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Brittleness of fracture in flowing magma

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Understanding the transition from fluid-like response to solid-like response of flowing magma is essential for estimating the explosiveness of a volcanic eruption. Intuitively, this explosiveness is related to the brittleness of fracture. However, two essential problems remain for quantifying fracture of a flowing material like magma, which are: how to define a criterion for the initiation of fracture and how to measure the brittleness of that fracture process. Although currently there is great interest in exploring the mechanisms causing the non-Newtonian response of magma at high strain rates and their potential influence on fracture, quotations on this subject in the literature present a somewhat confused picture of the relationship between shear thinning and brittle fracture and the competing effects during heating of decreased brittleness due to viscosity reduction and increased brittleness due to increased strain rate. For a Maxwell viscoplastic model it is clear that the material response becomes more elastic as the total strain rate is increased. However, since steady-state response is characterized by no change in elasticity it is unclear whether the brittleness of fracture can be inferred by shear thinning measured at steady-state. The objective of this study is to present a quantitative measure β of brittleness of fracture and to eexamine these issues.

The parameter β represents the ratio of the rate of change of the elastic strain energy to the mechanical power. From the perspective of β, dependence of the brittle fracture of magma on stress, decompression rate, strain rate, and shear-thinning effects are reviewed. The experimental data for rapid decompression of analogous materials to bubbly magma have also been reexamined. In a previous study [Kameda et al.,2008], the observed transition from ductile expansion to brittle fragmentation was related to the ratio between the relaxation time and the decompression time, and the brittleness of fragmentation was quantified by the magnitude of this ratio after sufficient pressure reduction occurred. However, this quantification depends explicitly on the temporal profile of the decompression in the experiments and is not necessarily applicable to general cases. Here, it is shown that β exhibits a strong transition which correlates well with the observed transition of the fragmentation behaviors.

Moreover, β is shown to be useful in considering the effects of shear thinning and steady-flow conditions on brittle fracture. Statements in the literature which suggest that materials behave in a brittle manner at sufficiently high strain rate are correct. However, since these statements have not precisely quantified the notion of high strain rate, they are easy to misinterpret when considering the effect of shear thinning. Although shear thinning tends to increase the absolute magnitude of the total strain rate, it does not necessarily increase brittleness. Also, in principle, it is unlikely for brittle fracture to occur at steady-state flow. Cracking observed in laboratory experiments during steady flow of magma [Lavallee et al.,2007; Lavallee et al.,2008] may be attributed to small fluctuations with sufficiently high frequencies, which are required to satisfy the conditions for brittle fracture.