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Coupled effect of magma degassing and rheology on silicic volcanism

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ABSTRACT

Explosive volcanism such as the 1991 Mt. Pinatubo, Philippines, and the 2008 Mt. Chaitén, Chile, eruptions is caused by violent vesiculation of hydrous magma. However, gas may efficiently separate from magma owing to the enhancement of gas permeability by shear deformation of magma flowing in a volcanic conduit. This makes it difficult to maintain the driving force of explosive volcanism although explosive volcanism is actually common. Here, we propose that shear localization in a volcanic conduit controls the eruption style and explosivity based on deformation experiments of vesicular magma linked with synchrotron radiation X-ray radiography and computed tomography. We observed, for the first time in situ, that the shear localization caused magma fracturing and formed a slip plane, and thus inhibited deformation and outgassing elsewhere. We also observed the compaction of vesicular magma into a dense "lava" as a result of outgassing when shear localization did not occur. In a natural setting, shear localizes along the edges of a volcanic conduit, where the strain rate is high, causing a highly permeable fracturing layer to form at the conduit's edge and leaving less-sheared and less-outgassed magma at its center. The less-outgassed magma in the center may ascend rapidly and cause explosive volcanism. Non-explosive lava effusion may occur only when shear localization does not occur effectively. This new view explains the rapid ascent of viscous magma and the formation of pyroclasts with contrasting vesicularity (pyroclastic obsidian and highly vesiculated pumice).

1. Introduction

Silicic volcanism ranges from explosive Plinian eruptions to lava effusions. The eruption style and explosivity are thought to depend on whether outgassing from the magma occurs efficiently during its ascent (Eichelberger et al., 1986; Jaupart and Allègre, 1991; Woods and Koyaguchi, 1994; Melnik and Sparks, 1999; Gonnermann and Manga, 2003). If outgassing is effective, magma vesicularity remains low, and poorly vesiculated lava erupts effusively onto the Earth's surface (Nakada et al., 1999; Voight et al., 1999; Iverson et al., 2006). If outgassing is ineffective, the magma vesiculates violently, leading to fragmentation and explosive eruptions (Papale, 1999; Zhang, 1999; Castro and Dingwell, 2009). Permeable gas transport through connected bubbles is an efficient degassing mechanism for highly viscous silicic magma because the buoyant migration of individual bubbles is negligible in this type of magma (Sparks, 2003). At low porosity, the bubbles generally tend to remain spherical owing to their surface tension, and thus are isolated and poorly interconnected; however, shear deformation causes elongation and coalescence of the bubbles, resulting in a sufficient increase in the gas permeability for efficient degassing to occur (Okumura et al., 2009; Caricchi et al., 2011). Degassing by this mechanism is efficient in flowing magmas, even in those with a low vesicularity. For example, at a depth of a few kilometers, the gas permeability of flowing sheared rhyolite with a water content of 5 wt% is more than $\sim 10^{-12}$ m^2 (Okumura et al., 2009) and the gas flow velocity relative to the magma body calculated on the basis of Darcy's law is $>10^{-2}$ m s^{-1}. This is high enough to induce efficient degassing during the timescale of magma ascent with the velocity of $>10^{-2}$ m s^{-1} for explosive eruptions (Liu et al., 2007; Castro and Dingwell, 2009) and 10^{-4}–10^{-1} m s^{-1} for effusive eruptions (Rutherford and Hill, 1993; Noguchi et al., 2008). In contrast, the gas permeability of magma without shear deformation is a few to several orders of magnitude lower than the gas permeability of flowing magma with shear deformation (Takeuchi et al., 2009; Okumura et al., 2012).

Since magma cannot avoid shear deformation as long as it behaves like a Newtonian fluid as it ascends in the conduit, there must be some unknown mechanism that suppresses the shear deformation of magma when explosive eruptions occur. A possible explanation is that non-Newtonian behavior of bubbly magma leads to the localization of shear deformation, allowing the dominant part of the magma to ascend without shear deformation; consequently,

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the rate of degassing during the ascent is low. To test this hypothesis, we experimentally simulated flowing magma and investigated the relationship between degassing and magma rheology.

2. Experiments

2.1. Experimental system for in situ observation of magma deformation

We simulated flowing magma experimentally in an originally developed high temperature–pressure deformation apparatus (HTP-DA) and observed magma deformation in situ using synchrotron radiation X-ray (BL20B2 of SPring-8 in Japan). A schematic illustration of the deformation apparatus is shown in Fig. 1. In this apparatus, a sample placed in a graphite cylinder is deformed by rotating the upper piston, which is connected to a servomotor. The graphite cylinder is encased in an Inconel alloy 600 cylinder. The sample in the graphite cylinder is heated using cartridge heaters inserted into the Inconel alloy cylinder. The X-rays are transmitted through a hole, which is 10 mm in diameter, on the side of the Inconel alloy cylinder. The stainless steel case and insulator, which also have a 10-mm diameter hole, cover the Inconel alloy block. Thus, the X-ray passes only through the graphite and the sample. An N-type thermocouple is set next to the cartridge heater for temperature control. The temperature of the sample is measured using a K-type thermocouple inserted into the side of the sample through the circular hole.

We used X-ray radiography and fast X-ray computed microtomography (X-ray CT) to observe the evolution of the three dimensional (3-D) microstructure of magma at high temperatures and pressures. The X-ray system is briefly summarized here (Uesugi et al., 2010). The radiation is monochromatized with a crystal monochromator using Si (111) reflection. The X-ray detector consists of a beam monitor and an electron multiplying CCD camera. The effective pixel size of the X-ray detector is 4.9 μm × 4.9 μm, and the image has dimensions of 1000 × 1000 pixels. For the fast micro X-ray CT, the image acquisition (timing of shutter opening, stage rotation, and image detection) is synchronized with a trigger pulse. Under the experimental conditions used in this study (900 projections at an X-ray energy of 25 keV and an exposure time of 40 or 60 ms), the measurement time is about 90 s. It should be noted that the observation time is only 90 s; however, the deformation apparatus has to be moved twice to acquire the background images, and this process also requires about 90 s. Therefore, one CT scan requires a total of about 180 s.

The 3-D image is reconstructed from the transmission images acquired at different angles. To obtain these images, the deformation apparatus is rotated using a high-precision theta stage. On the stage, the graphite cylinder and sample are rotated together with the pistons, rotational motor, and load frames. Meanwhile, the Inconel alloy cylinder, insulator, and stainless case with the circular hole for X-ray transmission remain stationary; these are fixed by two rods that are connected to the stationary stage during the rotation of the deformation apparatus. The two rods set at a 45° position are used alternately, because the two load frames that support the internal sample pressure cut across the rods. The 3-D image is reconstructed on the basis of the transmission images, but the 65–66 images corresponding to angles of 13–13.2° cannot be obtained because the load frame in the deformation apparatus obstructs the transmission images. For these images, we assume that no signal was available. The reconstruction of the 3-D images is performed on a computer using graphics processing units (GPUs) and a programming interface (CUDA), through which very short reconstruction times (a few minutes for the images in this study) can be achieved (Uesugi et al., 2010).

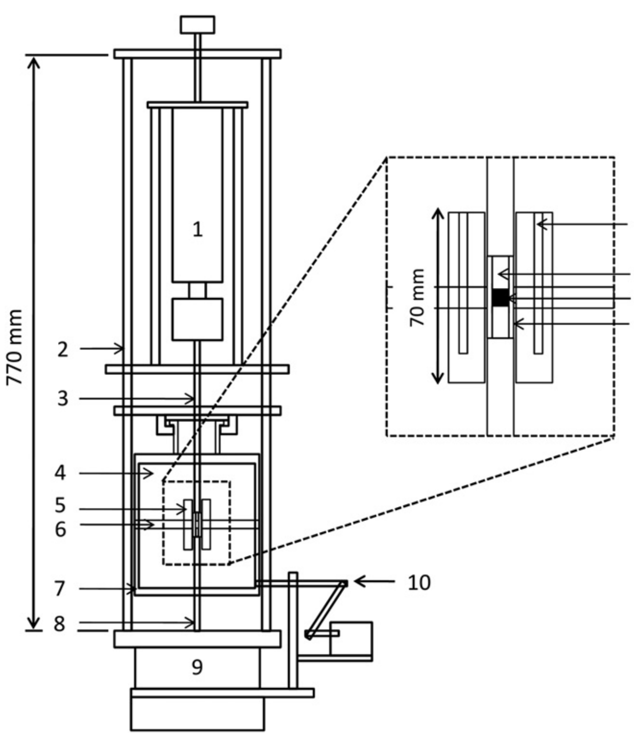

Fig. 1. A schematic illustration of the newly designed high temperature–pressure deformation apparatus (HTP-DA). (1) Servomotor, (2) load frame, (3) upper piston, (4) insulation, (5) inconel alloy cylinder, (6) hole for X-ray transmission, (7) stainless case, (8) lower piston, (9) theta stage, (10) fixed rod, (11) cartridge heater, (12) Piston, (13) sample, and (14) graphite cylinder.

2.2. Viscosity measurement using HPT-DA

The relationship between magma viscosity and the torque necessary to deform the magma in HPT-DA was calibrated using a synthesized standard glass (STD) (SiO_2=73.5, Na_2O=8.1, K_2O=6.7, and CaO=11.6 in wt%), which has the same chemical composition as soda-lime–silica (NBS standard reference material 710) glass. The STD was synthesized by mixing the oxides and then melting them in a Pt crucible at a temperature of ~1500 °C. On melting, glass fibers were formed, and then the viscosity of the melt was measured at temperatures of 556–665 °C using a fiber elongation method (Taniguchi, 1992). The measured viscosity is identical to that of NBS710 within 0.5 log units over the viscosity range of 10^8–10^{12} Pa s. Because the viscosities of STD and NBS710 show good agreement, we assume that the viscosity of STD at low and high temperatures is the same as that of NBS710 and can thus be calculated from the viscosity model of NBS710.

To measure the torque necessary to deform STD at a given temperature, i.e., a given viscosity, discs with a diameter of ~5 mm and a few to several millimeters thick were cored from the STD and heated in the HPT-DA to temperatures of 730–800 °C, which corresponds to the viscosities of 2.0×10^5 to 3.2×10^6 Pa s. The torque was measured during the deformation at a rotational rate of 0.5 rpm. After modification of the torque, by normalized by the sample thickness that was directly measured using in situ X-ray radiography, the relationship between torque and melt viscosity (calibration line) was obtained. This calibration line was used to calculate the viscosity of samples from the torque measured in HPT-DA.

2.3. In situ observation of magma deformation

In this experiment, an obsidian core (~5 mm in diameter and 2–5 mm long; SiO_2=77 wt% and H_2O=0.5 wt%) was used as a