Earth and Planetary Science Letters 500 (2018) 97–104

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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Fragmentation and Plinian eruption of crystallizing basaltic magma

Pranabendu Moitra [a,b,*], Helge M. Gonnermann [b], Bruce F. Houghton [c], Chandra S. Tiwary [d,e]

[a] Department of Geology and Center for Geohazards Studies, University at Buffalo, Buffalo, NY, USA
[b] Department of Earth, Environmental and Planetary Sciences, Rice University, TX, USA
[c] Department of Geology and Geophysics, University of Hawai'i at Manoa, Honolulu, USA
[d] Department of Material Science and NanoEngineering, Rice University, Houston, TX, USA
[e] Materials Science and Engineering, Indian Institute of Technology Gandhinagar, Gujarat, India

ARTICLE INFO

Article history:
Received 14 December 2017
Received in revised form 30 July 2018
Accepted 2 August 2018
Available online xxxx
Editor: T.A. Mather

Keywords:
basaltic Plinian eruption
explosive magma fragmentation
oscillatory shear rheometry
extensional rheometry
bubble growth and crystallization
conduit model

ABSTRACT

Basalt is the most ubiquitous magma on Earth, erupting typically at intensities ranging from quiescently effusive to mildly explosive. The discovery of highly explosive Plinian eruptions of basaltic magma has therefore spurred debate about their cause. Silicic eruptions of similar style are a consequence of brittle fragmentation, as magma deformation becomes progressively more viscoelastic. Magma eventually crosses the glass transition and fragments due to a positive feedback between water exsolution, viscosity and decompression rate. In contrast to silicic eruptions, the viscosity of basaltic magmas is thought to be too low to reach conditions for brittle fragmentation. Pyroclasts from several basaltic Plinian eruptions, however, contain abundant micron-size crystals that can increase magma viscosity substantially. We therefore hypothesize that magma crystallization led to brittle fragmentation during these eruptions. Using combined oscillatory and extensional rheometry of concentrated particle-liquid suspensions that are dynamically similar to microcrystalline basaltic magma, we show that high volume fractions of particles and extension rates of about 1 s^{-1} or greater result in viscoelastic deformation and brittle fracture. We further show that for experimentally observed crystallization rate, basaltic magma can reach the empirical failure conditions when erupting at high discharge rates.

1. Introduction

The fragmentation and dynamics of Plinian eruptions of basaltic magma have been a subject of debate (e.g., Giordano and Dingwell, 2003; Houghton and Gonnermann, 2008; Costantini et al., 2010; Goepfert and Gardner, 2010). The critical deformation rate at which silicate melt dynamically crosses the glass transition is $\sim 10^{-2}/\tau_{\mathrm{relax}}$ (e.g., Dingwell and Webb, 1989). Here τ_{relax} is the relaxation time scale of silicate melts, defined as $\tau_{\mathrm{relax}} = \eta_0/G_\infty$, where η_0 is the shear viscosity at zero frequency, and $G_\infty \sim 10$ GPa is the shear modulus at infinite frequency. For crystal-poor basaltic melt η_0 is of the order of 10^2–10^3 Pa s (Hui and Zhang, 2007) and τ_{relax} is 10^{-8}–10^{-7} s. Deformation rates of greater than 10^5 s^{-1} would be required for basaltic melt to reach the glass transition, which is difficult to reconcile with the dynamics of magma ascent (e.g., Wilson and Head, 1981; Papale, 1999). Consequently, fragmentation during explosive basaltic eruptions is thought to be of hydrodynamic nature (e.g., Parfitt, 2004; Namiki and Manga, 2008; Valentine and Gregg, 2008; Gonnermann, 2015).

Pyroclastic eruptive deposits from several explosive basaltic eruptions, for example the 1886 eruption of Mt. Tarawera (Sable et al., 2009), New Zealand and the 122 BCE eruption of Mt. Etna, Italy (Coltelli et al., 1998; Sable et al., 2006), indicate sustained eruption columns of approximately 25–30 km height, over durations of hours, and at mass discharge rates of about 10^8 kg s^{-1}. They are therefore classified as Plinian eruptions. Recent quantitative studies on these eruptions used existing stress- or strain rate-driven fragmentation criteria (e.g., Moitra et al., 2013; Campagnola et al., 2016). However due to very small τ_{relax}, as discussed above, the question remains whether in analogy to their silicic counterparts these eruptions were associated with brittle fragmentation. The pyroclasts from these eruptions contain a high abundance of micron-size crystals (up to 90% in volume of the matrix; Fig. 1) that likely formed as a consequence of water exsolution during eruptive magma ascent (e.g., Hammer and Rutherford, 2002; Goepfert and Gardner, 2010; Arzilli et al., 2015).

To assess whether microlites affect the mechanics of magma fragmentation, this study uses a novel approach by examining

* Corresponding author at: Department of Geology and Center for Geohazards Studies, University at Buffalo, Buffalo, NY, USA.
E-mail address: pranaben@buffalo.edu (P. Moitra).

https://doi.org/10.1016/j.epsl.2018.08.003
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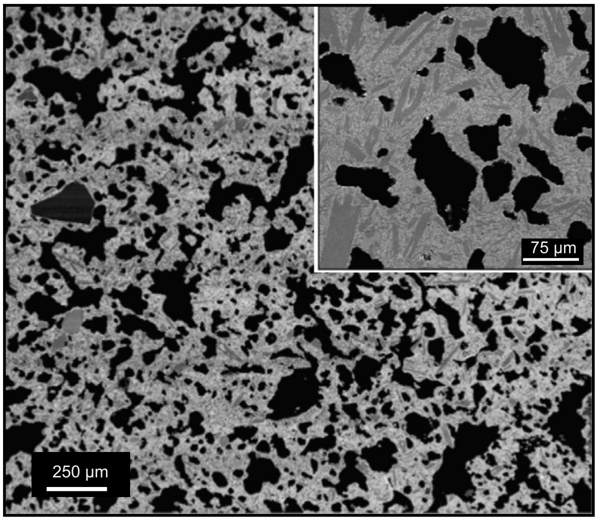

Fig. 1. Back-scattered electron (BSE) images of pyroclast sections from Mt. Tarawera, 1886 basaltic Plinian eruption. The inset shows two distinct microlite populations with larger high aspect ratio plagioclase crystals and smaller equigranular to high aspect ratio plagioclase and pyroxene crystals in the glass matrix (gray) surrounding vesicles (black).

the extensional deformation and fracture behavior of concentrated liquid-particle suspensions that are dynamically similar to microcrystalline basaltic magma. Using scaling analysis and conduit model of magma ascent in volcanic conduit, it is demonstrated that under what conditions crystallizing basaltic magma can reach brittle fragmentation during explosive Plinian style eruptive activity.

2. Experimental methods

2.1. Overview

We performed a series of experiments in viscous fluids with suspended micron-size solid particles to assess the potential effect of high microlite concentrations on the rheological behavior of basaltic magmas. These suspensions have rheological properties that are dynamically similar to basaltic melt with high volume fraction of microlites (see Appendix A). The suspensions consisted of silicone oil with a Newtonian shear viscosity of 100 Pa s and 3–10 μm glass spheres at a volume fraction of $\phi_x = 0.55$, which is close to the maximum packing limit of $\phi_m = 0.56$. To characterize the viscoelastic properties of the concentrated suspension and its potential for fracture development, we performed oscillatory shear and extensional deformation experiments (Fig. 2). Particle settling was negligible during our experiments because the characteristic settling time was much smaller than the experimental time scales.

2.2. Oscillatory shear rheology

Oscillatory shear experiments, consisting of amplitude and frequency sweeps (e.g., Heymann et al., 2002; Sumita and Manga, 2008; Namiki and Tanaka, 2017), were performed using an Anton Paar Physica MCR 301™ rotational rheometer with parallel plate geometry and a 1 mm gap (Fig. 2a). The amplitude sweep experiments were performed at a fixed angular frequency, ω, in the range of 10^{-1} to 10^{2} rad s^{-1} and 10^{-4} to 10^{-1} of total strain, γ_s. The frequency sweep experiments were performed at angular frequency of 10^{-1} to 10^{2} rad s^{-1} and a fixed strain amplitude of about 10^{-4}, which corresponds to the linear viscoelastic range obtained from the amplitude sweep experiments. In order to

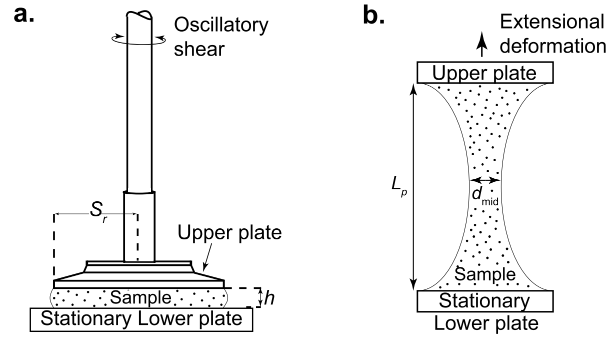

Fig. 2. Schematic diagrams of experimental methods. (**a**) The oscillatory shear rheology experiments were performed using a parallel-plate geometry, where S_r is the radius of the disk of sample in between two plates, and h is the sample thickness. (**b**) The extensional rheometry (tensile test) was performed by placing a cylindrical sample in between two parallel plates, where the upper plate moved upward while the lower plate stayed stationary. L_p is the plate separation length and d_{mid} is the diameter at the middle of the cylindrical sample.

avoid normal forces due to sample placement, the samples were pre-sheared. The resultant complex shear modulus, G^*, can be expressed as

$$G^* = G' + iG'', \tag{1}$$

where G' and G'' are the storage or elastic shear modulus and the loss or viscous shear modulus, respectively.

2.3. Extensional rheometry

The extensional rheometry (tensile tests) was performed using an Instron Electropuls™ E3000. The suspension was placed between two parallel plates that moved apart in the vertical direction, resulting in an increase in the gap between the two plates (Fig. 2b). In order to obtain a purely uniaxial elongation the gap was increased at an exponentially increasing rate (e.g., McKinley and Sridhar, 2002; White et al., 2010). The position of the upper moving plate is thus given as

$$L_p(t) = L_0 \exp(\dot{E}t), \tag{2}$$

where L_0 is the initial gap length (i.e., the initial length of the sample), t is time, and $\dot{E} = \dot{L}_p/L_p$ is the axial stretch rate. Equivalent to pre-shearing in shear rheology experiments, a small initial stretch rate of ≈0.05 s^{-1} was applied for few seconds prior to each experiment.

The elongating fluid in the center of the gap underwent a nearly shear-free flow whose effective extensional rate of deformation can be defined as

$$\dot{\gamma}_{\text{eff}}(t) = \frac{-2}{d_{\text{mid}}} \frac{d(d_{\text{mid}})}{dt}, \tag{3}$$

where d_{mid} is the diameter at the middle of the suspension filament. The effective Hencky strain is defined as

$$\gamma_{\text{eff}} = 2 \ln\left(\frac{d_0}{d_{\text{mid}}}\right), \tag{4}$$

where d_0 is the initial diameter of the sample at its midpoint and is much greater than the particle diameter. The change in mid-filament radius with respect to time was calculated from conservation of fluid volume and with the aid of photographs of the extending cylindrical sample.