V080-008 Room: 304 Time: May 29 10:45-10:57

Viscoelastic effects on magma fragmentation in conduit flows

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Fragmentation of vesicular magma is one of the main processes governing explosive volcanism. So far two criteria have been proposed for magma fragmentation in volcanic conduit models. First, magma disrupts due to the instability of thin film of magma-foam when gas volume fraction exceeds a critical value (referred to as expansion fragmentation). Secondly, magma fragments when stress around bubbles exceeds a critical value (referred to as stress fragmentation). Recently, it has been suggested that viscoelastic nature of magma critically determines the behavior of fragmentation; brittle failure occurs when the strain rate is large enough for the magma to behave as an elastic material (i.e. when a condition of glass-transition is satisfied). However, because the viscoelastic nature of magma has not been explicitly taken into account in the conduit models, whether the glass-transition condition is satisfied has not been correctly evaluated in the models. For this reason, the concept of brittle failure is often confused with that of stress fragmentation in the literature.

We develop a coupled model for 1-dimensional conduit flow and bubble expansion to investigate fragmentation mechanisms of bubbly viscoelastic magmas. Gas-overpressure and hoop stress around each bubble are calculated by applying the cell model; a single bubble surrounded by a small shell of incompressible melt expands against viscoelastic resistance of the melt. We take the effects of the viscoelasticity into account by treating the magma as a Maxwell body. It is assumed that the magma fragments and the flow changes from bubbly flow to gas-particle dispersion when one of the above two criteria (i.e. that of expansion fragmentation or stress fragmentation) is satisfied.

Our numerical results and scaling analyses show that two dimensionless parameters control the fragmentation behavior; those are defined as A and B, here. The physical meaning of A is the ratio of the stress due to wall friction to the tensile strength of magma. This parameter primarily depends on magma viscosity; it increases as viscosity increases. The stress around bubbles grows during magma ascent under conditions where A is greater than unity. The parameter B is given by A squared times the ratio of the tensile strength to the rigidity of magma. The elastic term of Maxwell's constitutive equation is dominant when B is greater than normalized stress (stress normalized by the tensile strength of magma). Therefore, brittle fragmentation in the sense that the elastic term is dominant at the time of fragmentation occurs when B is greater than unity. Judging from recent experimental results that the values of tensile strength of silicate melts are 2 or 3 orders of magnitude smaller than those of rigidity, this condition is satisfied only when A is greater than 10.

On the basis of the above parameters, the criteria of magma fragmentation are summarized as follows. Expansion fragmentation of magma occurs in conduits when A is smaller than 1, while stress fragmentation occurs when A is greater than 1. Brittle fragmentation of magma occurs under conditions where A is much greater than 10. When A is between 1 and 10, the mode of fragmentation is stress fragmentation, but it is classified into ductile fragmentation rather than brittle one in the sense that a large viscous deformation is accompanied with the failure. It is suggested that the concepts of brittle fragmentation and stress fragmentation can be clearly distinguished by introducing a viscoelastic constitutive equation of magma in conduit models.