause chamber pressurization. Pressure increase thus stands as an intuitive consequence of magma chamber replenishment. However, new numerical simulations demonstrate that pressure evolution is highly non-linear, and that decompression dominates when large density contrasts exist between injected and resident magmas. This apparent paradox originates from the compressible nature of volatile-rich magma and the dynamics of convection associated with injections of buoyant magma. While decompression can dominate in a shallow chamber, pressure increase develops in the connected deep regions of magma provenance. These results contradict classical views adopted to interpret observations at active as well as fossil magma chambers, and demonstrate that a simple reliance on intuition is insufficient: what may be perceived as a paradox, magma chamber decompression upon replenishment, is instead likely, and rooted in the complex physics that governs the multiphase, multi-component dynamics of magma transport in geometrically composite, spatially extended magmatic systems.

Petrographic assessment on possible drainback processes of the andesitic lava filled in the crater of Shinmoedake, 2011 eruption of Kirishima volcano

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Drainback of emplaced lava in vent and crater is common phenomena for basaltic magmas (e.g., EPR, Kilauea, and Izu-Oshima). This is consistent with small supercooling and viscosity increase of basaltic magmas by magma degassing and crystallization during extrusion. In contrast, dacitic and rhyolitic magmas tend to show large increase of viscosity by degassing and crystallization during eruption, thus prohibiting magma drainback to the conduit and chambers. (e.g., Mt. Unzen, Mt.St.Helens). This work examines the case of andesitic lava emplaced in the 850m diameter crater of Shinmoedake, Kirishima volcano after three subplinian eruptions in January, 2011 eruption of Shinmoedake, Kirishima volcano group. The emplaced andesitic lava is ca. 600m in diameter and ca. 130m thick. We analyzed the blocks thrown from the crater-filled lava by subsequent Vulcanian explosions to evaluate the possible drainback processes of the crater-filled lava. The andesitic blocks have SiO2 contents of ca 57-58 wt% coinciding with the brown pumice of the subplinian ejecta, both of which are the mixing products of more mafic and silicic magmas. The SiO2 contents of the matrix glass in the block is 71-73 wt%, slightly higher compared with 67-69 wt% of the matrix glass of the brown pumice of the subplinian eruption. Crystal contents of the block is 20-35 vol% for phenocryst and 40-45 vol% for microlite. The temperatures of the lava blocks were estimated by the compositions of pyroxenes and iron-titanium oxides giving values from 950 to 1020 degree C. The water content of the matrix glass was estimated to be 0.1-0.4 wt% from the measurements of bulk water contents. The viscosity of the crater-filled magma just after the extrusion was estimated to be ca. $10^{9\text{-}11}$ Pas. The conduit radius is constrained by the eruption rate of the sub-Plinian eruptions at ca. $2\text{-}3*10^6$ kg/s to be 12-16m by using the conduit model of CONFLOW. Simple drainback rate of the lava by their weight including the thickness of the extruded lavas is estimated at $5.9\text{-}13.6*10^{-2}$ m^3/s. This rate of drainback causes less than 1.6 percent of the total amount of the effused lava within a month. SAR observation did not show evidence of drainback after the eruption, possibly partly sustained by refilling of the chamber as observed by GNSS measurement of the volcano by NIED. This work suggests that degassing and crystallization of the andesitic magma during emplacement may cause increase of the magma viscosity by 6 orders of magnitude, prohibiting drainback of the crater-filled lava after the emplacement.

Textural analysis of obsidian lava flow in Shirataki, Northern Hokkaido, Japan

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Formation process of obsidian is poorly understood and it is thought that gas loss (outgassing) plays an important role. Glass formation needs the high-effective supercooling resulted from a high ascent and decompression rates, and this process increases magma viscosity. The ascending process of such a highly viscous magma is also unclear. In this study, we conducted textural and chemical analyses for Tokachi-Ishizawa (TI) obsidian lava one of Shirataki rhyolite lava, Hokkaido, northern part of Japan, in order to elucidate the magma ascent and outgassing process.

In Shirataki rhyolite lava area there are monogenetic volcanoes composed of 10 obsidian lava flow units, which were erupted at 2.2Ma. Rhyolite lava area with well-exposed outcrops allow us to observe the internal structure of obsidian lava flow. The TI lava is 50 m in height and stratigraphic sequence from the bottom is a brecciated perlite layer, obsidian layer (7m), banded obsidian layer, and rhyolite layer. In this study, we define the obsidian and rhyolite based on the difference in appearance of specimen and rock texture, especially crystallinity. Rhyolite has perlitic cracks on glass, and contain the crystalline materials (i.e. spherulite and lithophysae). Banded obsidian layer which is located at the boundary between the obsidian and rhyolite layer, is composed of obsidian and rhyolite. Volume fraction of the crystalline materials in rhyolite layer is up to 40 vol.%.

Obsidian in TI lava is almost aphyric, composed of glass (>98 % in volume), rare plagioclase phenocrysts, plagioclase microlites, magnetite phenocrysts, oxide microlite, and rare biotite. Chemical compositions of obsidian glass, plagioclase and magnetite were analyzed by electron microprobe.

The maximum depth of magma chamber is estimated as <300MPa from the rhyolite-MELTS (Gualda et al., 2012) and petrographic characteristics. Magmatic temperature is calculated as T= 800 –820 [℃] from the plagioclase-melt geothermometer (Putirca, 2005). Magma viscosity is estimated as log μ= 4.9 –8.7 [Pa s] (Giordano et al., 2008).

We measured length, width and number of oxide microlite based on three-dimensional measuring method (Castro et al. 2003), and oxide microlite number density (N_v [/m^3]) was obtained. N_v of oxide microlite is $2.1\times10^{13} – 1.4\times10^{14}$. Water exsolution rate and ascent rate are inferred as 4.0×10^{-8}–2.2×10^{-7} [wt.%/s], and 6.8×10^{-5}–5.6×10^{-4} [m/s] respectively, from N_v and glass chemical compositions (Toramaru et al., 2008). These results means that obsidian and rhyolite experienced the same degassing rate, that is, ascent rate. This constraint provides an insight into the formation process of obsidian.

Magmatic connections: The interplay of magmatic systems with their crustal containers

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Magmatic systems develop on many different temporal and spatial scales and are influenced by internal process such as magma chamber convection, phase change, melt composition evolution and associated physical property changes, as well as external controls such as larger scale stresses and hydrothermal systems. The geophysical and geochemical datasets that describe these systems also focus on different aspects of their spatio-temporal histories and are often treated in isolation. Here we present a modeling framework to describe these coupled systems in order to integrate and interpret these perspectives and datasets. The magmatic model accounts for the following set of processes and the coupling between them: 1. Deformation of host rocks in response to pressure variations in the chamber. 2. Heat transfer from the magma chamber to the wall rocks and growth or decline of a viscoelastic shell around the magma body. 3. Crystallization and accumulation of crystals in different portions of the chamber in response to cooling which affects the mineral and melt compositions as a function of time and space.

The stress that a magma body imposes on its crustal container is an important indicator of changes in magma chamber conditions that can influence the surrounding crustal environment and produce measurable signals at the surface including ground deformation, changes in hydrothermal circulation and focusing of dikes toward the chamber, and importantly can also impact phase equilibria. The phase equilibria determines the latent heat contribution, and ultimately influences the thermal viability, convective vigor, magmatic timescales, melt-crystal separation and overpressure of the system.

We use a multiphase approach to compute extraction in magmatic systems. Each phase, melt or crystal, is represented by conservation equations for the mass, momentum and enthalpy. Enthalpy closure is determined from a version of MELTS with callable library functions that provide phase equilibrium results to the fluid dynamics code. This method accounts for the partitioning of latent and sensible heat in complex geochemical systems. Chemical species for each phase have separate transport equations permitting the exploration of fractionation behavior as well as providing detailed geochemical information that can be used to compare to field observations. We describe those regimes that can lead to sustained overpressure in a magmatic system, potentially making them more prone to erupt, and predict both petrologic and geophysical conditions accompanying these magma chamber conditions.

Positive correlation between crystal size and chemical composition of core; numerical simulation of the crystallization of plagioclase

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The plagioclase microlite sometimes show positive correlation between their size and chemical composition of core as shown by some studies (e.g. Noguchi et al., 2006, 2008). We analyze crystal size and An# (Ca / Ca + Na) of plagioclase microlites witch were ejected by Shinmoe-dake 2011 eruption. Crystal size is positively correlated with An#. An# of microlites range in 0.65 – 0.57, for the smallest size (10 μm) and increase with size converging to 0.65 for the largest size. They are distributed within upper and lower bounds. This correlation can be explain the continuous nucleation and growth process including the evolution of melt composition, namely high and low An# evolution series.

In order to quantitatively interpret this correlation, we develop a simple model. We assume that growing surfaces of nucleated crystals are in local equilibrium with adjacent melt in their compositions, namely the effective partial coefficient is defined. We calculate An# with software package Rhyolite-MELTS (Gualda et al., 2012). We denote the rate of nucleation and crystal growth, as J [$m^{-3}s^{-1}$] and G [ms^{-1}] respectively. In the case that rate of crystallizing change P is constant, if we set J as constant, G is automatically calculated, because G depends on the total crystal surface area S and P = SG. In our calculation, G is decrease with time, because surface area is increasing. Crystals that nucleate at earlier stage grow by large G. We calculate final crystal size distribution and An# with as a varying parameter J.

The correlation between crystal size and An# become tight with increasing J, and round with decreasing J. When J is high, crystals mostly crystallize at early stage and later growth is few. When J is low, crystals grow later stage. High An# evolution series can be explain cooled at high J, and low An# evolution series can be explain cooled at low J condition. As a result of simulation, it is found that a relatively higher value of J and vice versa, corresponds to low An# evolution series in size vs. An# trends.

Linking petrology and volcano monitoring data at active arc volcanoes

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Many active volcanoes worldwide are continuously monitored through a variety of methods, such as seismicity, gas flux, and ground deformation that look for signs that may indicate an impending eruption. These monitored signals provide a real-time record of the current state of the volcano. One of the enduring volcanological challenges is how to relate these signals to magmatic processes beneath the volcano. However, timescales of magmatic processes prior to eruption are poorly constrained, but may be a key to our understanding of active volcanic systems.

Petrological methods allows us to interrogate recent volcanic eruptions and compare those to the monitoring record. As a result, we are able to examine the relative timing of monitored precursors to an eruption. Zoned volcanic crystals potentially preserve a record of the changing magmatic conditions within their crystal structure. As magma evolves, changes in temperature, volatile content, pressure or composition result in renewed growth of a different composition generating zoned crystals. Diffusion chronology enables timescales of magmatic processes to be calculated. Using known eruption dates, this petrological timeseries can be correlated to monitoring data to constrain pre-eruptive processes.

Case studies from Mount St. Helens (MSH), USA and Mt. Ruapehu, New Zealand will be presented. Pyroxene crystals from both of these volcanoes have been investigated through a combination of back-scattered electron images and major element chemistry using electron probe microanalyser. At MSH and Ruapehu, over 500 pyroxene crystals were investigated and revealed multiple crystal populations. Diffusion chronometry from MSH show that rims grew within two years prior to eruption, many within months of eruptions. Peaks in crystallisation correlate with peaks in seismicity and SO2 flux, providing evidence for a relationship between seismicity and the arrival of new magma pulses into the magma chamber. Diffusion chronometry of clinopyroxene at Mt. Ruapehu indicate peaks in crystallisation 4-5 months prior to eruption that correlate with changes in the geochemistry of Crater Lake. Results from these studies provide evidence that time-series information locked up in zoned volcanic crystals can be used to assess precursory activity of past eruptions. In turn this information can be used to better evaluate monitoring signals at active volcanoes.

Bubble coalescence in magmas: Insights from in-situ high-temperature synchrotron-based X-ray tomographic microscopy

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The possibility of removing gas from magma during its rise to the surface decreases the probability of an explosive volcanic eruption to occur. In this respect, bubble coalescence and the achievement of a permeable network play a pivotal role in favouring magma degassing and limiting the explosivity of eruptions. Significant growth and interaction between bubbles occur in natural volcanic systems during ascent of the magma to the surface. Thus, we performed real time, 4D, high-temperature experiments at atmospheric pressure using laser heating and synchrotron-based X-ray tomographic microscopy at the TOMCAT beamline of the Swiss Light Source (SLS). We forced gas exsolution in natural magmas and observed bubble nucleation and growth in situ. The experiments were performed from room temperature up to 1300 K on two different types of crystal-free rhyolitic samples: one vesicle-free obsidian and one obsidian containing pre-existing vesicles. We characterized the main textural variations (bubble volumes, size distributions, shapes, and bulk textures) during the nucleation and growth of bubbles in these highly viscous systems, and tracked the evolution of parameters such as viscosity and overpressure in the foaming samples, which are essential for retrieving information on the processes preceding an eruption from the interpretation of the textures observed in eruptive products. The microstructural features of the starting material, nominally the presence of initial vesicles, strongly influence the dynamics of bubble coalescence. The presence of bubbles in the starting material tends to limit coalescence, therefore increasing the possibility of bubble overpressure. A possible implication of these experiments is that volcanic systems where magma is volatile-saturated already in the subvolcanic reservoir may have a higher tendency to feed explosive volcanic eruptions.

Effects of Shear Strain on the Deformation and Degassing of Highly Viscous Magmas

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To characterise the rheological behavior and the influence of deformation on degassing of magmas containing gas bubbles (12-36 vol.%) and crystals (0-42 vol.%) suspended in a silicate melt matrix, we performed simple shear experiments at high pressure and temperature (150-200 MPa; 723-823 K) in a Paterson-type deformation apparatus to total strains between γ=0 and γ=10. The experimental setup allows for escape of gas if bubble connectivity is reached on the outer portions of the samples. Three-dimensional imaging and analysis of deformation microstructures was performed by x-ray tomography using Blob 3D and Quant 3D software. Bubble coalescence begins at gammas as low as 0.3 at bubble contents of 20 vol.% and increases with deformation to produce planar bubble networks at gamma 5 with bubble contents of 16 vol.%. Bubble connectivity, localization of strain and the tendency for brittle failure of samples increase with crystal content. Decreasing bubble content with increasing strain, along with strain-hardening rheological behaviour, suggests significant shear-induced outgassing due to the development of connected bubble or fracture networks. Three dimensional analysis of samples provides evidence for the formation and subsequent closure of permeable pathways, which is an effective mechanism for degassing of samples, and may be analogous to the modality of degassing of magma during ascent in volcanic conduits. These experiments provide insights into the processes leading to the transitions from explosive to effusive activity observed at many silicic volcanoes, as well as the formation of flow-banded obsidian.

Foam collapse in conduits and its implications for eruption transitions and volcano monitoring.

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The inflation and contraction of magmatic foam may control the permeability of the volcanic conduit and the ability of the gas to pressurise pores and drive eruptions. Following an explosive eruption, pores depressurize and outgas as magmatic foam densifies to form a plug. Constraints on this mechanism are recorded in, (1) typical textures of dense magmatic plugs and domes, (2) timescales between explosive and effusive eruptive episodes, (3) deflation of active dome surfaces, and (4) deflation of volcanic edifices measured between vulcanian eruptive episodes. Here, we integrate this set of constraints with a series of foam collapse experiments. We heated cylindrical rhyodacitic pumice samples (20mm by 40mm and 10mm by 20mm), from the Pebble Creek Formation, Mt Meager, British Columbia, Canada, until collapse occurred. The original sample contained sheared connected bubbles 5 mm- 5 microns with a large proportion connected below 30 microns.Two types of experiment were performed; at atmospheric pressures in air at temperatures of 950-1000C for 30 mins to 10 hrs, and in autoclaves with water pressures of up to 10 MPa at 300 to 700C for 4 hrs. Samples variably dehydrated or hydrated, and deformed.Video during the experiments, 3D tomography, thin sections, SEM images, and helium pycnometry record the bubble textures, porosities and volumes during the densification process. As the sample densifies, the rate of porosity reduction decreases proportionally to the decrease in volume and this rate decreases as densification proceeds. Volume reduction is manifested by similar shrinkage in both diameter and length. The rate of shrinkage reduces with decreasing temperature. The samples hydrated in the pressurized steam environment collapsed at lower temperatures compared to the dehydrated samples in the dry oven, but the collapsed textures and final porosities were similar. The densified samples show a decrease in the number of small and intermediate connected bubble sizes (between 10-30 microns), thickening of bubble walls, and distortion of large connected bubbles. Gas escape pathways become simpler and fewer in the densified sample. We interpret the porosity reduction (up to approx. 50%) as outgassing from collapsing small connected bubble pathways. We hypothesize that surface tension drives connected small-intermediate sized bubbles to collapse and coalesce with larger bubbles. This outgassing drives volumetric reduction by up to 50% in a few hours. The volumetric reduction has important implications for the interpretation of deformation of the lava surface and volcano edifice. The change in vesicle structure affects (1) the permeability of the magma and degassing, and (2) fluid flow associated seismicity in the interval between explosive, and effusive eruptions. The texture produced replicates those seen in natural samples and the experimental timescale allows reinterpretation of historic eruptions and prehistoric deposits.

A new model for bubble growth, deformation and coalescence in viscous magmas

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Exsolved volatiles provide the driving force for explosive eruptions. During the magma's ascent to the surface, the silicate melt becomes super-saturated with volatiles (mostly water), driving bubble nucleation and growth. The increasing vesicularity of the magma significantly affects its physical properties.

The general processes that govern the growth of a bubble in a decompressing melt are well established. Yet, the complexity of the non-linear processes that control the evolution of bubble suspensions during the ascent of magma to the surface has limited our current focus to highly idealized models. These models generally assume (1) a monodisperse array of equally spaced spherical bubbles, (2) an infinite medium (expansion is not confined by boundaries), (3) bubbles neither deform nor coalesce. These assumptions are challenged by observation of textures in pumices, where deformation, coalescence and polydispersed bubble size distributions are reported. The model we propose alleviates the three assumptions mentioned above and allows us to study the deformation and growth of bubbles in a suspension while bubble deform because of shear flow conditions and/or hydrodynamic interactions with neighbor bubbles or solid boundaries (conduit wall). The aim of this model is to provide a more accurate description of the effect of bubbles on ascending magmas as they reach high vesicularities, and ultimately, build bubble dynamics parameterizations for the inclusion of these processes as subgrid scale feature in conduit flow models.

After an introduction to the numerical model based on the lattice Boltzmann method for free surface flows, we present validations for the growth of a bubble by expansion (mechanical work) and diffusion (mass increase). We also show an application of interaction between bubbles of different sizes and validate our model with diffusion coarsening (Ostwald ripening), where a small bubble shrinks by exchanging mass with a larger one. Finally, we focus on the effect of hydrodynamic interactions between bubbles on the distribution of deformation and orientation of bubbles during simple shear calculations.

Thermo-rheological feedbacks in silicic lavas and ignimbrites

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The rheology of lava is highly dependent on temperature, both directly (via non-Arrhenian temperature dependence of melt viscosity) and indirectly (via increasing crystal content). Rheology feeds back to temperature, because rapidly sheared melts can undergo viscous heating (heat production = viscosity $\times$ [strain rate]^2), and rapid disequilibrium crystallization can cause heating due to latent heat release (ΔH_{xt}). The heat budget of partially crystalline lava offsets these gains with conductive losses controlled by thermal diffusivity (D) and conductivity ($k = D\rho C_{\mathrm{P}}$, where ρ is density and C_{P} is heat capacity).

We measured the apparent viscosity of several crystalline dacitic lavas from Santiaguito, Guatemala. At conditions appropriate to lava flows (shear stress ~0.1 to 0.4 MPa, strain rate ~10^{-8} to 10^{-5} s^{-1}), apparent viscosity is best modeled as a power-law with no yield strength. Viscosity of the flow core, at ~850 ℃, is estimated ~ 5×10^{10} Pa.s. There is no evidence for significant crystallization during flow emplacement at Santiaguito, but viscous heating may be significant ongoing heat source within these flows ~ 100Wm^{-3} if most shearing is restricted to a ~1m wide zone), enabling highly viscous lava to travel long distances (~4 km in ~2 yrs for Santiaguito).

Extremely high-grade, lava-like welded ignimbrites are produced by many large explosive (super-)eruptions. The lava-like and rheomorphic Grey's Landing ignimbrite, Idaho, provides abundant field evidence supporting the upward migration of a transient, 1-2 m thick, sub-horizontal ductile shear zone at the interface between the pyroclastic density current and deposit, through which all of the deposit passed. Using rheological experiments and thermo-mechanical modeling, we demonstrate that syn-depositional welding and ductile flow is achievable within a very restricted field of likely time-temperature-strain space where rapid high-strain deformation ($\leq$1000%) is favored by higher emplacement temperatures ($\geq$850 ℃). The field of ductile deformation is broadened significantly by accounting for strain-heating, which permits a sustained temperature increase up to 250 ℃ within the shear zone, and helps to explain the enormous extents of lava-like lithofacies and intense rheomorphism recorded in extremely high-grade ignimbrites. Recognition of short-lived but very powerful ($\geq$1MWm^{-3}) strain-heating within rheomorphic ignimbrites suggests that large pyroclastic flows may travel over a hot substrate.

We conclude that strain heating, an inevitable result of magma transport that feeds back to rheology and transport, should be taken into account in thermal modeling of volcanic processes at both high and low strain rates, and both pre- and post-eruption.

Crystal shape exerts a first order control on magma rheology

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Suspended crystals have a strong impact on the rheology of magma. It is well known that magma viscosity increases non-linearly as crystal fraction increases, and that shear thinning, yield stress and other non-Newtonian phenomena emerge at moderate-to-high crystal fractions. It is less widely recognized that the shape of the crystals also plays a crucial role in determining suspension rheology. We present a simple model for the rheology of suspensions of crystals, which accounts for crystal shape.

Our model is based on the results of laboratory analogue experiments which quantify the rheology of suspensions of particles in a Newtonian liquid. The aspect ratio of the particles is systematically varied in the range 0.04 to 22 (i.e. from strongly oblate to strongly prolate). For each aspect ratio, we quantify the suspension viscosity η_r as a function of particle fraction ϕ_m from close to the dilute limit to close to the maximum packing fraction ϕ_m. We find that viscosity increases as a power law function of particle fraction for all aspect ratios, and that the increase is more dramatic the more oblate or prolate the particles are. The data are well described by the Maron Pierce model: $\eta_r = (1 - \phi/\phi_m)^{-2}$ when ϕ_m treated as a fitting parameter. Another way of saying this is that the curves of viscosity against particle fraction collapse to a single curve when particle fraction is normalized by the maximum packing fraction. We use this fitting approach to determine ϕ_m for each particle aspect ratio dataset and find a systematic relationship between particle aspect ratio and maximum packing fraction, which is well captured by a (purely empirical) log-Gaussian function. This relationship allows maximum packing fraction to be calculated for particles of known aspect ratio.

Application of the model to determine the viscosity of a crystal bearing magma is straightforward when crystal fraction and aspect ratio are known. We demonstrate this by incorporating our viscosity model into a test bed conduit flow model. The results show that crystal shape has a profound influence on model predictions and that ignoring crystal shape introduces serious errors into models of magma flow. We adopt a benchmark case of the explosive eruption of magma with 30% fraction of crystals with aspect ratio of 10 (a reasonable value for prolate microlites). If we ignore particle shape and treat crystals as equant, the crystal fraction has to be increased from 30% to greater than 50% to obtain the same results.

Non-Newton Man: An exploration of magmatic shear thinning sources.

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Natural magmas display at different levels a viscosity dependency with the stress. This non-Newtonian behavior often come off as a decrease of the measured apparent viscosity or shear thinning. However the shear thinning sources, necessary to scale back the flow behavior to natural scales, are poorly constrained. If a few hypothesis have been proposed, none have yet stood up or been clearly quantified. For pure melts we already demonstrated that Non-Newtonian behaviors simply result from viscous heating. With this study we investigate several potential sources to explain the decrease of viscosity in crystal bearing systems. If most of our arguments are based on literature, a rheological characterization of rigid particles suspensions has been performed with a cone and plate rheoscope and is here used as reference.

We present various theoretical limits of the potential sources cited in literature for shear thinning (viscous heating, particle migration and crystal breakage) and compare them to experimental results. The reference system does not allow crystal breakage and so remove this potential source for the effect measured in our experiments.

Additionally, numerical simulations are presented to theoretically support the simpler models presented. They are based on elementary lattices and display the variation of local and bulk viscosity for rigid or deformable particles under various strain in 2 and 3 dimensions.

We first discuss spherical particles suspensions and extend it next to various eccentricities. Numerical simulations are presented to theoretically confirm the suggested processes. From these results the sources of Non-Newtonian effects may results from only two effects. The first commonly mentioned in literature is a layering of particles for which we fix for the first time the limits. The second is a violation of volume conservation where the model is here presented for the first time.

These observations conclude that the present problems is first experimental design and the necessity to rethink rheological and viscosity measurements for magmas. Only better constrained apparatus will allow to fully understand Non-Newtonian behaviors and make possible the scaling to Earth like systems.

The formation and hydration of cracks in cooling volcanic glass

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Volcanic domes, plugs and lava flows often show intricate, small-scale, geometric crack patterns. These cracks act as pathways for fluids and may jeopardise the structural stability of the dome, plug or flow. The circulation of volatiles allows crystal growth and surrounding glass hydration. Here, we study the cracking of magma directly or indirectly caused by cooling, based on analyses of textural, chemical and physical properties of natural samples and experimentally altered volcanic glasses.

Rhyolitic volcanic glass from the Ngongotaha dome (New Zealand) shows different generations of cracks, which we infer to reflect correspondingly different cooling history. Cooling from a temperature slightly higher than the glass transition interval (ie., from a relaxed state) spherulitic, anhydrous minerals crystallised. Spherulite growth produced cracks that served as channels to redistribute water. After further cooling below the glass transition temperature, perlitic cracks formed allowing water to flux through the dome. At ambient temperatures (10℃ average), additional cracks opened that were not subsequently hydrated. From examining hydration patterns in these natural samples, we conclude that hydration occurred only at temperatures between the glass transition temperature and $\approx$ 400℃ over timescales of days to months. Rapid quenching of rhyolitic volcanic glass from 900℃ induced fractures. X-ray computed tomography imaging of the fracture pattern shows a comparable texture to that characteristic of natural perlites. This similarity suggests that perlitic cracks form in tension as a result of thermal stressing during the cooling phase. The permeable network of perlitic cracks allows the circulation of fluids, which favours hydration and/or formation of hydrous minerals. We are currently investigating the effects of crystal growth by combined thermo-gravimetric analysis and differential scanning calorimetry of glass in situ in a water-saturated atmosphere. This on-going study promises to resolve the mechanism underlying the development of cooling structures commonly present in volcanic rocks as well their influence on permeable gas flow and the structural stability of lava domes, plugs and flows

Ductile and brittle processes of permeability development and outgassing during hybrid explosive-effusive activity at Cordon Caulle, Chile (2011-12)

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After initial Plinian to sub-Plinian phases of activity, the 2011-12 eruption of Cordon Caulle, Southern Chile, transitioned into a months-long period of ash jetting and Vulcanian blasts, with effusion of a voluminous obsidian lava flow. Ejected pyroclasts ranged from fine tube-like pumiceous ash to large (<3 m) bombs of dense obsidian. Field campaigns before, during, and after the eruption allow us to describe the shallow conduit that fed the eruption using direct observations of activity and features of the pyroclasts.

The vent complex and site of lava effusion was represented by two loci of Vulcanian blasts within a single tephra cone. These loci each consisted of clusters of long-lived sub-vents that expressed correlated shifts in eruption intensity, indicating the presence of partially connected and/or branching zones of high permeability within the upper conduit. Sub-vents ejected the tube-like pumiceous ash, with porosity (39-67 %) and anisotropic Darcian permeability (3.1×10^{-15} m^2 perpendicular to fabric to 3.8×10^{-11} m^2 parallel) indicating that the permeable networks consisted of highly sheared, tube-like bubbly magma. These contrasted with the low porosity (17%) and nul permeability of bombs ejected to hundreds of metres from the vent in Vulcanian blasts. Residual H_2O content of ash (0.14 wt%) and bombs (0.2-0.25 wt%) indicate pyroclast degassing to near-atmospheric pressures. Together, the pyroclasts demonstrate that both ductile and brittle processes of permeability development and gas transfer were important.

Ash textures and modeling indicate the onset of permeability by ductile processes of shear-enhanced bubble coalescence in the upper 1 to 1.5 km of the Cordon Caulle conduit. Textures in pumices collected early in the eruption indicate a significant role for shear localization in the ductile development of permeability, which we extrapolate to the hybrid activity. Bombs of tube pumice collected after the eruption indicate that the ash represents fragmented parts of larger bodies. Ongoing work aims to reconcile the very low H_2O equilibration pressures of the ash (< 1 MPa) with the considerably higher overpressures (5.7-12.5 MPa) theoretically required to fragment melt with the measured porosity and permeability.

Ash jetting and Vulcanian blasts show that ductile processes were not sufficient to accommodate degassing, and additional brittle (e.g., fragmentation) events assisted in gas transfer to the atmosphere. Brittle processes of gas transfer are examined through the frequency of Vulcanian blasts recorded during the eruption, as well as in textures of dense-to-breadcrusted, tuffisite vein-bearing obsidian bombs collected afterwards. Ductile and brittle processes combined to permit the open-system degassing required for hybrid explosive-effusive activity.

Volcanic pseudotachylyte and self-driven stick-slip motion

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Dome-building eruptions have catastrophic potential, with dome collapse leading to devastating pyroclastic flows with almost no precursory warning. During dome growth, the driving forces of the buoyant magma may be superseded by controls along conduit margins; where brittle fracture and sliding can lead to formation of lubricating cataclasite, gouge and, under extreme friction, pseudotachylyte.

High velocity rotary shear (HVR) experiments demonstrate the propensity for melting of the andesitic and dacitic material (from Soufriere Hills and Mount St. Helens respectively) at upper conduit stress conditions (less than 10 MPa). Starting from room temperature, frictional melting of the magmas occurs in under 1 s (less than 1 m) at 1.5 m/s (a speed that is achievable during stick-slip motion). At lower velocities melting occurs comparatively later due to dissipation of heat from the slip zone (e.g. 8 to 15 m at 0.1 m/s). Given the ease with which melting is achieved in volcanic rocks, and considering the high ambient temperatures in volcanic conduits, frictional melting is a highly probable consequence of viscous magma ascent. The shear resistance of the slip zone during the experiment is also monitored. Frictional melting induces a higher resistance to sliding than rock on rock, and viscous processes control the slip zone properties. Variable-rate HVR experiments which mimic rapid velocity fluctuations in stick-slip behavior demonstrate velocity-weakening behavior of melt, with a tendency for unstable slip. We postulate that pseudotachylyte generation could be the underlying cause of stick-slip motion and associated seismic "drumbeats", which are so commonly observed at dome-building volcanoes.

When a melt layer forms at the conduit margin the shear resistance of the slip zone is increased, acting as a viscous brake and halting slip (the "stick" of stick-slip motion). Sufficient buoyancy-driven pressures from ascending magma below eventually overcome resistance to produce a rapid slip event (the "slip") along the melt-bearing slip zone, which is temporarily lubricated due to velocity-weakening. New magma below experiences the same slip event more slowly (as the magma decompresses) to produce a viscous brake and the process is repeated. This allows a fixed spatial locus that explains the repetitive drumbeat seismicity and the occurrence of "families" of similar seismic events.

This view is supported by field evidence in the form of pseudotachylytes identified in lava dome products at Soufriere Hills (Montserrat) and Mount St. Helens (USA). Both eruptions were characterised by repetitive, periodic, fixed-source seismicity and lava spine extrusion of highly viscous magma. We conclude that stick-slip motion in volcanic conduits is a self-driving, frictional-melt-regulated force common to many dome building volcanoes.

Relating vesicle shapes in pyroclasts to eruptions styles

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Pyroclasts provide a direct record of magma ascent and a key feature of pyroclasts is the shape of vesicles. For explosive eruptions vesicle shapes are the integrated result of magma deformation, bubble growth and bubble coalescence. Here we focus on vesicles that bear little evidence for shear deformation and examine vesicle shapes with the objective of relating shape to magma expansion. We use a shape factor Ω, which quantifies the degree of complexity of a vesicle's bounding surface. Among the samples analyzed, we find a clear distinction between Hawaiian and Strombolian eruptions and Vulcanian, Plinian and ultraplinian eruptions, with the former having a larger value of Ω than the latter (Moitra et al., 2013). We interpret this difference in vesicle shapes as a consequence of the relative importance of structural changes during magma decompression and bubble growth, such as coalescence and shape relaxation of bubbles by capillary stresses. This force balance can be expressed by the capillary number, Ca, based on the expansion velocity and obtained from bubble growth modeling. Small values of Ca are estimated for Hawaiian and Strombolian eruptions ($Ca \ll 1$), indicating that capillary forces dominate bubble shapes. In contrast, $Ca \gg 1$ for eruptions with smaller values of Ω. Interestingly, we also find that the basaltic Plinian eruptions of Mt. Etna, Italy (122BC) and Mt. Tarawera, New Zealand (1886) are characterized by relatively low values of Ω and predicted values of $Ca \gg 1$, similar to Vulcanian, Plinian and ultraplinian eruptions of more silicic magmas. We interpret this to be the result of syneruptive magma crystallization, ensuing high magma viscosity and reduced rates of bubble growth. Our model results indicate that during these basaltic Plinian eruptions bubble growth was viscously limited, so that they remained at sufficiently high pressure for brittle magma fragmentation.

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The significance of the opening angle of pyroclast ejection during explosive volcanic eruptions

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Explosive volcanic eruptions may occur with little or no warning. Assessing the related hazards has advanced greatly in the recent past through a multidisciplinary approach including fieldwork, laboratory experiments and numerical modelling. However, a comprehensive quantification of the physical processes affecting eruption style is still lacking.

Here we show results from laboratory experiments that help shed light on some of these to date, unobservable, processes. At ambient temperature, washed volcanic particles of varying mode (2 mm and smaller, monodisperse) and porosity (scoria and pumice) were filled into a cylindrical and vertical high-P autoclave (25 mm diameter) and pressurised to 5-15 MPa by Argon gas. Upon rapid decompression, the particles were accelerated vertically and ejected into a low-P section. The aim of this study was to constrain and explain the behaviour of particle-laden, underexpanded jets upon leaving a straight vent. We used three different initial configurations to allow for variable particle/gas-ratios and distance of sample surface from outlet: (1) 60 mm filling height, 300 mm distance from vent, (2) 240 mm filling height, 100 mm distance from vent and (3) 60 mm filling height, 100 mm distance from vent. The geometry of gas-particle-ejection was recorded with a high-speed video camera at 10.000 fps. After the experiments, particles were collected and checked for possible changes of grain-size distribution.

Expansion of the particle-laden jet takes place as long as the jet is overpressurised at the vent. More specifically, we find that: (i) the ejection speed of particles increased systematically with applied pressure and smaller distance of the sample surface from the vent (up to 200 m/s); (ii) the maximum opening angle of particle ejection is negatively correlated with the initial distance of the sample surface from the vent (larger distance = smaller opening angle); (iii) the opening angle is negatively correlated with sample density and grain size. In experiments of configuration (2), a clear development of the opening angle (from 30 °to vertical) could be observed during the course of each experiment. We also (iv) observed a considerable generation of fine ash, most likely due to decompression-induced fragmentation and particle-particle interaction. The high-speed videos have been modelled computationally to explain the observed Prandtl-Meyer expansion and ambient air ingestion.

Apart from conduit/vent geometries, these experiments highlight the strong influence of the conditions inside a volcanic conduit (overpressure, fragmentation depth) on the characteristics of particle ejection. As this is the first of only few directly observable features of particle ejection during explosive eruptions, the opening angle should be constrained during the monitoring of erupting volcanoes to gain a more complete view of the depth and efficiency of the physical processes ongoing.

Continuous survey of ash particles by automatic sampling system and field survey

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There are many active volcanoes in southern Kyushu, Japan. Most of the recent eruptions are ash emission. Especially, activities in recent decades at Sakurajima and Suwanosejima volcano, are characterized by long-term successive ash emission such as vulcanian and strombolian eruptions. But in contrast, Plinian (or sub-Plinian) eruptions occurred at the two volcanoes in 1914 and 1813, respectively, as well as relatively large effusive eruptions in 1946 and 1884, respectively. Sub-Plinian eruption occurred also suddenly in 2011 at Shinmoedake volcano in Kirishima volcanic complex, without evident precursory phenomena. How do they evolve into such explosive phases from quiescent period or moderate ash emission? To solve this issue we have done two approaches in terms of petrological analyses; (1) Continuous survey of ash particles of ash emitting eruptions, and (2) reconstruction of pre-climactic phase by field survey of ancient deposits.

We started collection of ash fall at Suwanosejima at the end of 2000 when it became more active after a decade of quiescent period. We have analyzed several samples of different eruption styles and found two types of particles in each sample that differs in crystallinity. The ratio of crystalline and less-crystalline particles changed systematically. Less-crystalline particles were rich for eruptions with long duration and high plume height, whereas they decreased for intermittent eruptions with violent explosions and lower plume height. We also found temporal changes in surface phenomena (i.e., eruption styles, vent condition, etc.) with changes in morphological features of the products. However, as we collected samples by ourselves in this remote island, continuous chase of eruptive products was not possible.

Thus, we started collection of ash at Sakurajima in 2008 by establishing automatic sampling system. We have been successful in daily collection of samples for five years at one locality 2.3 km from active vent. Although petrological features are rather complex than Suwanosejima, they also consist of crystalline and less-crystalline particles. We firstly classified the particles into several types, and then analyzed chemical composition of matrix glass of less-crystalline particles and color of bulk ash sample in terms of photochrometry, in order of date. We found systematic temporal changes in these data with some geodetic observations.

We also analyzed pre 1813 ash deposit of Suwanosejima volcano for comparison with those of recent products. The deposit consists of the alternation of ash layers very similar to those of recent decades. The chemical compositions of matrix glass are also very similar that we could not find drastic change in petrological features between climactic sub-Plinian and preceded phases. But close look at of the chemical composition show relative enrichment of MgO content with time, although each sample has larger ranges in composition than that temporal change.

Temporal variation in volcanic ash texture during single vulcanian eruption at Sakurajima volcano, Japan, revealed by real-time collection of ash samples

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Vulcanian eruptions have been recognized as explosive emissions of volcanic gases and tephra in short duration and modeled as instantaneous bursts of pressurized gas chambers at the shallow part of the conduit. However, detailed observation of the eruption process reveals most vulcanian explosions consist of an intense explosion at the onset followed by continuous emission of volcanic gases and tephra for several minutes to several hours. To model vulcanian eruptions, it is important to consider the temporal evolution of their eruptive process, which is controlled by the structure of the vent-conduit system. Examination of the temporal variation in petrological character of the ejecta is crucial for understanding changes in the vent-conduit system because the ejecta carries a record of magma properties and eruptive processes as crystalline and vesicle textures and chemical composition. Previous studies have reported daily or inter-event variation in the eruptive processes of small eruptions including vulcanian and strombolian styleson the basis of petrological analysis of volcanic ash. However, durations of vulcanian eruptions are actually much shorter than the time resolution determined by these studies.

Here we discuss the progress of vulcanian eruptions with short duration on the basis of temporal variation of texture of volcanic ash from Sakurajima volcano, Japan. We performed the real-time collection of the falling ashes every 2-50 min and the collected ashes are petrologically analyzed. These ashes consist of juvenile particles, altered rock fragments, and fragments of crystals. The juvenile particles are subdivided into blocky, vesicular, and fluidal particles. Because the crystallinities of the vesicular and fluidal particles are smaller than those of the blocky particles, we termed the vesicular and fluidal particles as low-crystallinity particles (LCPs with 25-28 vol.% of plagioclase), and the blocky particles as high-crystallinity particles (HCPs with 28-35 vol.% of plagioclase). Analysis of temporal variation in ash texture revealed that the number ratio of LCP to HCP (LCP/HCP) was minimal in the deposits of initial eruption and increased with the progression of each eruption. The higher crystallinity of HCPs suggests crystallization under lower pressure (10-30 MPa) and longer duration than that of LCP magma (20-40 MPa). The temporal variation in LCP/HCP suggests that emission of less-viscous or vesicular magma under a dense cap increases with the progress a single vulcanian eruption. Such temporal variation in ash texture may correspond with the progress of the emission style of sudden, explosive to continuous during a vulcanian eruption.

Structural role of Fe in a pantelleritic melt

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Iron in silicate melts can play a variety of structural roles involving different coordination numbers and oxidation states. Common Fe species in the melt include 4-Fe2+, 5-Fe2+, 4-Fe3+, and 5-Fe3+. The relative proportions between these species can vary considerably according to bulk glass composition and oxygen fugacity conditions. However, in most natural and synthetic silicate glasses 4- and 5- fold coordinated Fe2+, and 4-fold coordinated Fe3+ are the most common Fe species. Being a major element in silicate melts, Fe can affect considerably important physical properties like density and viscosity of a magma. Moreover, even at constant bulk composition and Fe content, also the Fe oxidation state is known to affect the melt viscosity.

In order to study the Fe structural role in peralkaline silicate melts and its effect on their viscosity, a set of silicate glasses with pantelleritic composition have been synthesized at different oxygen fugacity conditions (ranging from air down to IW buffer). These glasses have been previously characterized by titration to get the Fe oxidation state. Moreover, the viscosity (and glass transition temperature) has been measured for each glass/melt at different temperatures. During the course of this study the glasses were analyzed by 57Fe Moessbauer spectroscopy (MB). The spectra were taken at 298K in transmission mode and fitted by applying an extended Voigt-based lineshape according to Botcharnikov et al., 2005. The MB spectra of all samples display three lines which can be described to two different doublets. One doublet with an isomer shift (IS) of ca. 0.9 mm/s relative alpha-iron and a quadrupole splitting (QS) of ca. 2 mm/s can be attributed to ferrous iron. The second doublet with IS of ca. 0.3 mm/s relative alpha-iron and QS of ca. 0.9 mm/s can be attributed to ferric iron. The later values are close to that of ferric iron on tetrahedral site in ferrobasaltic glasses (Botcharnikov et al., 2005). With increasing oxidation the QS of ferric iron increases slightly from 0.85 mm/s (0.3 Fe3+/Fetotal) to 0.95 mm/s (0.8 Fe3+/Fetotal) in contrast to ferrobasaltic glasses where a decrease of QS for ferric iron as a function of oxidation was observed. The IS of 0.9 mm/s for ferrous iron remains constant up to an oxidation state of about 0.6 Fe3+/Fetotal and with increasing oxidation a rapid decrease to IS of 0.6 mm/s at 0.8 Fe3+/Fetotal occurs. At the oxidation state of 0.6 Fe3+/Fetotal the constant QS of 2.0 mm/s for ferrous iron increase up to 2.45 mm/s at 0.8 Fe3+/Fetotal in contrast to ferrobasaltic glasses, where a QS of 2.0 mm/s remains constant over the whole oxidation state (Botcharnikov et al., 2005). In allusion to tektites the doublet with IS of 0.9 mm/s and 0.6 mm/s can be attributed to ferrous iron on a five-fold and four-fold coordinated sites, respectively (Rossano et al., 1999).

Biot number influence on the crust-magma thermal regime under the volcano: evidences from integrating petrology and numerical models

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In volcanology the processes that operate in the magma conduit between the host-rock and the magmatic intrusion are essential to know the thermal regime during the process of crustal partial melting. The appropriate parameter to advance in the knowledge of this rock-magma interaction is the Biot number. However its use in volcanic models are normally taken in broad ranges (Biot tends to zero or Biot tends to infinity depending on the higher thermal resistance in the host or in the magma, respectively) instead of as precise values. To achieve the latter, an interactive approach that combines realistic samples from volcanic conduits (through crustal xenoliths) and numerical modelling of fluid dynamics, is indispensable.

We investigate the crust-magma thermal regime in the conduit by operating with different and precise Biot values in 2-D numerical approaches. They are further combined to the crustal samples erupted from depth in order to interactively both constrain the numerical parameters and boundary conditions before modelling, and interpret more accurately what the rocks have to tell us. The natural silicic samples from El Hoyazo volcano (SE Spain) where rapidly erupted after incorporated into dacitic lava by rooting up from the wall-rock and/or dropping into the magma conduit at 13-18 km depth. These crustal xenoliths represent unique natural scenarios to endeavour on the thermal history of magma flow in the conduit and, consequently, the crustal contribution -xenolith history- before (and during?) the eruption episode.

The results -depending on the different conduit depths, temperature gradients at the host and conduit, and conduit's radius- evidence significant differences in the heat transfer between magma and crust along the magma ascent process.

Effective parametric inversion of pre-eruptive ground deformation for hydrokinetic model of magma plumbing system

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We numerically simulated a transient magma accumulation process in the magma plumbing system beneath an active Showa Crater of Sakurajima Volcano (Japan). Our objective is to find what would be dominant geophysical parameters in the accumulation process before eruption. Geodetic observations showed that a periodic inflation and deflation event had lasted 30 hours before an explosive eruption on April 9, 2009. Our model consists of two reservoirs, one shallower filled mainly with gas and the other deeper filled with magma, connected by a volcanic conduit as inferred from the past geophysical observations. A pressure difference between the two reservoirs forces the magma to move from the deeper up to the shallower reservoir. We assumed a constant rate of magma supply to the deeper reservoir as an input to the magma plumbing system. In a cylindrical volcanic conduit, a viscous multiphase magma flow is simulated by either Hagen-Poiseuille or permeable flow with the effects of the relative motion of gas in magma, the exsolution of volatiles in melt, the crystallization of microlites in groundmass, the change in height of magma head, etc. As a result of comparison between the observed and calculated volumetric variations in the reservoirs, we found the permeable model could reproduce the observed event observed before the eruption than the Hagen-Poiseuille flow model. We also found that the radius of the volcanic conduit, the bulk modulus of the deeper reservoir and the relative gas permeability in magma are the key parameters to reproduce the observed volumetric variations before the eruption. Among these parameters, our sensitivity analysis indicates that the initial height of magma head, the temperature and the radius of the magma reservoir would have much less influence on the volumetric variations of the reservoirs than the key parameters. We propose our numerical model as one of quantitative simulation methods that could be applied to the future eruptive events not only at Sakurajima Volcano but for the other volcanoes.

Magma database of large-scale volcanic eruptions in Japan during the last one hundred thousand years

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In order to assess future large-scale eruptions, it is important to understand characteristics of past large-scale eruptions. For Japanese volcanoes, high-quality databases of volcanic eruptions have been developed, for example Japanese active volcanoes (Kudo and Hoshizumi, 2006-) and one-million years chronology of volcanic eruptions (Hayakawa, 1996-). These databases involve eruptive age, eruptive style and eruption magnitude, M, defined by Hayakawa (1993) and Pyle (2000). In contrast, it is often the case that properties of magma that caused these eruptions remain unrevealed. We have sampled and analyzed eruptive products of ca. 90 eruptions in Japan during the last one hundred thousand years and are constructing a database of magmatic properties. This database involves mainly large scale eruptions with M=4-8 and additionally historic famous small eruption of M=1-3. In this presentation, we show magma and melt compositions, and phenocryst contents. These magmatic properties are important factors controlling physical properties of magmas, and thus eruption dynamics. We examine relationship between these magmatic properties and eruption characteristics.

Bulk rock compositions (magma compositions) were obtained by XRF analysis. For groundmass compositions (assumed to be melt compositions at preeruptive chamber condition) and phenocryst contents, two methods were taken depending on occurrence of groundmass crystallization. For microlite-free groundmass, compositions of groundmass glass were obtained by EPMA analysis. Phenocryst contents were estimated by chemical massbalance calculation of K2O between bulk rock, phenocryst and groundmass. For microlite-bearing groundmass, groundmass compositions were estimated by chemical massbalance calculation between bulk rock, phenocryst and groundmass. Representative compositions of phenocryst were obtained by EPMA analysis. Modal abundances of phenocryst were obtained by image analysis of back-scattered electron images and elemental maps with 1-4 cm^2 area by EPMA.

Examining relationship between eruption magnitude, M, and magmatic properties, some interesting correlations are found. Rhyolitic melt (>70 wt% SiO2)-bearing magmas (andesitic to rhyolitic magmas) caused M=4-8 eruptions. In contrast, basaltic to dacitic melt (<70 wt% SiO2)-bearing magmas (basaltic to andesitic magmas) caused M=1-5 eruptions. For rhyolitic melt-bearing magma, the maximum eruption magnitudes are correlated with phenocryst content. Phenocryst-rich magmas with 20-50 vol% phenocryst have the maximum eruption magnitude with ca.6, where phenocryst-poor magmas with 0-20 vol% cause caldera-forming eruption with M=8 at the maximum. These correlations may be important clues to petrological assessment for future large-scale eruption.

Rheology of Crystal- and Bubble-bearing Magmas: insights into volcanic conduit dynamics

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Magmas are multiphase mixtures composed of crystals and gas bubbles suspended in a silicate melt. The relative proportions of these phases and their interaction control the rheological behavior, the modality of emplacement within the Earth's crust and the eruption of magmas. The rheology of crystal- and bubble-bearing magmas (ranging from dilute suspensions to crystal mushes) has been experimentally investigated. Hydrous haplogranitic magmas (1.6-2.6 wt% H2O) containing variable amounts of quartz crystals (24-65 vol%), and CO2-rich bubbles (9-12 vol%) were deformed in simple shear with a Paterson-type rock deformation apparatus at high temperature (823-1023 K) and high pressure (200 MPa), in strain-rate stepping (10-5 s-1 - 4*10-3 s-1) from low to high deformation rate. The rheological results show that three-phase suspensions are characterized by strain rate-dependent rheology (non-Newtonian behavior). Two kinds of non-Newtonian behaviors were observed: shear thinning (decrease of viscosity with increasing strain rate) and shear thickening (increase of viscosity with increasing strain rate). Microstructural observations suggest that: shear thinning dominantly occurs in crystal-rich magmas (55-65 vol% crystals) because of crystal size reduction and shear localization; shear thickening prevails in dilute suspensions (24-44 vol% crystals) due to outgassing promoted by bubble coalescence. To illustrate the impact of these new findings in magma rheology, we present two applications on volcanic conduits where magmas are characterized by shear thickening and shear thinning behavior. The two types of rheological behavior determine the modality of magma ascent in the volcanic conduit and, ultimately, the type of volcanic eruption.

How does crystal-rich magma erupt? A preliminary model for the rheology of three-phase suspensions

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Current models of highly-concentrated particle suspensions predict that magma with very high crystal content should not erupt. However, field observations demonstrate not only that such magma can erupt, but that it can form fluidal pahoehoe flows. For example, the lava flows produced by the 1780 eruption of Volcan Llaima have well-developed pahoehoe textures, yet contain up to 60 vol. % phenocrysts. These observations beg the question: how does such crystal-rich magma erupt and flow?

We propose that the magma was made mobile by the presence of a distributed gas phase; i.e. the magma contained bubbles as well as crystals on eruption. Subsequent to emplacement, the gas was lost, leaving lavas that are crystal-rich, but almost bubble-free. As the lavas appear today, their crystal content is high enough that the crystals are all in contact, forming a dense framework throughout the lava. The crystal volume fraction is well above the maximum packing fraction (given the aspect ratio of the crystals) which should prevent flow of the lava.

Modelling such a lava as a two-phase suspension (crystals and melt) may not be truly representative of its state at the point of emplacement - the gas phase, no longer present, must also be accounted for. We present a preliminary model that accounts for the impact that gas bubbles have on the effective viscosity of the fluid phase surrounding the crystals. The model follows the approach of Farris (1968) and treats the bubbly liquid as an 'effective medium' in which the crystals are suspended; i.e. the crystals do not 'feel' the effect of individual bubbles, only the altered viscosity of a continuum fluid phase. The model predicts that the effective viscosity of the suspension will drop considerably above a certain bubble fraction, potentially allowing a locked suspension to flow.

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Investigating the rheological controls on the explosive-effusive transition at Tungurahua volcano

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Tungurahua volcano has been active since 1999 culminating in the voluminous August 2006 VEI-3 eruption, a series of explosive events terminated by the effusion of a lava flow. Understanding such a rapid shift in eruption style is crucial to eruption forecasting at andesitic arc volcanoes. Here, rheological changes occurring during magma ascent are invoked to explain eruptive style.

Erupted material from the August 2006 bimodal eruption is described as chemically homogeneous (bulk rock approx. 57 wt.% SiO_2) and texturally variable. The explosive phase showed a wide range of porosities (1-60%), crystallinities (20-30% phenocrysts), with an interstitial glass composition of 63-65 wt.% SiO_2. In comparison, the lava material is more crystalline (30-40% phenocrysts, high microlite content), less porous (1-5%) with an interstitial glass with 67 wt.% SiO_2. During fragmentation experiments, the pore overpressure required to achieve fragmentation of the explosive magma was 3MPa, whereas 6-10 times more pore pressure is required to fragment the lava.

Rheological behaviour of ascending magma (undergoing crystallization, volatile exsolution and chemical fractionation) is a chief determinant of eruptive style. A variety of experimental techniques were combined to map the rheological evolution of magma during ascent at Tungurahua. In the reservoir, the magma is envisaged as crystal poor with a composition similar to that of the bulk rock. The non-Arrhenian temperature dependence of the viscosity of the (dry) magma in the reservoir (from re-melted whole rock material) and the increase in melt viscosity due to initial (20 vol.%) crystallization were measured using a concentric cylinder. The end viscosities of the erupted products were elucidated using a uniaxial press and show apparent viscosities 5 orders of magnitude above the pure interstitial melt and 7-8 orders above the viscosity of the reservoir magma. The effusive material was more viscous and shear-thinning than the explosive material. Thus, the lava flow represents the late effusion of a more viscous (possibly related to ascent rate) magma with diminished stored energy to drive fragmentation.

Crystal plasticity as a strain marker of the viscous-brittle transition in magmas

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Quantifying magma transport requires rheological models. Models of suspension rheology have long attempted to deal with crystal fraction, shape and aspect ratio as rheological variables. Recent advances in experimental magma deformation and imaging now provide a substantial opportunity for completing our picture of the viscous behaviour of multi-phase systems. This study reports the first observation of crystal plasticity, identified using electron backscatter diffraction (EBSD), in the phenocrysts and microlites of two natural andesitic magmas that have been deformed experimentally at magmatic temperatures. The deformation yields a plastic response of the crystalline fraction, observable as a lattice misorientation, which grows with increasing stress and strain. Misorientations are less pronounced in pyroxene than in plagioclase (which is both less coherent and strongly anisometric). Phenocrysts which contain brittle fractures show crystal-plastic deformation in the intact segments. Apparently, crystal plasticity plays a significant role in strain accommodation under volcanic conditions. Thus the viscous-brittle transition during magma ascent may incorporate a regime of crystal-plastic deformation, the remains of which may be used as a strain marker. With higher crystal fraction internal misorientations are larger, a phenomenon that will favour strain localisation, shear zone formation and plug flow.

Effects of crystallization and bubble nucleation on the elastic properties of magmas

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Seismic tomography of potentially hazardous volcanoes is a prime toolto assess the physical state of magma reservoirs. Processes occurring in the magma conduit or chamber, such as crystallization, bubble exsolution and growth, control the magma rheology, hence the style of volcanic eruptions. Elastic parameters of vapor-saturated, partially molten systems are thus providing fundamental information for the identification of such reservoirs under active and seemingly dormant volcanoes. This knowledge will potentially serve to assess their risk.

For this investigation we selected a chemically simplified melt analogous to andesite and trachyte, in the system CaO-Na2O-Al2O3-SiO2-H2O-CO2 (Picard et al, 2011), which undergoes plagioclase crystallization and bubble exsolution upon cooling and/or decompression. Seismic velocities of such a system are of prime importance as plagioclase is the principal microlite phase crystallizing during ascent-driven decompression (e.g. Cashman and Blundy, 2000).

Phase equilibria of the considered system are computed for various pressure, temperature and water contents using PerpleX (Connolly and Kerrick, 2002). These thermodynamic data are used to estimate variation of elastic moduli and density, and thus wave propagation velocities.

The theoretically computed values are compared to laboratory measurements of compressional and shear wave propagation velocities on synthetic melts. Ultrasonic velocities are simultaneously measured in a Paterson-type internally-heated gas pressure apparatus at confining pressures up to 300 MPa and temperatures up to 1000degC. Using the pulse transmission technique, the experiments are performed at frequencies ranging from 0.1 to 3 MHz. Variations in the elastic parameters induced by the presence of bubbles or dissolved water in super-cooled liquids and glasses are discussed for various pressures and temperatures. As the investigated melt undergoes plagioclase crystallization, a thermal plateau is maintained over a specific duration in order to measure the changes in seismic properties associated with in-situ crystallization of the magma. This maintained temperature varies between 800 and 1000degC depending on the amount of dissolved water in the system.

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Syn-eruptive oxidation of sulfides in the recent eruption products of the Sakurajima volcano

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Sulfide mineral occurs as inclusions and as isolated crystals in the recent eruption products of the Sakurajima volcano, Kyushu, Japan. In the pumices of the 1914–15 Plinian eruption, Pyrrhotite (Po) crystals have partly reacted to form spongy Fe oxides. A similar texture has been reported in some previous studies (Hattori, 1993), but the mineral phases and formation processes of the spongy Fe oxides have not been clarified. Our quantitative and compositional map analyses with electron probe microanalysis (EPMA) revealed that the spongy Fe oxides are mostly Ti-free magnetite (Mt), with a thin rim (<3 μm) of hematite on rare occasions. The spongy texture includes unreacted regions of Po, mesh-like pores, and S-rich spots, showing that it was formed by desulfidation of Po. Ti was scarcely detected, even in the outermost rim; this indicates that the reaction occurred syn-eruptively in the 1914–15 activity, since Ti-enrichment in the rim via diffusion is expected if equilibration with the surrounding melt proceeded. Thermodynamic calculations showed that Po is stable at log $fO_2 < \Delta NNO + 2$ at a pressure of 1 bar and magmatic temperature, which is 1–2 log units higher than the usual magmatic fO_2. These constraints on the timing and oxidation condition of desulfidation lead to the conclusion that the reaction was caused by oxidation of the magma in a shallow volcanic conduit, not in magma chamber processes. The pumice groundmass consists mostly of glass, indicating that the rate of the desulfidation reaction is faster than the decompression-induced crystallization of microlites in the andesitic magma. Therefore, the desulfidation reaction of Po has the potential to be used as a geospeedometer for very fast magma ascent in vigorous explosive eruptions.

Outgassing: influence on speed of magma fragmentation

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Predicting explosive eruptions remains an outstanding challenge. Knowledge of the controlling parameters and their relative importance is crucial in order to deepen our understanding of conduit flow dynamics and accurately model the processes involved. This experimental study sheds light on one important parameter, outgassing, and evaluates its influence on magma fragmentation behavior. We perform fragmentation experiments based on the shock tube theory at room temperature on natural pyroclastic material with a connected porosity ranging from 15% to 78%. For each sample series, we determine the initial pressure (P) required to initiate magma fragmentation (fragmentation threshold, P_{th}). Furthermore, we measure the permeability of each sample for $P<P_{th}$ and the fragmentation speed for $P>P_{th}$. A significant loss of initial pressure, caused by outgassing in samples with permeability $\geq$ 1e-12 m^2, is observed within the fragmentation time scale (a few milliseconds). The samples are classified into: (a) dome/conduit wall rocks and (b) pumice/scoria. Substantial outgassing during fragmentation leads to higher fragmentation thresholds. Experimental fragmentation speeds are significantly higher than the modeled fragmentation speeds for high-permeability dome/conduit wall rocks, but lower, for high-permeability pumices. Experimental fragmentation speeds for low-permeability dome/conduit wall rocks and low-permeability pumice/scoria are as expected. We also find that low-porosity, low-permeability, altered dome/conduit wall rocks fragment at significantly higher speeds than expected. Because fragmentation threshold and fragmentation speed are among the determining parameters for the initiation, sustainment and cessation of an eruption, outgassing should be considered in the modeling of magma fragmentation dynamics.

Temporal cycles in glass composition within volcanic ash from Showa Crater, Sakurajima volcano, southern Kyushu, Japan

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Sakurajima in southern Kyushu, Japan, is one of the most active volcanoes in the world. Sakurajima volcano erupted from Showa Crater in June 2006 after a hiatus in magmatic activity of 58 years. We have investigated petrologically the volcanic ash samples erupted from Showa Crater from January 2011 to May 2012. Juvenile clasts within the samples studied are composed of volcanic fragments and orthopyroxene, clinopyroxene, plagioclase, and Fe-oxide phenocrysts. The groundmass in rock fragments is characterized by glass, pigeonite, augite, plagioclase, and Fe-oxides. The volcanic glass within groundmass have compositions of SiO_2 = 67.8-79.7 wt.%, Al_2O_3 = 10.3-14.2 wt.%, FeO = 0.8-7.2 wt.%, CaO = 0.4-3.6 wt.%, Na_2O = 2.3-4.2 wt.%, and K_2O = 2.1-5.5 wt.%, with SiO_2 concentrations showing negative correlations with TiO_2, Al_2O_3, FeO, and CaO, and positive correlations with K_2O. Compositional cycles were observed in the eruption sequence from January 2011 to May 2012, with these cyclical changes being most readily apparent in changing SiO_2 concentrations. Early parts of a cycle produce volcanic ash with high SiO_2 concentrations (77-79 wt.%), and volcanic ash SiO_2 concentrations show a gradual decrease during subsequent parts of a cycle. Plagioclase anorthite (An) contents vary widely between An39 and An82, even within the same clasts, and An contents generally increase between January 2011 and May 2012. These results indicate that the compositions of Sakurajima volcanic glass fluctuated in approximately 100-day cycles between January 2011 and May 2012; the variations within each cycle can be explained by fractional crystallization of microcrystals, indicating that this fractionation occurred during magma ascent within Sakurajima volcano.

Syn-Plinian vigorous lava fountain in andesitic volcanoes: Case study of the Sakurajima 1914 and 1779 eruptions and the Asama 1783 eruption, Japan

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Concrete examples of complex behaviors of erupting magma during explosive eruption will be reported on the basis of geological observations. The eruptive products of the Sakurajima 1914 and 1779 eruptions and the Asama 1783 eruption include evidence of a large-scale deposition of pyroclastic materials in the proximal areas during these Plinian eruptions and suggest syn-Plinian lava fountaining.

The geology, eruptive sequence, and eruption styles have been investigated for the above three eruptions (e.g. Yasui and Koyaguchi, 2004, Yasui et al., 2013). The initial Plinian eruption occurred from flank fissures on two sides of Sakurajima volcano in 1914 and lasted for about 36 hours (Stage 1). It was followed by the outflow of lava (Stages 2 and 3). The 1779 eruption followed a similar sequence as the 1914 erupiton. Old drawings and photographs of these eruptions show that a large amount of pyroclastic materials fell from the Plinian column in the proximal area. Pyroclastic cones are recognized along the fissures on the upper to middle flank slopes. Thus, the cones were considered to have formed simultaneously with the Plinian eruptions. Extensive clastogenic lava flows are also recognized on the slope. These cones and lava flows are composed of welded pyroclastic materials and are characterized by eutaxitic textures and abundant highly broken crystals.

In the case of the Asama 1783 eruption, the activity culminated in a climactic, explosive eruption after the intermittent Vulcanian eruptions of about three months. The eruptive style of the climactic stage of the Asama 1783 eruption is quite similar to that of Stage 1 of the Sakurajima 1914 and 1779 eruptions.

These eruptions have the common features of the formation of proximal cones and generation of clastogenic flows as well as dispersal of the pumice fall in the distal areas. Concerning the Asama 1783 climactic eruption, the volume of pyroclastic materials that fell onto the proximal area is estimated to be 20 times as large as that entrained in the Plinian column. This indicates that these eruptions have similar aspects to the high fountaining with minor tephra observed at Kilauea and Etna. The coexistence of a Plinian column and lava fountain indicates a complex behavior of erupting magma in the conduit. Annular, misty flow in the conduit may be a possible explanation in the case of the Asama 1783 eruption. That is, a gas-rich center is surrounded by a pyroclasts-rich lining and a Plinian column may originate from the center part. In the cases of the eruptions in Sakurajima, the progress from an explosive eruption at a higher flank in Stage 1 to the effusion of lava at a lower flank in Stage 2 could be explained by the propagation of a radial dyke. The condition of misty flow in the dyke system may be similar to that in Asama 1783 eruption.

Repose periods in cyclic Vulcanian activity: Textures and timescales of shallow magma densification

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Degassing and densification are often linked in conceptual models of shallow magma conduits. Cyclic Vulcanian eruptions are associated with inflation and deflation and commonly interpreted as periods of gas pressurisation and depressurisation in partially degassed plugs. Inflation and deflation could be explained by changes in pore-volume in cracks or bubbles in or beneath this plug. However, the specific mechanism by which this occurs and the timescales over which pore-networks can collapse remain poorly constrained. To investigate a densification scenario we present results from experiments using pumice from the February 2010 partial collapse of Soufrière Hills volcano (SHV). We measured the change in volume and the pore network by helium pycnometry, P and S wave velocities and permeability. We used X-ray computed tomography and optical microscopy to compare the 3D and 2D textural evolution of experimentally deformed samples with naturally deformed and dense samples from the same eruption. Sample core volume, porosity and texture were measured and assessed before and after experiments. We heated samples under atmospheric pressure conditions at 2 $^{\circ}$C.min^{-1} and 20 $^{\circ}$C.min^{-1} to isotherms of 860 $^{\circ}$C, 900 $^{\circ}$C and 940 $^{\circ}$C for intervals up to 8 hours before cooling. Over an 8 hour timescale relevant to SHV cyclicity, samples show a $\leq$ 54% volume loss. For a given peak temperature, samples with initial total porosities of 80-84% reduce in volume an order of magnitude more quickly than samples with an initial total porosity 70-74%. Using thermo-gravimetric analysis (TGA) we confirm that the total volatile content is $\leq$ 0.16 wt.% and thus the de-volatilisation effect on melt viscosity does not contribute significantly to the collapse rate. Samples of similar porosity but different aspect ratios collapse proportionally, leading to the exclusion of gravity as the significant mechanism driving densification in our experiments. Consequently, we propose that surface tension acts to increase pore connectivity and reduce internal surface area. We show that the initial rate of volume loss can be correlated with the initial connected pore volume and the experimental temperature. Therefore we propose that for a given melt composition the collapse under static atmospheric conditions can be estimated from the initial connected porosity. In a volcanic context, the pore and confining pressures modify the effective pressure, thus the dynamics. Our experiments provide a constraint of the timescale and resultant textures during the collapse of bubble-bearing magma at temperature conditions relevant to SHV following explosive eruptions.

Frictional control on spine growth at Mt. Unzen, Japan

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The 1991-1995 eruption at Mt. Unzen was characterised by the growth of 13 lava lobes. The onset (May 1991) and end (Oct. 1994) of the dome-building phase was punctuated by the extrusion of spines; the ultimate period of spine extrusion was accompanied by rhythmic seismic activity occurring as vigorous high-frequency swarms at <0.5km depth every 40-60 hours during the course of spine erection. Exogenic spine extrusion requires the seismogenic failure of magma and we infer the seismic swarms to represent discreet spine extrusion events, reaching up to metres of slip.

Frictional properties of magma ascent and spine growth were modelled through high-velocity rotary shear experiments on dome rocks from Mt. Unzen. These were conducted on a range of slip velocities (0.1-1.5m/s), axial load (0.4-5MPa) and slip distance (<20m). During slip at low axial load (<1Mpa) rock-rock friction took place, achieving a low friction coefficient in agreement with Byerlee's rule. Slip at higher axial load ($\geq$1MPa) induced melting at a mechanical work threshold; higher slip velocities led to increased melt productivity with a diminishing control on shear resistance at the slip zone. This relationship is accentuated with increasing load, which shows that the rheology of frictional melt induces slip dynamics which do not abide to Byerlee's rule. During frictional melting the characteristic mechanical response showed a progressive increase in shear resistance, peaking at a point when the melt layer extended across the slip zone. Lubrication of the frictional plane caused a decrease in shear stress to a steady state. We monitored heating up to 1800℃/s and stabilisation at ca.1200℃ during steady state. We note that the total slip required to undergo frictional melting diminishes with axial stress and slip velocity. The shear resistance of the frictional melt (at steady state) is proportional with the axial load, yet dependent on slip rate, which suggests that the rheological control on slip may be that of a non-Newtonian liquid.

This study concludes that frictional melting changes the mechanical properties of rocks at a fault surface and thus, the rheology driving dome extrusion may not be derived directly from the dome material itself. We envisage that seismogenic events during spine growth at Mt. Unzen may have been accompanied and controlled by frictional melting in the upper conduit.

Cristobalite in volcanic domes: crystallisation of a meta-stable mineral

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Cristobalite is a high-temperature, low-pressure (>1470 °C, 1 atm) crystalline silica polymorph that can persist in ambient conditions as a meta-stable mineral. It crystallises in volcanic domes through devitrification of groundmass glass and deposition from silica-saturated vapours. However, active dome environments are typically 800-900 °C, and within the stability field of the crystalline silica polymorph tridymite; this begs the question: why does cristobalite crystallise preferentially?

The nature and mode of formation of cristobalite in lava domes was investigated through analysis of 45 dome rock samples collected from 6 different dome-forming volcanoes worldwide (Colima, Merapi, Mount St Helens, Santiaguito, Soufrière Hills and Unzen). Textural (SEM imaging), compositional (EDS, WDS, CL) and structural (CL, Raman spectroscopy) analyses were combined to provide a detailed description of the physicochemical properties of cristobalite in dome rock and revealed no volcano-specific differences. Electron microprobe was used to quantify compositional purity (i.e., deviation from pure SiO_2), and showed that cristobalite contains up to 4 wt. % aluminium. In general, devitrification cristobalite contains more aluminium than vapour phase cristobalite, likely due to the local abundance of Al within glass and the high diffusivity of charge-balancing cations (e.g., Na). X-ray diffraction and differential scanning calorimetry analyses show that cation substitutions result in a disordered crystal with a low enthalpy of fusion.

We have determined experimentally that cristobalite can form below its stability field, and at dome-relevant temperatures (<1000 °C), from amorphous silica. In these experiments, doping with aluminium favours cristobalite formation, and low sintering temperatures result in poorly-ordered crystals. Although further experiments are required to set these results within the context of the complex dome environment, we rationalise the crystallisation of meta-stable cristobalite below its stability field in all domes studied through the structural incorporation of aluminium and sodium. We further suggest that the presence of these interstitial ions physically bolsters the crystal structure, preventing the immediate reconstructive phase transformation to quartz. Constraining the mechanism for cristobalite crystallisation allows us to define the origin and physicochemical properties of the crystalline silica hazard in volcanic ash to most effectively aid the risk mitigation work of disaster managers globally.

Rheology of crystallizing lava: an experimental approach

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The viscosity of magmas is a key parameter in magma transport processes and volcanic eruptions. In nature, magmas are transient. Changes in P-T conditions force the magma to chemically and physically evolve, resolving a transient viscosity of the melt, overprinted by the complex rheological effects of the suspended fraction (crystals and bubbles). Such a dynamic understanding of transient rheology escapes our ability to fully assess the extent of volcanic hazards (e.g., lava flow reach out). To date, rheological studies provide a static view on individual contributions (e.g., chemical composition of the interstitial liquid vs physical effects of the suspended phases), without consideration of the feedback involved in the thermodynamic process underlying the evolution of the magmatic system. Alternatively, thermodynamic calculators provide a static view of mineral assemblage equilibrium, disregarding kinetic information on the physical evolution of the system during crystallization. Here, we assess the adequacy of combining rheological, petrologic and thermodynamic models in a transient system (such as lava flow dynamics) by comparing their outcome to dynamic rheological experiments on crystallizing and flowing natural melts with various (andesitic to basaltic) compositions. We optimized previous experimental methods for the concentric cylinder apparatus to measure the dynamic apparent viscosity of a magmatic suspension undergoing cooling and crystallization. The spindle is left in situ during quenching of the experimental products, to preserve the complete developed texture of the sample. Experiments are carried out in air or under controlled oxygen fugacity in order to avoid extensive oxide crystallization. Below the liquidus we record a transient evolution of the system; when crystals nucleate and when crystals grow. Thermodynamic equilibration is then reached after some hours. With each further cooling increment equally complex rheological response (overprint by non-Newtonian behavior) is observed. Quantification of the evolving mineralogical assemblage as well as the crystal fraction and distribution reveal that the steady state flow conditions are reached upon completion of crystallization at equilibrium (under a given T increments). Comparatively, the apparent viscosity at each investigated temperature is calculated as a function of the crystallization sequences (via MELTS), the residual liquid composition (via GRD model) and the characteristics of the solid fraction, presenting the discrepancies of employing static models in a dynamic system.

Investigating the collapse and inflation of erupting lava domes

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Actively growing lava domes can produce devastating block and ash flows from collapse of parts of the dome. These pyroclastic flows contain large blocks of rhyolitic lava of varying densities. The viscosity, volatile content and permeability of the lava control whether decompression associated with collapse will induce vesiculation in the clasts in the block and ash flow and the remaining lava in the collapse scar of the dome. A feature observed in many block and ash flow deposits are breadcrust bombs; rhyolitic lava that has inflated after collapse of the dome to produce a highly vesicular clast with a distinctive cracked surface.

The AD1315 Kaharoa eruption of Tarawera Volcano, New Zealand, produced 3 large, rhyolitic lava domes along with significant block and ash flow deposits on the surrounding plains. The domes at Tarawera have a vesicular and highly sheared solid carapace surrounding a denser, similarly sheared, interior. However, on one of these domes, Ruawahia Dome, we have found highly vesicular and large slabs of breadcrusting on the outer edge of the dome that correspond to the breadcrust textures observed in the block and ash flows. These vesicular zones are texturally distinct with large (up to 5mm) spherical (not sheared) vesicles. We theorise that the spherical nature of the bubbles suggests that the lava vesiculated in situ, following the cessation of shearing and movement of the lava. We propose that a collapse may expose the hot, dense interior of the dome, which will respond like the breadcrust bombs and vesiculate, inflating and partially erasing evidence of the collapse event.

To test this, we heat (750°C) dense lava dome material in an autoclave and vary the steam pressure from 0-5 MPa. In a series of experiments, we reduce the pressure at differing rates and compare the textural evolution of each sample. Porosity, permeability and textural analysis are performed on each sample post inflation, and we compare these textures to the breadcrust textures found in block and ash flows. Using the experimental data and extent of the vesiculated outcrops from mapping on Tarawera, we constrain conditions for in situ vesiculation of the dome during a collapse event. We use this to propose limits on the timeframe, temperature and pressure conditions of dome collapse events. We discuss the implications of this mechanism to erase collapse events from the morphology of the domes.

Interaction between rhyolitic lava flow and unconsolidated sediments, the Membo volcano, Kozushima Island, Japan: an implication for silicic phreatomagmatism

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The rhyolitic lava flow of the 30-40 ka Membo volcano located at the southern Kozushima Island interacted with its subjacent unconsolidated deposit, leading to phreatomagmatic explosions. The lava flow, 150 m in thickness and 0.2 km3 in volume, is elliptically distributed on the slope inclined at 5-6 degrees southwestward. The lava whose base is not visible above sea level comprises basal breccia zone, massive lava zone and pumiceous breccia zone from the bottom. Basal breccia zone comprises lava blocks cut by a number of minor faults and welded, ash-sized matrix, which suggests that brittle fracturing of highly viscous melt was caused by accumulation of shear stress due to flowage of the lava. Massive lava zone accounting for the large fraction of the lava represents flow-banded, intact rhyolite. Pumiceous breccia zone comprises moderately to highly vesiculated lava blocks.

At Senryoike located at the southwestern edge of the lava, siltstone intrudes empty spaces of the basal breccia zone, forming the peperite zone. The siltstone comprises well-sorted crystal splinters, which are perhaps derived from the substrate. Some clastic dikes, 0.1-5 m in width, are almost vertically developed from the peperite zone and penetrate into massive lava zone. These dikes comprise lava blocks and ash-sized fragments of both lava and siltstone. Dip and strike of these dikes are concordant with that of minor faults developed in the basal breccia zone. Formation processes of the Senryoike outcrop are interpreted as follows. Brittle failure of basal part of the lava prompts fluidization of the substrate sediments due to the rapid heat transfer from lava to sediments and the decompression by roof rock failure, which results in coarse mingling of lava and sediments. The local equilibrium between steam and water is formed in the peperite zone. Further faulting of lava triggers destruction of the equilibrium condition, leading to sudden decompression and following explosive expansion of the water. Clastic dikes in the lava are the resultants.

This series of processes is plausible for the model of phreatomagmatic explosions due to interactions between degassed, highly viscous magma and unconsolidated sediments. Thus, auto-brecciation of magma not only facilitates mingling between silicic magma and unconsolidated sediments but also can trigger phreatomagmatic explosions.

The role of confining pressure in submarine silicic effusive eruptions

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Our understanding of submarine volcanism is in its infancy with respect to subaerial eruption processes. Two fundamental differences between eruptions in seawater compared to those on land are that (1) eruptions occur at higher confining pressures, and (2) in a seawater medium which has a higher heat capacity, density and viscosity than air.

A vital yet unresolved first-order question is how degassing under conditions of high confining pressure modulates processes of silicic magma degassing during ascent and fragmentation in the conduit. Confining pressure will influence the degassing behaviour, particularly the rates of exsolution of CO2 and H2O- volatile species that that drive volcanic eruptions.

We use clasts collected from two edifices of Sumisu volcanic complex, Izu-Bonin Arc, Japan, where compositionally identical magma was erupted at different water depths. Thee samples were collected from dome carapace at 1300 and 945 meters below sea level. Microtextural analysis has revealed only slight differences between pumice carapace erupted at different depths, however significant variance from subaerial counterparts.

Our results from the deep water domes show i) relatively homogeneous textures with a dominance of round bubbles; iii) highly sheared zones adjacent to highly vesicular expanded zones; iii) bubble number densities equivalent to subaerial sub-plinian eruptions. The dominance of round bubbles, and high porosities and bubble number densities of these deep dome samples vary significantly from subaerial counterparts. Our preliminary observations of pumice microtextures would suggest that confining pressure reduced volatile exsolution to a degree that magma viscosities still allowed for bubble relaxation. Our quantitative data suggest that heterogeneous nucleation could continue to relatively high in the conduit, however, high permeability of the system must have played a dominant role during ascent.