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SHORT SCIENTIFIC COMMUNICATION

Volcanic conduit failure as a trigger to magma fragmentation

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Abstract In the assessment of volcanic risk, it is often assumed that magma ascending at a slow rate will erupt effusively, whereas magma ascending at fast rate will lead to an explosive eruption. Mechanistically viewed, this assessment is supported by the notion that the viscoelastic nature of magma (i.e., the ability of magma to relax at an applied strain rate), linked via the gradient of flow pressure (related to discharge rate), controls the eruption style. In such an analysis, the physical interactions between the magma and the conduit wall are commonly, to a first order, neglected. Yet, during ascent, magma must force its way through the volcanic edifice/structure, whose presence and form may greatly affect the stress field through which the magma is trying to ascend. Here, we demonstrate that fracturing of the conduit wall via flow pressure releases an elastic shock resulting in fracturing of the viscous magma itself. We find that magma fragmentation occurred at strain rates seven orders of magnitude slower than theoretically anticipated from the applied axial strain rate. Our conclusion, that the discharge rate cannot provide a reliable indication of ascending magma rheology without knowledge of conduit wall stability, has important ramifications for volcanic hazard assessment. New numerical simulations are now needed in order to integrate magma/conduit interaction into eruption models.

Keywords Brittle failure · Eruption · Tuffisite · Hydraulic fracturing · Permeability

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Introduction

During periods of volcanic unrest, magma is transported to the surface through an evolving conduit, which, to propagate, must overcome the strength of the country rock (Gudmundsson and Brenner 2005). Upon nearing the surface, magma faces two choices: it may ascend slowly and (generally) erupt effusively or ascend quickly to erupt explosively (Woods and Koyaguchi 1994). This assessment is based on knowledge of the viscoelastic properties of magmas and their discharge rate, whereby the ability of magma to relax following application of stress controls the eruption style (Dingwell 1996). However, key processes of magma interaction with its conduit (Costa et al. 2009) are not understood and thus not considered in the balancing of forces used in this rheological analysis. Such information is important because during ascent, magma needs to force its way through the volcanic edifice, and this both greatly affects the stress field and creates conditions conducive for fracturing of the conduit wall (Chadwick et al. 1983). In the extreme, such overpressure can even jeopardize the stability of the volcanic edifice. This was exemplified on a large scale by the May 18, 1980, partial collapse of the Mount St. Helens' edifice, which triggered an explosive eruption. In

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what is typical for such scenarios, that explosion is usually interpreted in terms of magma pressurization (Spieler et al. 2003), with little consideration of the exact process by which the edifice failed.

Conduit fracturing experiments

We experimentally simulate mechanical magma/conduit interaction during magma ascent and fracturing of the conduit wall rock. Conduit fracturing involved uniaxial compression of a 20-mm-diameter cylinder of crystal-poor rhyolitic magma residing at 918°C within a 60-mm annular basaltic wall rock shell (see Fig. 1). These experiments are novel because in conventional rock mechanics, hydraulic fracturing has been studied at low temperatures on systems dominated by fluids (e.g., water, oil; Vinciguerra et al. 2004) with viscosities far lower than magmatic ones. In our experiments, fracturing of the wall rock was simulated by cyclically pressing a solid plug (of basalt) onto a viscous rhyolitic magma, thereby compressing the rhyolite and causing cyclical deformation at axial strain rates of 1.3×10^{-6} for 180 s and 3.2×10^{-5} s^{-1} for 30 s. During deformation, the load was monitored. The fractures were observed, in real time, via the released microseismicity, recorded as acoustic emissions (AEs), and post-experimentally imaged using high-resolution (30 μm) neutron computed tomography as well as optical microscopy.

These deformation experiments were characterized in their initial stages by cyclic stressing and relaxation of the magma and an absence of acoustic emissions, indicating viscous flow (see Fig. 1). [Note: very little stress initially accumulated, as the magma was not in contact with the shell, due to the narrow mismatch resulting from sample preparation.] As magma began to deform against the inner wall of the basalt rock shell, stress accumulated. Failure of the annular shell was accompanied by a brief, 126-ms burst in released AE energy at an applied stress of 16 MPa and was followed by a stress drop to 0 MPa.

Post-experimental optical analysis revealed the presence of two radially oriented extensional cracks along the entire length of the shell (see figure). Tomographic analysis of the fracture network revealed much more—namely, the extension of the radial cracks into the magma itself (see figure inset). Microscopic analysis showed the presence of a 5-mm-wide damage zone containing multiple dendritic extensional fractures at the interface between the rhyolite and the basalt. The fractures converged 1 mm inside the rhyolite. In the basalt, the fractures were not intruded by the dyking of magma (as the viscosity was too high, and the experiment was stopped before its occurrence), but they were partially filled by tuffisitic ash fragments.

Brittle failure of this magma, whose viscosity (η) at 918°C is $10^{8.3}$ Pa s, was not anticipated from the imposed axial strain rates ($<3.2\times10^{-5}$ s^{-1}). Using the Maxwell relation for viscoelastic relaxation time (Dingwell and Webb 1989)

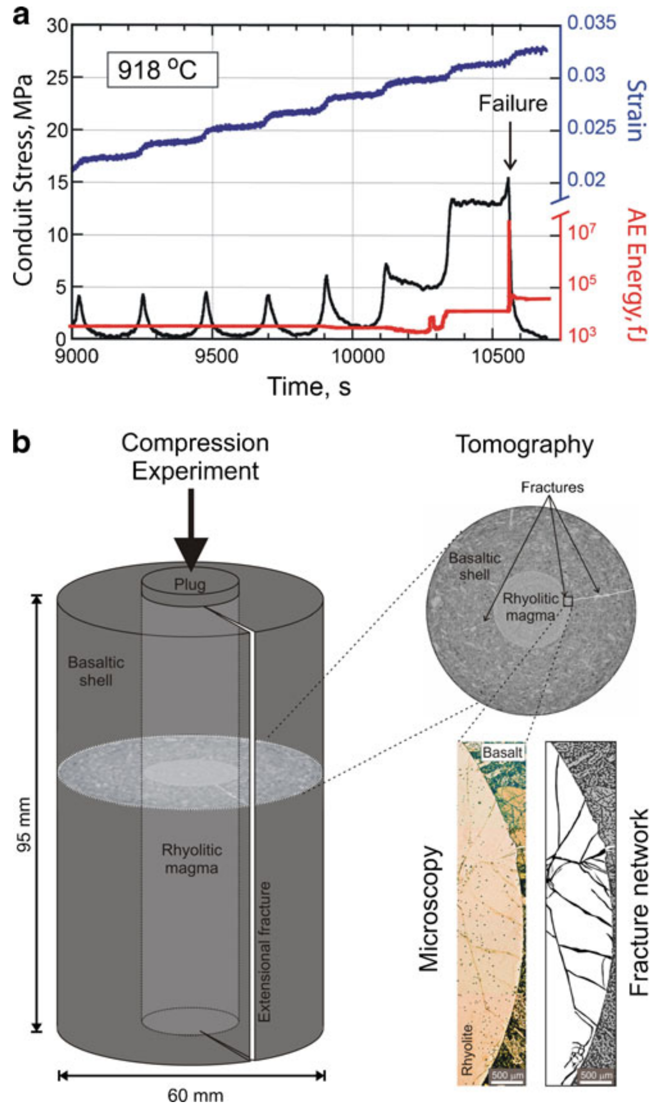

Fig. 1 Magma/conduit interaction experiment. The application of pressure onto a solid basaltic plug compressed a rhyolitic magma (*light gray*) against the solid inner shell of basalt (*dark gray*). Pressurization was achieved by cyclically stepping the strain rate between 1.3×10^{-6} for 180 s and 3.2×10^{-5} s^{-1} for 30 s. Cyclic deformation of the magma was monitored as an increase in stress followed by a period of relaxation. Hydraulic fracturing occurred at a peak stress of 16 MPa and was followed by an instantaneous stress drop. Hydraulic fractures propagated radially along the length of the sample and were internally imaged using neutron computer tomography as well as microscopy (provided with a sketch). A 5-mm-wide dendritic network of extensional fractures formed and penetrated 1 mm inside the rhyolitic melt

$$\tau = 10^{\,10/\eta} \quad (1)$$

our magma would be expected to fail at a strain rate (τ) of $10^{1.7}$ s^{-1}, which is more than six orders of magnitude faster than the axial strain rate at the time of failure. Thus, the source of the stress/strain-rate conditions that generated magma fracturing here must be sought elsewhere. We propose that stress which accumulated in the shell during compression was elastically released at failure, generating a tangential shock that locally fractured the magma. The opening of a 100-micron-wide extensional fracture within a 5-mm-wide damage zone would correlate to a near instantaneous strain of 0.02 (which is more than the total axial strain produced by the experiment). AE data show that the most energetic fracturing lasted 126 ms, which signifies that the tangential strain rate reached approximately $10^{-0.8}$ s^{-1}, which concurs with Dingwell and Webb's (1989) assessment that the onset of melt failure may take place at strain rates up to three orders of magnitude slower than that at the Maxwell viscoelastic limit.

Implications

The novel observation here—that conduit wall fracturing can cause magma failure—is potentially a critical one for volcanic hazard assessment. It implies that local deformation of the volcanic edifice may temporally subject magma (even under slow ascent rates) to local strain-rate peaks that may drive or sustain fragmentation. This finding suggests that knowledge of the rheology of ascending magma cannot be gained from assessment of the discharge rate alone, but strongly relies on the understanding of elastic stress and strain accumulated within the conduit walls. Whether failure of the wall rock and subsequent fragmentation of the magma would lead to formation of tuffisite and a permeable network, resulting in enhanced degassing and eruptive quiescence, or to catastrophic failure, serving as a trigger for explosive volcanic eruption, may then depend on the resulting decompression (Mueller et al. 2008). Both outcomes are possible. We conclude that the evaluation of volcanic stability requires an understanding of the response of the volcanic conduit wall rock to magmatic pressure and the potential for magma fragmentation in response to fracturing of wall rock in the conduit. We strongly recommend that numerical simulations be done to assess the likelihood of magma fracturing/fragmentation by conduit wall failure when evaluating volcanic stability.

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