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# Pore structure of volcanic clasts: Measurements of permeability and electrical conductivity

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ABSTRACT

The pore structure of volcanic clasts is examined using measurements of porosity, permeability, and electrical properties. Permeability varies by several orders of magnitude among volcanic clasts and does not depend solely upon porosity. Electrical property measurements of saturated volcanic samples illustrate the influence of pathway tortuosity and pore shape on permeability. For equivalent eruption conditions, silicic samples show higher tortuosities, smaller vesicle sizes, and lower permeabilities than mafic samples. These differences are largely due to variations in vesiculation and crystallization history. Differences between explosive and effusive samples reflect the relative ability of bubbles to form and maintain connected pathways during bubble expansion and collapse. Isotropic samples (variably expanded breadcrust bombs and most pumice fall samples) have pore pathways that simplify with increasing porosity. Highly vesicular anisotropic samples (e.g., tube pumice) have high permeabilities and low tortuosities parallel to pore elongation and low permeabilities and high tortuosities perpendicular to elongation. These pathways simplify with increasing deformation (i.e. tortuosity decreases as porosity decreases), until pore geometries collapse sufficiently to form intersecting cracks. More generally, Archie's Law (power law) relationships between electrical conductivity formation factor ($F$) and porosity ($\phi$) have an Archie's exponent, $m$, between 1 and 4 (where $F=\phi^{-m}$) for low porosity volcanic clasts. However, samples with higher connected porosities (>20% for silicic samples and >50% for mafic samples) have $m$ values that increase with increasing porosity, reaching up to 15. We also find that a single Archie's Law fit to a suite of samples is not appropriate either for sample suites with widely varying porosities or for anisotropic samples with a directional variation in measured properties. These measurements caution against simple application of cross-property relationships derived from sedimentary rocks to models of permeability in volcanic samples.



## 1. Introduction

Understanding the physical movement of volatile phases through magmatic systems is critical not only for understanding variations in the style of eruptive activity, but also for interpreting volatile emissions during pre- and post-eruptive periods. For example, efficient gas migration through connected pore pathways within ascending magma can prevent pressurization and magma fragmentation, leading to effusive eruptions. Alternatively, gas accumulation beneath impermeable magma plugs can precipitate the abrupt onset of explosive activity. Assessment of the explosive potential of a given system thus requires models of magma ascent that include the development of permeable gas pathways as magma decompresses and vesiculates (e.g., Clarke et al., 2002a,b; Melnik and Sparks, 2002a,b; Diller et al., 2006). However, theoretical models of permeability–porosity relationships (e.g., Sahimi, 1995) make simplifying assumptions about pore geometry (e.g., Katz and Thompson, 1986; Blower, 2001; Melnik and Sparks, 2002a,b) that do not account for the topological complexities arising from multi-stage histories of vesiculation and bubble deformation in volcanic systems. Such complexities create permeability variations of several orders of magnitude, even at constant porosity (Fig. 1; e.g., Klug and Cashman, 1996; Saar and Manga, 1999; Melnik and Sparks, 2002a,b; Rust and Cashman, 2004; Mueller et al., 2005).

The range in permeability shown in Fig. 1 demonstrates that porosity, alone, does not control the efficiency of gas escape from porous material; also important are pore size, pore aperture size, pore shape, tortuosity of pore pathways, and pore size distributions (e.g., Carman, 1956; Katz and Thompson, 1986; Wong, 1999; Le Pennec et al., 2001). In volcanic rocks, these parameters vary during magma ascent and eruption because of bubble growth, coalescence, shear, collapse, and the presence of crystals. Moreover, a single batch of vesiculating magma may exhibit a hysteresis effect, such that the pore

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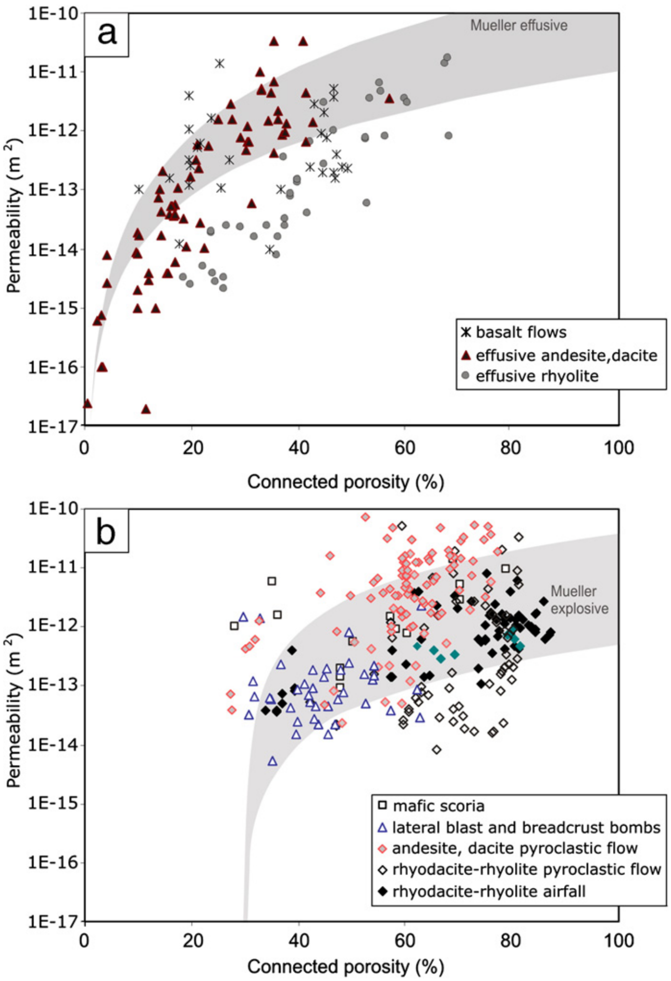


**Fig. 1.** Darcian permeability versus connected porosity for (a) effusive volcanic products and (b) explosive volcanic products. Data from Bernard et al. (2007), Jouniaux et al. (2000), Klug and Cashman (1996), Melnik and Sparks (2002a,b), Mueller et al. (2005), Platz et al. (2007), Rust and Cashman (2004), Saar and Manga (1999), Wright et al. (2007), Wright et al. (2006); and this study.

structure formed by bubble expansion has a lower permeability (less connectivity) than that formed by bubble collapse at equivalent porosity (e.g., Rust and Cashman, 2004).

The complexity of pore geometries and the resulting range of clast permeabilities have led to numerous models of permeability–porosity relationships for volcanic rocks. Klug and Cashman (1996) suggested that porous volcanic rocks may follow power law relationships between porosity and permeability similar to, but offset to higher porosities than, those developed for sedimentary rocks (e.g., Berryman and Blair, 1987). New data for andesitic dome samples (e.g., Jouniaux et al., 2000; Melnik and Sparks, 2002a,b) showed more similarities to crack-dominated sedimentary rocks. Mueller et al. (2005) thus suggested separate power law trends for effusive and explosive volcanic products, with explosive samples having a higher threshold porosity than effusive samples (Fig. 1). Although published data suggest that these trends are not robust, permeability data from most effusive samples can be fit with percolation thresholds at lower porosities (typically <20%; Jouniaux et al., 2000; Melnik and Sparks, 2002a,b; Rust and Cashman, 2004; Fig. 1a) than for explosive samples (30–over 60%; Eichelberger et al., 1986; Gardner et al., 1996; Gaonac'h et al., 2005; Namiki and Manga, 2008; Fig. 1b). Additionally, mafic samples have higher permeabilities than silicic samples with the same connected porosity. We hypothesize that compositional variations result from kinetic controls on pore size distributions and connectedness, while variations between explosive and effusive samples reflect variations in syn-eruptive vesicle coalescence and deformation and crystal content. Testing these hypotheses requires an improved understanding of the relationship between the pore structure and gas flow through connected pores.

Pore structure is commonly evaluated in sedimentary rocks by measuring electrical conductivity (Archie, 1942; Vidal-Beaudet and Charpentier, 2000). Although well established in the hydrology literature, electrical conductivity measurements of volcanic materials are limited to three studies of (primarily) andesitic lava (Jouniaux et al., 2000; Le Pennec et al., 2001; Bernard et al., 2007). We extend this approach by measuring the electrical conductivity of volcanic samples for which both permeability and connected porosity are known (Fig. 2). We focus on well characterized samples of dacite and rhyolite compositions that vary in macroscopic pore structure, bulk crystallinity, and eruption conditions. We measured electrical conductivity to examine the role of path tortuosity on permeability and to evaluate assumed Archie's law relationships commonly invoked

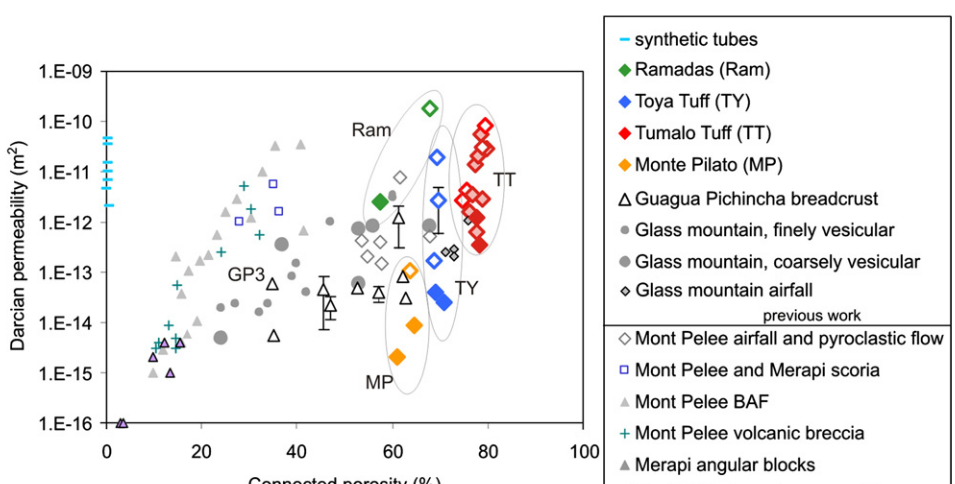


**Fig. 2.** Darcian permeability versus connected porosity for samples with known electrical conductivity properties in this study. Tube pumice samples are designated with open diamonds where oriented parallel to vesicle elongation, dark filled diamonds where perpendicular to elongation, and light filled diamonds indicate Tumalo samples oriented at an intermediate degree to elongation.