Volcanic conduit failure as a trigger to magmatic 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 a magma to relax an applied strain rate) is linked via the gradient of flow pressure (related to discharge rate), which 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 found that magmatic fragmentation occurred at strain rates seven orders of magnitude slower than theoretically anticipated from the applied strain rate. The conclusion that the discharge rate cannot provide a reliable appraisal of ascending magma rheology without knowledge of the conduit wall stability has important ramifications for volcanic hazard assessment and urges numerical simulation to integrate magma/conduit interaction in eruption models.

INTRODUCTION

During periods of volcanic unrest, magma is transported to the surface through a conduit, which must overcome the strength of the country rock in order to propagate (Gudmundsson and Brenner 2005). Upon reaching the surface, magma faces two choices: magma ascending slowly generally erupt effusively, whereas magma ascending quickly lead to an explosive eruption (Woods and Koyaguchi 1994). This assessment is based on knowledge of the viscoelastic property of magmas and discharge rate, whereby the ability of magma to relax an applied stress controls the eruption style (Dingwell 1996). However, key processes relating to the coupled magma/conduit (Costa et al. 2009) interaction are not considered in the balancing of forces necessary to this rheological analysis. Such information is important, as, during ascent, magma must force its way through the volcanic edifice, which both greatly affects the stress field and creates conditions conducive for the 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, triggering an explosive eruption. In 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 the 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 wall rock shell (see Figure). These experiments are unique as 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 values. In our experiments, fracturing of the wall rock was simulated by compressing a conduit of viscous rhyolitic lava that was encapsulated by an outer shell of basalt, cyclically deforming 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 micro-seismicity, recorded as acoustic emissions, 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 Figure). [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 rock shell, stress accumulated. Failure of the annular shell was accompanied by a brief 126-ms burst in released acoustic emission (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 2 radially oriented, extensional cracks along the entire length of the shell (see Figure). Tomographic and analysis of the fracture network revealed much more - namely, the extension of the radial cracks in the magma itself (see Figure inset). Microscopic analysis (under normal and fluorescent light) showed the presence of 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), yet, 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)

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

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 uniaxial 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 the stress accumulated in the shell during compression is elastically released at failure, generating a tangential shock that locally fractures the magma. The opening of a 100-micron wide extensional fracture within a 2.4-mm wide damage zone would correlate to a near instantaneous strain of 0.042 (which is more than total axial strain produced by the experiment). Acoustic emission data show that the most energetic fracturing lasted 126 ms, which signifies that the tangential strain rate reached approximately $10^{-0.5}$ s^{-1}, which concurs with Dingwell and Webb's (1989) assessment that melt failure takes place before Maxwell viscoelastic limit.

IMPLICATIONS

The novel observation here - that conduit wall fracturing causes 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 sustain magmatic 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 undergone by the conduit wall. Whether failure of the wall rock and subsequent fragmentation of the magma would lead to formation of tuffisite and permeable network resulting in enhanced degassing and eruptive quiescence or to catastrophic failure serving as a trigger of an explosive volcanic eruption may then depend on the resulting decompression (Mueller et al. 2008). Nevertheless, each scenario stands as a potential outcome. 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 magmatic fragmentation in response to fracturing of wall rock in the conduit. We urge the numerical simulation of the consideration of magmatic fracturing/fragmentation by conduit wall failure in volcanic stability scenarios.

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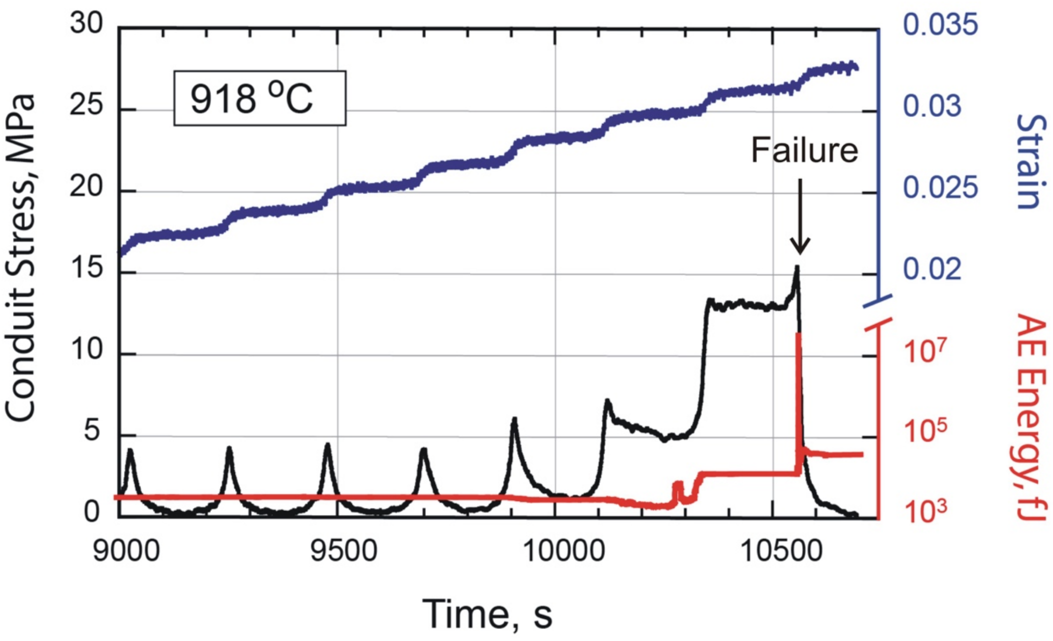
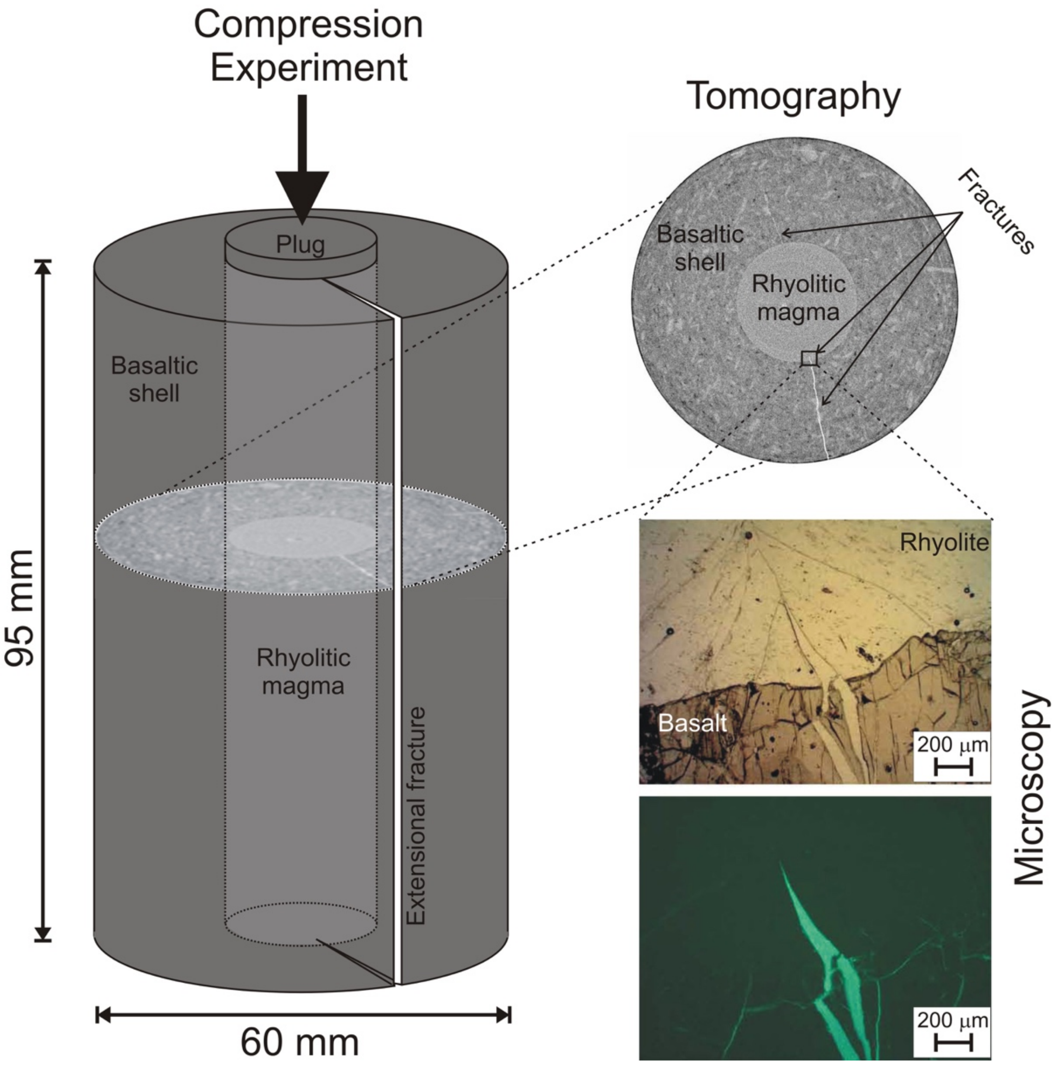
Figure caption

Magma/conduit interaction experiments. 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 period of relaxation. Hydraulic fracturing occurred at a peak stress of 16 MPa and was followed by an instantaneous stress drop. (b) Hydraulic fractures propagated radially along length the sample and were internally imaged using neutron computer tomography as well as microscopy under normal light (upper microphotograph) and fluorescence (lower microphotograph). A 2.4-mm wide dendritic network of extensional fractures formed and penetrated 1 mm inside the rhyolitic melt.


918 °C
Failure
Conduit Stress, MPa
0
5
10
15
20
25
30
Strain
0.02
0.025
0.03
0.035
AE Energy, fJ
10^3
10^5
10^7
9000
9500
10000
10500
Time, s


Compression
Experiment
Plug
Basaltic
shell
Rhyolitic
magma
Extensional fracture
95 mm
60 mm
Tomography
Basaltic
shell
Rhyolitic
magma
Fractures
Rhyolite
Basalt
200 μm
200 μm
Microscopy