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Surface tension driven processes densify and retain permeability in magma and lava

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ABSTRACT

We offer new insights into how an explosive eruption can transition into an effusive eruption. Magma containing >0.2 wt% dissolved water has the potential to vesiculate to a porosity in excess of 80 vol.% at atmospheric pressure. Thus all magmas contain volatiles at depth sufficient to form foams and explosively fragment. Yet gas is often lost passively and effusive eruptions ensue. Magmatic foams are permeable and understanding permeability in magma is crucial for models that predict eruptive style. Permeability also governs magma compaction models. Those models generally imply that a reduction in magma porosity and permeability generates an increased propensity for explosivity.

Here, our experimental results show that surface tension stresses drive densification *without* creating an impermeable 'plug', offering an additional explanation of why dense magmas can avoid explosive eruption. In both an open furnace and a closed autoclave, we subject pumice samples with initial porosity of ~70 vol.% to a range of isostatic pressures (0.1–11 MPa) and temperatures (350–950 °C) relevant to shallow volcanic environments. Our experimental data and models constrain the viscosity, permeability, timescales, and length scales over which densification by pore-scale surface tension stresses competes with density-driven compaction. Where surface tension dominates the dynamics, densification halts at a plateau connected porosity of ~25 vol.% for our samples. SEM, pycnometry and micro-tomography show that in this process (1) microporous networks are destroyed, (2) the relative pore network surface area decreases, and (3) a remaining crystal framework enhances the longevity of macro-pore connectivity and permeability critical for sustained outgassing. We propose that these observations are a consequence of a surface tension-driven retraction of viscous pore walls at areas of high bubble curvature (micro-vesicular network terminations), and that this process drives bulk densification and permits continued outgassing. We propose a regime diagram of the relative dominance of surface tension and gravitational compaction that illustrates the interplay between viscosity, permeability, lengthscale and timescale. We contend that surface tension-driven magma densification is an as-yet overlooked phenomenon that extends our volcanological, geothermal and hydrothermal knowledge of how gas can escape densifying volcanic plugs and why dense lavas remain permeable.

1. Introduction

Eichelberger et al. (1986) proposed that obsidian lava flows form by densification of a permeable magmatic foam. Since then, compaction studies have predicted large changes in permeability (both increase and decrease) as magma densifies (Rust and Cashman, 2004; Quane et al., 2009; Michaut et al., 2009, 2013; Kendrick et al., 2013; Kolzenburg and Russell, 2014; Okumura et al., 2009; Okumura and Sasaki, 2014; Ashwell et al., 2015). The observed range in volcanic rock permeability has been interpreted as being a consequence of a spatially variable microstructure related to contributions from cracks, bubble networks and

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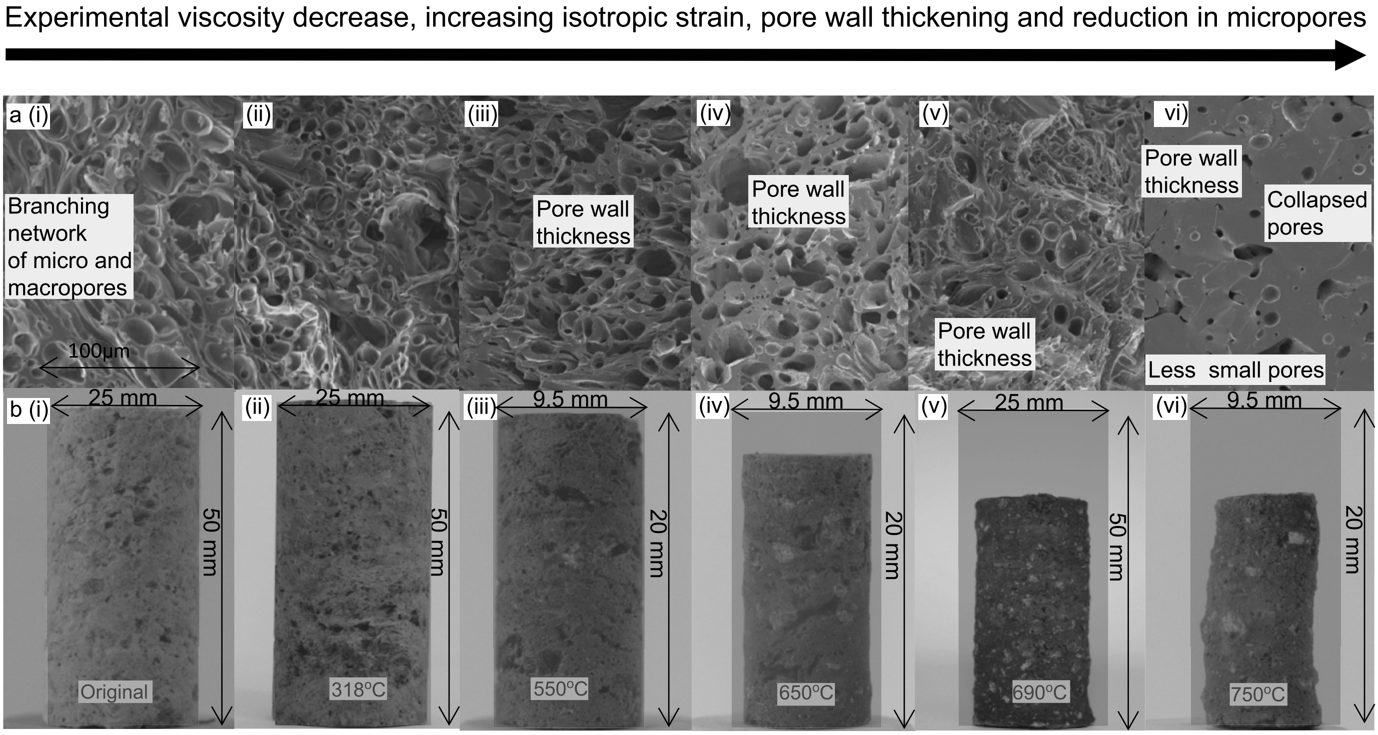

Fig. 1. Samples. (a, i–iv) Representative SEM images (same scale for all images) of the experimental samples heated to between 318 and 750 °C at 10.3 MPa in a steam environment for 4 h. (b, i–vi) Photographs of same samples, illustrating the isotropic strain. Shaded area represents the dimensions of the sample pre-experimentation.

a touching framework of crystals (Klug and Cashman, 1996; Saar and Manga, 1999; Rust and Cashman, 2004; Mueller et al., 2005; Takeuchi et al., 2005; Okumura et al., 2009; Wright et al., 2009; Degruyter et al., 2010; Heap et al., 2014; Gaunt et al., 2014). Even in the absence of cracks, such microstructures permit relatively dense lava to have a similar permeability to high-porosity pumice (e.g. Nguyen et al., 2014). Unfortunately, current perception of magma permeability is heavily influenced by laboratory measurements on rocks that may not be appropriate to explain the transient nature of the permeable networks (Okumura and Sasaki, 2014) and which may furthermore be compromised by natural quench-induced micro-cracking (Nguyen et al., 2014). Here, we perform high temperature experiments, during which bubbly magma is permitted to outgas, in order to test the hypothesis that pore surface relaxation allows lava densification, while maintaining high permeability in the absence of cracking.

Despite the demonstrable importance of surface tension in bubble nucleation, growth, and coalescence and resistance to shearing (e.g. Proussevitch and Sahagian, 1996; Castro et al., 2012; Rust and Cashman, 2004), it has been largely overlooked as a force contributing to density changes in permeable magma. Here, we define densification as increases in bulk density, such that it is the material metric inverse of porosity. We propose that in the absence of shear strain, densification can be driven by a density contrast between vapour and melt in a permeable magma (compaction) or by gradients in surface stress at bubble walls (surface tension). Thus far, studies have focused on densification processes induced during ascent, for example, lateral variations in shear strain across a conduit that can locally affect porosity and permeability (e.g. Okumura et al., 2009; Houghton et al., 2010; Degruyter et al., 2010; Caricchi et al., 2011; Schipper et al., 2013). Similarly, models of density-driven compaction suggest that vertical changes in porosity occur during magma ascent in the conduit (e.g. Michaut et al., 2013). Vertical and lateral changes in pore structure can promote cycles in eruption style at silicic and intermediate volcanoes and explain synchronous explosive and effusive eruptions (Schipper et al., 2013; Castro et al., 2014). Importantly, density-driven compaction in viscous magmas drives dramatic reductions in permeability (e.g. Michaut et al., 2013). In contrast, brittle magma failure tends to be dilatant and to increase permeability (e.g. Saar and Manga, 1999; Castro et al., 2012; Lavallée et al., 2013; Ashwell et al., 2015), and these trends pose a challenge for explaining the broader ability of lavas to densify and outgas efficiently without the need to shift eruptive style. Outgassing controls the build-up of pore pressure and hence resultant eruptive style (e.g. Westrich and Eichelberger, 1994; Edmonds and Herd, 2007; Mueller et al., 2008; Degruyter et al., 2012), therefore, it is crucial to model successfully outgassing and pore evolution during inter-eruptive periods of low ascent-driven strain. Here, we address the issue of isostatic magma densification with systematic experimental investigations of the textural modifications of porous networks in silicic magma.

2. Methodology

We drilled cores of rhyodacite pumice (Fig. 1a, b (i)) from a single 30 × 30 × 30 cm^3 block of Mt Meager volcano pumice, from the 2350 BP Pebble Creek Formation, British Columbia, Canada (Hickson et al., 1999). The sample was collected from a vent-proximal deposit with a distinctive coarse grain size (pumice blocks up to 75 cm). We consider the sample characteristic of the porous, conduit-dwelling magma that filled the vent immediately following a large explosive eruption. The dry pumice (i.e. dissolved water content of 0.1 wt%) has a calculated glass transition onset temperature of ∼740 °C (using the model of Giordano et al., 2008). We drilled two sizes of cylinders with a 2:1 length to diameter ratio (2 × 1 cm^2 and 4 × 2 cm^2). An additional suite of experiments was performed on 2 × 0.5 cm^2 and 2 × 15 cm^2 cylinders to distinguish relative roles of gravitationally-driven compaction and surface tension-driven densification. The porosity of each sample was determined by He-pycnometry at University of British Columbia (UBC) in Vancouver (Michol et al., 2008) and at Ludwig Maxim-