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Models for viscosity and shear localization in bubble-rich magmas

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ABSTRACT

Bubble content influences magma rheology and, thus, styles of volcanic eruption. Increasing magma vesicularity affects the bulk viscosity of the bubble-melt suspension and has the potential to promote non-Newtonian behavior in the form of shear localization or brittle failure. Here, we present a series of high temperature uniaxial deformation experiments designed to investigate the effect of bubbles on the magma bulk viscosity. The starting materials are cores of natural rhyolitic obsidian synthesized to have variable vesicularity ($\phi = 0$–66%). The foamed cores were deformed isothermally ($T = 750\,^{\circ}\mathrm{C}$) at atmospheric conditions using a high-temperature uniaxial press under constant displacement rates (strain rates between 0.5–$1 \times 10^{-4}\ \mathrm{s}^{-1}$) and to total strains of 10–40%. The viscosity of the bubble-free melt (η_0) was measured by micropenetration and parallel plate methods to establish a baseline for experiments on the vesicle rich cores. At the experimental conditions, rising vesicle content produces a marked decrease in bulk viscosity that is best described by a two-parameter empirical equation: $\log_{10} \eta_{Bulk} = \log_{10} \eta_0 - 1.47[\phi/(1-\phi)]^{0.48}$. Our parameterization of the bubble-melt rheology is combined with Maxwell relaxation theory to map the potential onset of non-Newtonian behavior (shear localization) in magmas as a function of melt viscosity, vesicularity, and strain rate. For low degrees of strain (i.e. as in our study), the rheological properties of vesicular magmas under different flow types (pure vs. simple shear) are indistinguishable. For high strain or strain rates where simple and pure shear viscosity values may diverge, our model represents a maximum boundary condition. Vesicular magmas can behave as non-Newtonian fluids at lower strain rates than unvesiculated melts, thereby, promoting shear localization and (explosive or non-explosive) magma fragmentation. The extent of shear localization in magma influences outgassing efficiency, thereby, affecting magma ascent and the potential for explosivity.

1. Introduction

Dissolved volatile contents strongly control the rheology of natural silicate melts. Moreover, all magmas vesiculate as they rise to the point of eruption and may continue to vesiculate during eruption, transport, and emplacement. Exsolved volatiles, expressed as magma porosity, also affect the rheology of magmas. Ultimately, the rheology of bubble-bearing magma controls the dynamics of volcanic eruption and can modify the eruptive style and the flow of magma and lavas, making it a central issue in volcanology. Whilst the effects of dissolved volatiles (mainly water) on melt viscosity are well known and predictable, the effects of exsolved fluid (i.e. bubbles) on the bulk viscosity of magmas remain unresolved (Fig. 1).

Experiments designed to investigate the bulk viscosity of porous melts have used a range of materials, including: analogue fluids (e.g., corn syrup, oil, water), packed particles of ceramic or industrial glass, and synthetic or natural melts (see Mader et al., 2013 for a review). A compilation of measurements of bulk or magma viscosity (η_{Bulk}) for bubble-bearing melts shows viscosity to decrease universally with increasing porosity (ϕ) relative to the bubble-free melt (η_0) (Fig. 1a). In contrast, models for the viscosity of porous melts show a range of behavior (Fig. 1b–d), ascribed to differences in material properties, particle shape, pore geometry and distributions, and flow regimes. The models in the literature include: i) models with theoretical bases (Fig. 1b), ii) empirical functions fitted to experiments on analogue materials (Fig. 1c), and iii) empirical functions constrained by experiments on natural materials (Fig. 1d). Further description of these models and the references are given in Appendix A.

Theoretical models predict the widest range of behaviors including a rise in viscosity (~1 order of magnitude) with increasing porosity. An equal number of theoretical models predict a near-linear decrease in relative viscosity with increasing porosity. In contrast, empirical models fitted to experimental data uniformly

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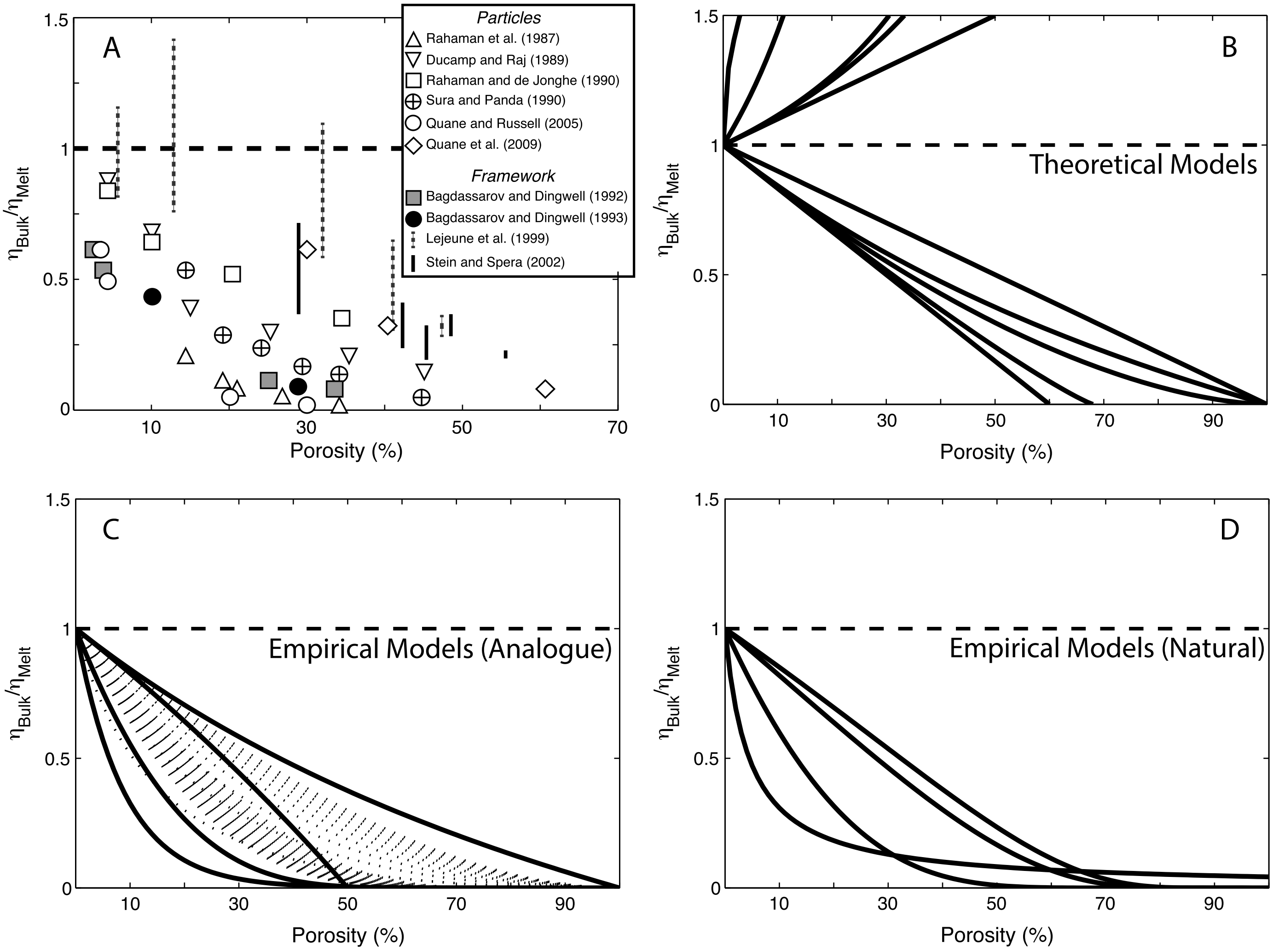

Fig. 1. Viscosity of porous magma (η_{Bulk}) ratioed to the viscosity of the melt (η_0) as a function of porosity (%). (A) Compiled data from the literature including experiments on foamed synthetic or natural melts and unconsolidated or sintered analogue and natural materials. Most data represent pure shear systems where samples were deformed by compression; two datasets (black circles and vertical bars) result from simple shear (torsion) experiments. All analogue data (pure and simple shear) show a monotonic decrease in relative viscosity with increasing porosity (see text). Model relationships between η_{Bulk} and porosity include: (B) theoretical models; (C) empirical models constrained by experiments on analogue materials (e.g., soda-lime beads); and (D) empirical models fitted to experiments on natural materials. See Mader et al. (2013) for review and Appendix A for full references.

suggest a linear or non-linear (concave upward) decrease in relative viscosity with increasing vesicularity (Fig. 1c, d).

The comparison of experimental datasets is hampered by differences in the experimental methods and starting materials. For example, studies on crystal-bearing (e.g., Pistone et al., 2012; Vona et al., 2013; Heap et al., 2014) are not easily compared to those on crystal-free magmas (e.g., Bagdassarov and Dingwell, 1992; Lejeune et al., 1999; Stein and Spera, 2002). Similarly, the potential strain and strain rate dependence of magma viscosity (Webb and Dingwell, 1990; Rust et al., 2003) precludes direct comparison of data derived from different rheometrical setups (i.e., simple shear vs. pure shear, or diverse strain rates $<10^{-4}$ s^{-1} to 10^1 s^{-1}). Lastly, the difference in the rheological response of bubbles suspended in a coherent melt (e.g., Bagdassarov and Dingwell, 1992; Lejeune et al., 1999; Stein and Spera, 2002) versus pores originating as space between solid particles (e.g., Rahaman et al., 1987; Quane and Russell, 2005; Robert et al., 2008; Quane et al., 2009) remains relatively understudied (i.e. Heap et al., 2014).

Here, we present a suite of high-temperature experiments designed to investigate the effects of vesicles on the viscosity of rhyolitic magmas (i.e. melt + bubbles). Our experiments comprise parallel-plate deformation of fully characterized, pre-vesiculated cores of rhyolite. These experiments have the following attributes: 1) our starting materials are variably vesiculated glass cores where isolated bubbles reside in contiguous melt (*versus* interclast pore space), 2) total strain in most experiments is ~10% so the bubble populations in the final products are not radically different from those in the starting materials, and 3) the strain rate is restricted to best approximate conditions consistent with emplacement of natural lavas, extrusion of lava domes, or compaction of lavas and ignimbrites. We use the mechanical data (load, displacement), the reduction in porosity, and changes in geometric properties of the cores to constrain an empirical model for the rheology of bubble-bearing magma. We conclude with an exploration of the implications of our model for limiting or enhancing non-Newtonian behavior during flow of vesiculated magmas.

2. Starting material and methods

Our starting material is a natural hydrous rhyolitic obsidian from Hrafntinnuhryggur, Krafla, Iceland (Tuffen and Castro, 2009). The composition has been measured previously and is reported in Table 1 (Tuffen and Castro, 2009; Ryan et al., 2015a).