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The percolation threshold and permeability evolution of ascending magmas

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ABSTRACT

The development of gas permeability in magmas is a complex phenomenon that directly influences the style of a volcanic eruption. The emergence of permeability is linked to the concept of percolation threshold, which is the point beyond which gas bubbles are connected in a continuous network that allows gas escape. Measurements of the percolation threshold, however, range from ∼30 to 78 vol%. No known combination of parameters can explain such a wide range of threshold values, which affects our understanding of the relationship between percolation and permeability. We present permeability calculations on bubble-bearing rhyolitic melts that underwent experimental decompression. Samples were analyzed by X-ray microtomography to image the bubble networks in 3D. We develop a percolation threshold for magmas that depends on the bubble network characteristics of this sample set. This relationship recovers the behavior of a wide range of volcanic samples by separating permeable samples from impermeable ones with a success rate of 88%. We use this percolation threshold to propose simplified permeability relationships that rely on parameters widely used in numerical modeling of magma flow. These relationships are valid within one order of magnitude for the viscous permeability coefficient and within two orders of magnitude for the inertial coefficient. They recover the ranges of values previously covered by isolated relationships, reassembling them within a single framework. We test the implications of such unification on eruptive dynamics with a 1D, two-phase conduit flow model. This test shows that varying the percolation threshold has little influence on vertical gas loss and ascent dynamics.

1. Introduction

During a volcanic eruption, magma ascends towards the surface and loses the volatiles it contains. In viscous magmas, volatiles are lost as gas bubbles that grow during ascent but hardly move relative to each other. The coalescence of the bubbles with each other transforms the bubbly magma into a connected network that is permeable to gas (e.g., Eichelberger et al., 1986). Permeability allows the gas to separate from the magma (e.g., Yoshida and Koyaguchi, 1999). An efficient separation promotes effusive eruptions, whereas bubble accumulation by growth promotes fragmentation and explosive eruptions (e.g., Jaupart and Allègre, 1991).

Studies aimed at understanding magma permeability have established relationships that depend on material properties, such as bubble size, total and connected gas volume fraction, throat size (aperture of inter-bubble connections), bubble aspect ratio, and network tortuosity (Klug and Cashman, 1996; Mueller et al., 2005; Wright et al., 2009; Yokoyama and Takeuchi, 2009; Degruyter et al., 2010a). Focusing on natural data, permeability relationships went from the apparent simplicity of depending only on total gas volume fraction (Klug and Cashman, 1996) to larger degrees of complexity as more data were acquired and more degrees of freedom were needed to describe the relationships (Saar and Manga, 1999). Another degree of complexity was reached when a second permeability coefficient was introduced alongside the original coefficient entering Darcy's law. While the first permeability coefficient, k_1, quantifies the effects of gas flow when viscous effects dominate, the additional coefficient, k_2, takes into account the inertial effects of turbulent flow (Rust and Cashman, 2004). It was also found that the relationships gain in accuracy of permeability prediction when using connected gas volume fraction instead of total gas fraction (Saar and Manga, 1999; Mueller et al., 2005; Gonnermann and Manga, 2007). The relationship between total and connected porosity is directly linked to the threshold at which

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Table 1
Symbol list. The mean bubble diameter is based on the diameter distribution and the average bubble diameter is based on volume distribution (see Methods).

Symbol	Description (unit)
A	Proportionality constant
a_i	Semi-axes of ellipsoid (m)
a_{KC}	Constant in Kozeny–Carman equation (m^2)
a_M	Constant in percolation equation (m^2)
B	Proportionality constant
b_{KC}	Exponent in Kozeny–Carman equation
b_M	Exponent in percolation equation
c_d	Percolation constant (m)
c_ϕ	Connected porosity constant
c_p	Connected porosity constant (m)
c_τ	Tortuosity constant
c_z	Percolation exponent
χ_i	Bubble aspect ratio
d_a	Average bubble diameter (m)
d_m	Mean bubble diameter (m)
d_t	Throat diameter (m)
ε_i	Bubble elongation
f_0	Inertial factor
ϕ_c	Connected porosity
ϕ_p	Percolation porosity
ϕ_t	Total porosity
i, k	Indices of spatial direction
k_1	Viscous permeability (m^2)
k_2	Inertial permeability (m)
l_i	Longest semi-axis of ellipsoid orthogonal to i (m)
m	Exponent in Archie's law
μ	Fluid viscosity (Pa s)
n	Exponent in Degruyter equation
N_m	Bubble number density per unit melt (m^{-3})
P	Pressure (Pa)
ρ	Fluid density (kg/m^3)
r_i	Radius of equivalent disk of ellipsoid cross-section orthogonal to i (m)
R_1, R_2, R_3	Sum of residuals
σ_a	Standard deviation of d_a (m)
σ_m	Standard deviation of d_m (m)
τ_i	Tortuosity
v_i	Fluid velocity (m/s)
$\vec{w}$	Vector of components a_i
x_i	Spatial direction
z	Calculated inter-bubble distance (m)
z_m	Measured inter-bubble distance (m)
Z	Scaled inter-bubble distance (m)
Z_p	Percolation threshold on Z (m)

the magma ceases to be impermeable to gas. Drawing from percolation theory (Sahini and Sahimi, 1994), this threshold has mostly been assumed to depend on a constant value of gas volume fraction (Blower, 2001). Characterizing the percolation threshold in natural products (e.g., Eichelberger et al., 1986; Klug and Cashman, 1996; Saar and Manga, 1999; Mueller et al., 2005), experimental magmas (e.g., Takeuchi et al., 2009; Martel and Iacono-Marziano, 2015), and analogue materials (e.g, Namiki and Manga, 2008) led to values ranging from ~30 to 78 vol%. Several possible controls of such a wide range of values have been proposed: crystal volume fraction, melt viscosity, shear stress, decompression rate, differences in experimental methodology, and the inaccuracy of theoretical models that do not take into account the time needed for interstitial film retraction (Okumura et al., 2013; Rust and Cashman, 2011; Lindoo et al., 2016). Some parameters, such as shear stress, give a partial explanation for the variability of measured percolation thresholds (Caricchi et al., 2011; Okumura et al., 2013), whereas others, such as melt viscosity, do not seem to control this variability (Lindoo et al., 2016). None explain the full spectrum of threshold values.

The transition of magma from being permeable to impermeable controls when gas escape ceases. The amount of gas escape, on the other hand, is controlled by permeability, which directly influences the style of the volcanic eruption (Yoshida and Koyaguchi, 1999; Kozono and Koyaguchi, 2009; Degruyter et al., 2012). Clarifying the relationship between percolation and permeability is thus an important issue.

Here we investigate the role of the bubble network geometry on the percolation threshold and on permeability. (See Table 1.) We use a subset of two series of experiments (Burgisser and Gardner, 2004; Gardner, 2007) on silicate melts in which bubbles grew during isothermal decompression and interacted to various degrees, sometimes creating a permeable network by coalescence. These crystal-free experiments were analyzed by X-ray Computed Tomography (CT) to obtain 3D reconstructions of the bubble networks, as described in Castro et al. (2012). Bubble network parameters and both viscous and inertial permeability coefficients were calculated so as to test the relationship of Degruyter et al. (2010a) against our data set. That relationship assumes that the state of percolation and network parameters are known. We relax these assumptions by making the relationships depend on 1) a percolation threshold related to bubble network geometry and 2) magmatic parameters widely used in conduit flow models. We establish that the percolation depends on bubble separation and on the degree of polydispersity of the bubble size distribution. The resulting relationship links inertial and viscous permeabilities to the average and standard deviation of the bubble size distribution, bubble aspect ratio, and total porosity. We show how the proposed percolation threshold captures the behavior of previously published data sets. Finally, we explore some implications of having a unified framework predicting magma permeability on conduit flow model outputs.

2. Methods

2.1. CT volumes

We analyzed a subset of 36 samples from experimentally decompressed rhyolite melts. Briefly, the Burgisser and Gardner (2004) and the Gardner (2007) experiments consisted of placing samples of rhyolitic glass in sealed Au-capsules with distilled water, and equilibrating them at 150 MPa for five days in order to saturate the melt with water. Some capsules were quenched, removed from the pressure vessel, and opened to extract the hydrated samples. These samples were reloaded into Au capsules without water, but with either silicate glass powder or MgO powder to serve as a sink for expelled water during decompression, allowing open-degassing conditions. Each capsule was then repressurized and reheated at the hydration conditions for 5 min before an applied sudden decompression nucleated small bubbles (mean radius <<10 μm). The other samples – i.e. those that had not been reopened and reloaded – remained in the pressure vessel until the nucleation step was performed, thus ensuring closed-system conditions. All samples were maintained at the nucleation pressure until bubbles reached thermodynamic equilibrium, which was checked by determining the glass water content (Gardner, 2007). Pressure was then released in increments to approximate a constant decompression rate until a final pressure was reached, at which samples were quenched rapidly.

All volumes analyzed by CT (Castro et al., 2012) come from hydrated and foamed cores that underwent decompression in either closed, or open degassing conditions. These samples were sometimes small pieces broken from the original cores and sometimes were parts of thin sections that were recut with a diamond saw so as to leave the smallest possible amount of thin section glass attached to the sample. As a result, while the former samples are often equant and yielded nearly cubic CT volumes, the latter samples were much thinner in one direction and yielded highly flattened volumes (details in Supplementary Text S1 and Fig. S1).

Connected bubbles have retained their original shapes. When these shapes are mostly spherical, we refer to the sample as be-