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Modeling the failure of magmatic foams with application to Stromboli volcano, Italy

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ABSTRACT

The failure of magmatic foams has been implicated as a fundamental process in eruptions occurring at open-conduit, basaltic volcanoes. In order to investigate the failure of magmatic foams we applied the fiber bundle model using global load sharing. The strengths of the fibers for the model were taken from bubble wall widths measured in four computer-simulated foams of low-porosity and from one very low-porosity and two high-porosity foams produced in the laboratory by heating hydrated basaltic glasses to 1200 °C. The relative strength of an individual fiber in the model was calculated from the square of a bubble wall's average width and absolute strengths of the foams were calculated based upon the correlation of the strength of one modeled foam with experimental data. The fiber bundle model is shown to successfully reproduce measured tensile strengths of porous volcanic rocks studied by other researchers and confirms previous findings of the primary importance of foam porosity, as well as the secondary importance of structural details that affect the number and size of bubble walls and permeability. Because of the success of the fiber bundle model in reproducing experimental foam failure, its results are compared to infrasonic measurements associated with bubbles at Stromboli (Italy) and demonstrate that within uncertainty the power-law exponents of the infrasonic energies and of the fiber bundle model energies are in agreement; both show a crossover from an exponent of 5/2 associated with the bursting of small bubbles in the infrasonic measurements to an exponent of 3/2 for normal Strombolian eruptions associated with infrasonic signals from meter-scale bubbles. The infrasonic signals for major explosions and a paroxysmal eruption at Stromboli fall near the extrapolation of the power law defined by the low-amplitude, bubble bursting events and are interpreted to reflect the bursting of multitudes of small bubbles, rather than a few large bubbles. The measurement of small-amplitude infrasonic events at Stromboli appears useful in predicting the recurrence interval of paroxysmal eruptions at this volcano and may also provide a tool that uses common, small-amplitude infrasonic events to constrain the frequency of larger eruptions at other volcanoes.

1. Introduction

Magmatic foams have been observed to play an important role during eruptions at active volcanoes. A foam perched on top of a magmatic column may be the only cap separating the magma chamber from the atmosphere. Or, a foam ascending through a magma conduit may be rapidly expanding due to decompression. If the foam fails due to breaching of the bubble walls as the internal pressure exceeds the external one, the pressure on the magma may instantaneously drop, resulting in further gas exsolution, bubble growth and eruption. Such foam disruption is believed to affect the nature of volcanic eruptions, influencing the frequency and intensity of eruptions (e.g., Proussevitch et al., 1993). The importance of magmatic foams has been observed at open vent volcanoes, such as Stromboli (Italy) where researchers have documented eruptive activity often occurring as intermittent explosions of magma due to the bursting of bubbles almost as wide as the entire conduit (Blackburn et al., 1976; Vergniolle and Brandeis, 1994, 1996; Vergniolle et al., 1996). A similar mechanism related to the build-up and collapse of foam is seen at Kilauea (Hawaii), where

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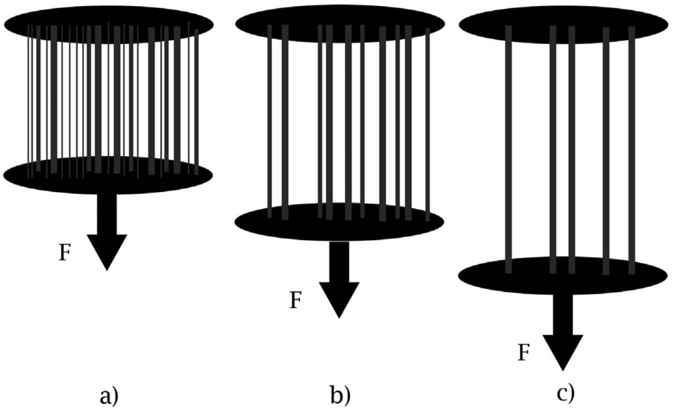

Fig. 1. Schematic representation of the evolution of a fiber bundle model as a load, F, is applied. a) The initial bundle. b) A possible state for the bundle after a failure event, where the weakest fibers have broken. c) Continued loading can either lead to a final state where the bundle is supported by its strongest fibers as shown here, or to catastrophic failure where all fibers fail.

fire fountaining propels lava clots hundreds of meters into the air (Jaupart and Vergniolle, 1988).

Numerous experiments and numerical simulations have been performed to investigate the formation of foams and the role they play in volcanic eruptions (e.g., Bai et al., 2008, 2010; Blower et al., 2001, 2002; Hurwitz and Navon, 1994; Jaupart and Vergniolle, 1989; Mangan et al., 2004; Stein and Spera, 1992; Zhang, 1999). These experiments demonstrated the importance of magmatic degassing and the formation of foams in the eruption process. The stability of foam was studied by Proussevitch et al. (1993) who found that melt expulsion from between bubbles causes thinning of bubble walls that leads to foam disruption. Understanding the failure of foams will improve our ability to explain and predict the occurrence and sizes of volcanic eruptions. This contribution details our use of a model of foam strength based upon statistical mechanics, the fiber bundle model, and its application to improve our understanding of the strength of magmatic foams and their failure at open-conduit volcanoes as exemplified by Stromboli.

2. Theory

2.1. Introduction to the fiber bundle model

The fiber bundle model is used to investigate the fracture and breakdown of disordered materials and is widely applied in both physics and engineering (Kun et al., 2007). The conceptual model consists of a bundle of N fibers, each characterized by its strength, attached to two parallel plates. To test the strength of the fiber bundle a force, F, is applied to the bundle, which may be considered as a load suspended from the bottom plate (Fig. 1). Much research has been done on extensions to the classical fiber bundle model in order to apply it to a particular problem (Kun et al., 2000; Pradhan, 2011; Raischel et al., 2008). These extensions are created by modifying one of the four main parts of the fiber bundle model: the failure law; the manner in which the load is shared; the distribution of failure thresholds; and, the time dependence of the strength (Kun et al., 2007). However, the choice of these properties is non-trivial because of their potential to greatly affect the simulations' outcomes (Kun et al., 2007).

The failure law is the response of a bundle subjected to load. In most models, the fibers are assumed to exhibit linearly elastic behavior until the point of failure where they irreversibly and instantaneously break (Kun et al., 2007). The load sharing function is the manner in which the load is redistributed among the remaining fibers in the bundle. The simplest type of load redistribution is global load sharing, which evenly distributes the load to the remaining fibers regardless of spatial location or fiber size (Pradhan et al., 2002). A second, more complex, type of load redistribution is local load sharing; when a fiber fails under local load sharing its load is redistributed to its intact nearest neighbors (Kun et al., 2000). Local load sharing takes into account the spatial distribution of the fibers within the bundle and creates areas with weaknesses and strengths, whereas global load sharing does not. The distribution of failure thresholds, i.e., the distribution of the strengths of fibers in the bundle, is defined by the investigator. The choice of an adequate distribution is made depending upon the process being modeled; the most frequently used distribution is a uniform one (e.g., Pradhan et al., 2002). The last aspect of the fiber bundle model is its time dependence. Fiber bundle models can be time independent, as in this study; in this case the model is characterized by having a constant failure threshold for all fibers during the entire duration of the simulation. Another type of time dependence uses failure thresholds that decrease as time progresses due to the applied load. This type of time dependence is useful for certain cases when studying material fatigue or creep rupture (Kun et al., 2007; Kovács et al., 2008). Because of their flexibility, failure analyses using the fiber bundle model are employed in multiple fields: physics, engineering, and Earth sciences; examples of their applications can be found in Kun et al. (2007), Kovács et al. (2008) and Pradhan et al. (2010).

3. Methods

3.1. Fiber bundle model applied to magmatic foams

In order to determine the strength of the samples we used the fiber bundle model described by Pradhan et al. (2002). This model was chosen because failure in both the fiber bundle model and magmatic foams is caused by tensional forces, for the fiber bundle model it is the applied force (load) to the bundle and for the foam it is bubble expansion through decompression (Sparks, 1978). Even though the fiber bundle model used in this study does not provide absolute values of the strength of materials, it provides a measure of relative strengths, which as we show below can be converted into absolute values of foam strengths, and these strengths are in good agreement with experimental measurements of porous volcanic rocks.

The model we apply does not contain any time dependence and uses an elastic constant of unity. Although intuitively it might be expected that both of these variables in a real foam may be related to the melt viscosity, current experiments on foam failure at temperatures from ambient to 950 °C demonstrate no significant effect of composition on the experimentally measured fragmentation of magmatic foams (Mueller et al., 2008; Spieler et al., 2004). Thus to first order it appears that we can use failure models that do not take into account differences in viscosities. This simplification of the model will be tested against the experimental data of Spieler et al. (2004) and Mueller et al. (2008) below. By ignoring time dependence in the model we lose any constraints on the rate of the failure process and are forced to consider that it occurs instantaneously. However, fragmentation studies demonstrate that once the critical conditions are reached, failure occurs almost instantaneously (Spieler et al., 2004; Mueller et al., 2008), thus lack of time in the model does not appear to be a serious limitation.

The chosen load redistribution algorithm was global load sharing. By using either global or local load sharing, we lose the details of possible spatial distribution effects, however local load sharing might affect the results more significantly by biasing spatial effects. Given the chaotic nature and the inherent disorder of the failure of bubble foams, global load sharing appears to be a more suitable