Microstructure of Bubbles in Flowing Magma

Since bubble growth and expansion in magmas are the driving forces of violent volcanic eruptions, the mechanism of degassing (outgassing) has been a central topic in volcanology. In the last two decades, the permeable gas-flow hypothesis has been widely accepted as an explanation of the degassing of viscous silicic magmas, in which bubbles scarcely rise in the time scale of eruptions. As magma ascends, the solubility of volatiles decreases and the bubbles expand due to decompression, resulting in an increase in magma vesicularity and the formation of foam. This foam should be highly permeable for effective degassing. A recent experimental study showed, however, that the simple decompression process yields very low permeability ($<10^{-16}$ m^2) until the vesicularity reaches *ca*. 70% (i.e., until the magma rises to a depth of a few hundred meters), because the melt films separating the bubbles remain unbroken and hinder the coalescence of bubbles [1]. Compared with the results of conduit flow modeling, this depth may be too shallow to result in nonexplosive eruptions. This suggests that an additional mechanism is necessary for vesiculated magmas to become permeable in deeper volcanic conduits. In this study, we experimentally investigated the effect of shear strain on the bubble microstructure and found that the interconnectivity of the bubbles is drastically enhanced by shear strain in flowing magmas.

We have performed a series of deformation experiments of vesiculated rhyolitic melts using an originally developed, torsion-type, high-temperature deformation apparatus [2,3]. Cylindrical obsidian samples (0.5 wt% water content) of *ca*. 4.7 mm in diameter were placed in a graphite container and sandwiched between the upper and lower pistons. The sample was then heated to 975°C in 50 minutes, kept at this temperature for 3 – 5 minutes for vesiculation, twisted by rotating the lower piston at 0.3 – 0.5 rpm for up to 10 rotations (R) and quenched. The vesicularity of the sample was increased from *ca*. 15 to 45% by adjusting the length of the obsidian cylinder in a fixed-volume container. The melt viscosity of the sample, the maximum shear strain and the strain rate in the experiments are 2.2×10^6 Pa·s, 30 and 0.025 s^{-1}, respectively, which are comparable to those under natural conditions. Three-dimensional images of the sheared samples were obtained by X-ray microtomography at beamline **BL20B2**. The photon energy and exposure time applied were 25 keV and 0.8 s, respectively, and 750 projections were obtained in each imaging. The images are composed of 1344×1344×1024 voxels of 4.34 μm^3. Geometrical analyses of the CT images were performed for the bubbles >10 μm using an algorithm similar to that described in Ikeda *et al*. (2000) [4]. The smaller bubbles may have been affected by relaxation during quenching.

The reconstructed 3D images of the experimentally obtained products are shown in Fig. 1. With increasing strain, the coalescence of the bubbles proceeds as well as elongation of each bubble. The strain rate does not affect the results significantly, as inferred from the large capillary number of the experimental sample. An interconnected tube-like structure was formed from the outside of the sample, at which shear strain is larger than inside the sample.

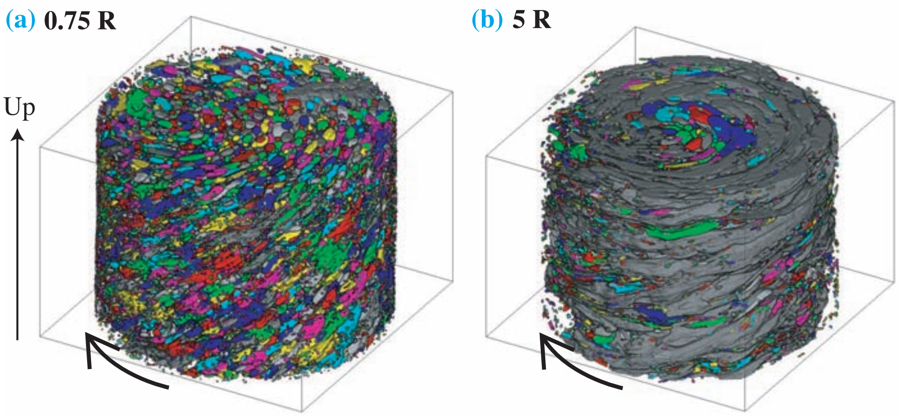

Fig. 1. 3D CT images of the samples undergoing **(a)** 0.75 and **(b)** 5 rotations (R) at 0.5 rpm. Neighboring bubbles that are not interconnected are colored differently. The gray bubble shows the largest interconnection.

The interconnectivity of the bubbles was quantified using a connectivity parameter, *C*, which is the ratio of the largest bubble volume to the total bubble volume [3]. *C* becomes unity when all the bubbles are interconnected and is potentially related to the permeability [5]. As shown in Fig. 2, *C* for the whole sample with >2.5 R begins to increase steeply at a critical vesicularity of 20 – 30% and reaches >0.8 at 40% vesicularity. The inner half of the same sample has a smaller *C* and a higher critical vesicularity than the whole sample, showing that the bubble connectivity increases with strain. The rhyolitic magma with 5 wt% initial water content achieves 40% vesicularity at a depth of *ca*. 1300 m, which is *ca*. 1000 m deeper than that in the case of isotropic vesiculation. These results suggest that the shear-induced networking of bubbles may provide a degassing pathway in deep volcanic conduits, and that the conduit geometry, which governs the shear strain, is an important factor in controlling the mode of volcanic eruption (Fig. 3).

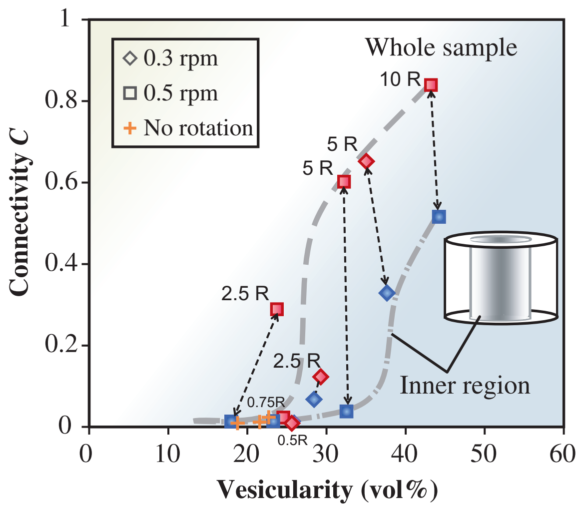

Fig. 2. The bubble connectivity starts to increase at a critical vesicularity of 20 – 30 vol% for the whole sample, whereas it is >35% for the inner region. The dashed arrows show the inner and whole regions for the same run.

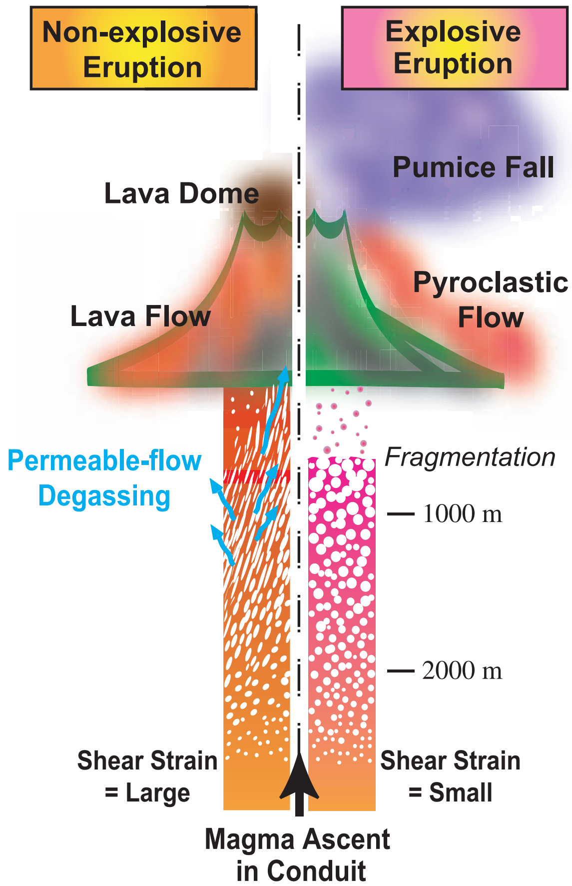

Fig. 3. A schematic diagram showing that non-explosive eruptions such as the formation of lava domes may result from permeable flow degassing through interconnected bubble networks in the flowing magma. The foamed magma under small shear strain has low permeability, which may result in fragmentation and explosive eruptions.

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