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An experimental study of permeability development as a function of crystal-free melt viscosity

A. Lindoo [a,*], J.F. Larsen [a], K.V. Cashman [b], A.L. Dunn [a], O.K. Neill [c]

[a] Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775, USA
[b] School of Earth Sciences, University of Bristol, Bristol BS81RJ, UK
[c] Peter Hooper GeoAnalytical Laboratory, School of the Environment, Washington State University, Pullman, WA 99164, USA

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ABSTRACT

Permeability development in magmas controls gas escape and, as a consequence, modulates eruptive activity. To date, there are few experimental controls on bubble growth and permeability development, particularly in low viscosity melts. To address this knowledge gap, we have run controlled decompression experiments on crystal-free rhyolite (76 wt.% SiO_2), rhyodacite (70 wt.% SiO_2), K-phonolite (55 wt.% SiO_2) and basaltic andesite (54 wt.% SiO_2) melts. This suite of experiments allows us to examine controls on the critical porosity at which vesiculating melts become permeable. As starting materials we used both fine powders and solid slabs of pumice, obsidian and annealed starting materials with viscosities of $\sim 10^2$ to $\sim 10^6$ Pa s. We saturated the experiments with water at 900° (rhyolite, rhyodacite, and phonolite) and 1025 °C (basaltic andesite) at 150 MPa for 2–72 hrs and decompressed samples isothermally to final pressures of 125 to 10 MPa at rates of 0.25–4.11 MPa/s. Sample porosity was calculated from reflected light images of polished charges and permeability was measured using a bench-top gas permeameter and application of the Forchheimer equation to estimate both viscous (k_1) and inertial (k_2) permeabilities. Degassing conditions were assessed by measuring dissolved water contents using micro-Fourier-Transform Infrared (μ-FTIR) techniques.

All experiment charges are impermeable below a critical porosity (ϕ_c) that varies among melt compositions. For experiments decompressed at 0.25 MPa/s, we find the percolation threshold for rhyolite is 68.3 ± 2.2 vol.%; for rhyodacite is 77.3 ± 3.8 vol.%; and for K-phonolite is 75.6 ± 1.9 vol.%. Rhyolite decompressed at 3–4 MPa/s has a percolation threshold of 74 ± 1.8 vol.%. These results are similar to previous experiments on silicic melts and to high permeability thresholds inferred for silicic pumice. All basaltic andesite melts decompressed at 0.25 MPa/s, in contrast, have permeabilities below the detection limit ($\sim 10^{-15}$ m^2), and a maximum porosity of 63 vol.%. Additionally, although the measured porosities of basaltic andesite experiments are ~10–35 vol.% lower than calculated equilibrium porosities, μ-FTIR analyses confirm the basaltic andesite melts remained in equilibrium during degassing. We show that the low porosities and permeabilities are a consequence of short melt relaxation timescales during syn- and post-decompression degassing. Our results suggest that basaltic andesite melts reached $\phi_c > 63$ vol.% and subsequently degassed; loss of internal bubble pressure caused the bubbles to shrink and their connecting apertures to seal before quench, closing the connected pathways between bubbles. Our results challenge the hypothesis that low viscosity melts have a permeability threshold of ~30 vol.%, and instead support the high permeability thresholds observed in analogue experiments on low viscosity materials. Importantly, however, these low viscosity melts are unable to maintain high porosities once the percolation threshold is exceeded because of rapid outgassing and collapse of the permeable network. We conclude, therefore, that melt viscosity has little effect on percolation threshold development, but does influence outgassing.

* Corresponding author.
E-mail address: alindoo@alaska.edu (A. Lindoo).

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1. Introduction

Vesiculation of ascending magmas drives volcanic eruptions. The explosivity of an eruption is modulated by the physical state of the conduit (Jaupart, 1998) and the degassing efficiency of the magma, which may proceed either through permeable bubble networks (Rust and Cashman, 2004) or magma fracture along conduit walls (Gonnermann and Manga, 2007). In silicic melts, degassing via permeable networks has been studied through analysis of eruptive products and decompression experiments on natural and analog materials. However, few studies have attempted to quantify and describe permeability development in low viscosity melts, and no experimental studies have been conducted. To address this gap, we extend decompression experiments to mafic and alkalic compositions. By comparing these results with those of their silicic counterparts, we address the role of melt viscosity in modulating the degassing process.

Magmas become permeable via one or both of two processes: connection of bubbles via coalescence to form permeable networks (e.g., Wright et al., 2009) or magma fracture (Castro et al., 2012a). Here we focus on development of permeable bubble networks, which is more likely than magma fracture to facilitate wholesale magma degassing in the conduit. As magma ascends, decreasing pressure causes the melt to become supersaturated with H_2O (e.g., Stolper, 1982), which triggers bubble nucleation and growth via diffusion and expansion. Vesiculation and bubble expansion can generate high vesicularities (>70 vol.%) and form magmatic foams, as observed in natural pumice clasts (e.g., Klug and Cashman, 1996; Wright et al., 2009). Once the magmatic foam expands sufficiently to allow bubbles to impinge on one another, melt films separating neighboring bubbles thin and rupture to form apertures between bubbles. Extensive coalescence can create a connected network of bubbles that acts as a passageway for volatiles to quickly exit the system. The vesicularity at which magma becomes permeable (critical porosity, ϕ_c) is termed the percolation threshold (Blower, 2001).

Bubble coalescence is primarily controlled by melt viscosity. In order for neighboring bubbles to coalesce, the melt films separating them must rupture; this is assumed to occur at a critical thickness (Proussevitch et al., 1993; Castro et al., 2012b). The timescales required to thin or stretch interstitial melt-films are controlled by melt viscosity and surface tension (Rust and Cashman, 2011). For this reason, coalescence occurs much more readily in lower viscosity melts; therefore, it has been assumed that the onset of permeability in mafic melts occurs at a lower porosity than in silicic melts.

Once degassing commences, bubbles may deform or shrink while still maintaining a permeable pathway. This results in a hysteresis effect where vesicularity decreases as a result of deformation and reduced overpressure, while connected bubble networks maintain streamlined passageways for permeable outgassing (Saar and Manga, 1999; Rust and Cashman, 2004, 2011). Effusive products typically exhibit this hysteresis effect (e.g. Mueller et al., 2008), implying they achieved permeability and degassed. The extent to which permeability networks are modified during explosive eruptions is unknown.

Previous work examining critical porosities in phenocryst-poor, natural and experimental silicic (rhyolite and rhyodacite) pumice suggest percolation thresholds between 56 and 78 vol.% (Eichelberger et al., 1986; Klug and Cashman, 1996; Takeuchi et al., 2009). Theoretical models based on packing geometry of spheres (Blower, 2001), in contrast, predict permeability at porosities ≥30 vol.%. These predictions appear to be supported by analysis of phenocryst-poor, basaltic scoriae (Saar and Manga, 1999), where measurements at high porosities were fit by a curve calculated using percolation theory (Blower, 2001). Crystal-poor basaltic melts in Hawaii, in contrast, commonly produce pyroclasts with vesicularities ≫70 vol.% (Rust and Cashman, 2011); these data are more consistent with an analog study that found permeability development to be delayed until $\phi_c \approx 70$ vol.% in low viscosity corn syrup (Namiki and Manga, 2008). This percolation threshold is significantly higher than the ∼30 vol.% proposed by percolation theory and more in line with results for natural and experimental crystal-free, high viscosity, silicic melts. One possible explanation for this discrepancy lies in the high micro-crystallinity of most analyzed scoria samples, and the potential role of crystals in reducing the percolation threshold (Rust and Cashman, 2011), although decompression experiments have yet to confirm this hypothesis (Okumura et al., 2012). Alternatively, the discrepancy between theoretical and observed percolation thresholds may reflect limitations in the models, which do not account for either bulk volume expansion or the time required to thin films that separate individual bubbles (Rust and Cashman, 2011).

To better understand this problem, we use high pressure and temperature decompression experiments to constrain critical porosities in phenocryst-free melts. The experiments employ rhyolite, rhyodacite, K-rich phonolite, and basaltic andesite starting materials to observe bubble exsolution and permeability development over melt viscosities that vary over four orders of magnitude (10^2 to $10^{6.2}$ Pa s). The initial starting conditions approximate water-saturated, supra-liquidus magma that is stored at approximately 6 km depth in the crust and ascends rapidly (∼10 to 300 m/s). The resulting permeabilities are measured with a bench-top permeameter constructed for small experimental samples. We find that percolation thresholds are similar for all melt compositions, but that melt viscosity exerts a profound influence on degassing and subsequent permeability development. We use these results to explore the role of magma viscosity in controlling syn-eruptive degassing and consequences for eruption styles.

Table 1
Major oxide compositions of starting materials.

Oxide	MC[a]	AnRd[b]	VP[c]	OK52A[d]
SiO_2	76.32 (0.29)	70.57	55.41 (0.38)	54.82 (0.51)
TiO_2	0.21 (0.17)	0.53	0.26 (0.11)	2.55 (0.5)
Al_2O_3	13.02 (0.06)	15.31	21.97 (0.45)	14.49 (0.2)
FeO*	1.03 (0.08)	2.69	2.90 (0.38)	11.03 (0.23)
MnO	–	0.16	0.24 (0.12)	0.18 (0.06)
MgO	0.04 (0.02)	0.61	0.65 (0.07)	3.38 (0.09)
CaO	0.53 (0.03)	2	3.69 (0.25)	7.36 (0.47)
Na_2O	3.93 (0.11)	5.38	5.32 (0.21)	4.16 (0.26)
K_2O	4.73 (0.10)	2.97	9.17 (0.39)	1.28 (0.1)
Cl	–	–	0.26 (0.14)	–
P_2O_5	–	0.11	0.12 (0.05)	–
Total	100	99.6	99.76 (0.58)	99.25
n[e]	4	1	19	4

[a] Mono Craters rhyolite. EPMA analysis.
[b] Aniakchak rhyodacite. XRF analysis (Larsen, 2006).
[c] EU2 Vesuvius 79AD k-phonolite. EPMA analysis (Shea et al., 2010a, 2010b).
[d] Okmok basaltic andesite. EPMA analysis (Wong and Larsen, 2010).
[e] Number of analyses.

2. Experimental and analytical methods

2.1. Experimental methods

Decompression experiments employed both continuous and step-wise decompression pathways. Sample materials included powders and solid slabs of glassy rhyolite, rhyodacite, K-rich phonolite, and basaltic andesite from (Table 1): rhyolite (Mono Craters, CA; 76.32 wt.% SiO_2), rhyodacite (Aniakchak; 70.57 wt.% SiO_2; Larsen, 2006), K-phonolite (79 AD Vesuvius; 55.41 wt.% SiO_2; Shea et al., 2010a), and basaltic andesite (Okmok; 54.82 wt.% SiO_2; Wong and Larsen, 2010). These melt compositions were selected to