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Permeability of volcanic rocks to gas and water

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ABSTRACT

The phase (gas or liquid) of the fluids within a porous volcanic system varies in both time and space. Laboratory experiments have shown that gas and water permeabilities can differ for the same rock sample, but experiments are biased towards rocks that contain minerals that are expected react with the pore fluid (such as the reaction between liquid water and clay). We present here the first study that systematically compares the gas and water permeability of volcanic rocks. Our data show that permeabilities to argon gas and deionised water can differ by a factor between two and five in two volcanic rocks (basalt and andesite) over a confining pressure range from 2 to 50 MPa. We suggest here that the microstructural elements that offer the shortest route through the sample—estimated to have an average radius ~0.1–0.5 μm using the Klinkenberg slip factor—are accessible to gas, but restricted or inaccessible to water. We speculate that water adsorption on the surface of these thin microstructural elements, assumed here to be tortuous/rough microcracks, reduces their effective radius and/or prevents access. These data have important implications for fluid flow and therefore the distribution and build-up of pore pressure within volcanic systems.

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1. Introduction

Permeability is a measure of the ability of a material to transmit fluids [Guéguen and Palciauskas, 1994]. The permeability of volcanic rocks therefore largely controls the movement of fluids and the distribution of pore pressure in a volcanic edifice. The build-up of pore pressure within a volcanic system is thought to promote explosive volcanism [e.g., Eichelberger et al., 1986; Sparks, 1997; Melnik et al., 2005; Farquharson et al., 2017] and flank collapse [e.g., Reid, 2004] and, as such, many experimental and theoretical studies have been devoted to better understanding the permeability of volcanic materials [e.g., Eichelberger et al., 1986; Saar and Manga, 1999; Blower, 2001; Rust and Cashman, 2004; Mueller et al., 2005; Costa, 2006; Mueller et al., 2008; Wright et al., 2009; Degruyter et al., 2010; Lavallée et al., 2013; Gaunt et al., 2014; Farquharson et al., 2015, 2016; Heap and Kennedy, 2016; Wadsworth et al., 2016; Lindoo et al., 2016; Heap et al., 2016, 2017; Burgisser et al., 2017; Kushnir et al., 2017a; Colombier et al., 2017; Vasseur and Wadsworth, 2017; Kushnir et al., 2017b]. These studies, and many others, have shown that the permeability of volcanic materials is not only an increasing function of porosity (a scalar), but also highlight the importance of a wealth of additional parameters, such as porosity type (pores and microcracks), pore geometry (size, shape, and preferred orientation), porosity connectivity, and alteration, amongst others.

The constitutive equation that describes fluid flow through a porous medium is Darcy's law [Darcy, 1856]. The equation relates a volumetric flow rate to a fluid pressure gradient using a coefficient called the permeability. Permeability is a property of the medium and is therefore independent of the fluid used in its determination. Darcy's law is valid for all porous media as long as the volumetric flow rate is linearly proportional to the fluid pressure gradient, i.e. the flow is laminar. For instances of nonlaminar flow, auxiliary corrections are required to derive the "true" (Darcian) permeability of a medium from pressure and flow rate data. For example, when measuring materials with very high permeabilities and/or using pore fluids with very low viscosities, fluid flow can be turbulent. In this regime, a new parameter is introduced in order to account for inertial forces: this is known as the Forchheimer correction [Forchheimer, 1901]. Another instance where the relationship between volumetric flow rate and fluid pressure gradient is nonlinear is specific to measurements using gas. When the mean free path of the molecules/atoms approaches the characteristic pore or aperture size, interactions between the gas molecules/atoms and the pore walls serve to reduce resistance to flow, a phenomenon known as "slip flow" or "gas slippage". In this case, the apparent permeability is corrected using the Klinkenberg correction [Klinkenberg, 1941].

Most of the experimental studies designed to measure the permeability of volcanic rocks use an inert gas as the pore fluid; only a handful of studies have used water [e.g., Kolzenburg et al., 2012; Kendrick et al., 2013; Heap et al., 2014a, 2014b; Gaunt et al., 2014]. To the knowledge of the authors, there are no studies that compare gas and water permeabilities in volcanic materials. Laboratory measurements have shown that permeabilities to liquid water and gas are essentially equal for granite

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[Brace et al., 1968; Zhang et al., 2000]. A difference between permeabilities to gas and water has been observed for rocks containing mineral constituents that can react with the pore fluid, such as the reaction between liquid water and clay [Faulkner and Rutter, 2000, 2003; Tanikawa and Shimamoto, 2006; Davy et al., 2007; Tanikawa and Shimamoto, 2009; Behnsen and Faulkner, 2011] or the reaction between CO_2-enriched water and calcite [Noiriel et al., 2004; Luquot and Gouze, 2009]. These studies have shown, for example, that permeabilities to gas and liquid water in clay-rich rocks can differ by as much as an order of magnitude [e.g., Faulkner and Rutter, 2000]. A higher permeability to gas in clay-rich rocks is explained by the expansion of clay minerals in the presence of water due to water adsorption – the swollen clay minerals effectively constrict pore throats thus reducing permeability [Faulkner and Rutter, 2003].

It is often assumed, after the appropriate corrections have been applied, that permeabilities to gas and water are equivalent for materials for which significant physicochemical reactions are not expected. However, a lack of data comparing the gas and water permeabilities of a range of materials obscures a complete understanding. For example, the complex microstructure presented by volcanic rocks—often a complex network of pores and microcracks [Heap et al., 2014a; Farquharson et al., 2015; Colombier et al., 2017]—may yield a difference in permeabilities to gas and water in the absence of significant physicochemical reactions. The phase (gas or liquid) of the fluids within a porous volcanic system varies in time and space [e.g., Giggenbach and Soto, 1992; Taran et al., 1998; Chiodini et al., 2000; Byrdina et al., 2014], exemplified by the occurrence of phreatic and phreatomagmatic eruptions that are driven by the boiling of liquid water [e.g., Houghton and Nairn, 1991; Barberi et al., 1992; Mayer et al., 2015; Montanaro et al., 2016]. As a result, quantifying potential differences in the permeability to gas and water in volcanic rocks emerges as an important, yet unexplored, avenue for research. With this in mind, we present herein a study in which we measured the gas and water permeabilities of samples of andesite and basalt.

2. Description of experimental materials

For the purpose of this study, we selected a suite of variably porous andesites from Volcán de Colima (Mexico) and a well-studied basalt from Mt. Etna (Italy). Volcán de Colima is an active andesitic stratovolcano located at the western end of the Trans-Mexican Volcanic Belt in Mexico [Varley and Komorowski, 2018] and Mt. Etna is an active basaltic stratovolcano located on the east coast of the island of Sicily (Italy) [Allard et al., 2006].

The five andesite blocks used in this study (A5, B4, B5, C8, and LAH4) have been used in a number of recent studies focussed on the mechanical behaviour of andesite [e.g., Kendrick et al., 2013; Heap et al., 2014a, 2015]. Using the classification scheme of Farquharson et al. [2015], sample B5 can be classified as an "altered lava" (B5 displays high-temperature alteration, as evidenced by the presence of cristobalite; Fig. 1a), while the remaining blocks can be classified as "lava". The andesites all have a porphyritic texture consisting of a glassy groundmass (with abundant microlites) that hosts pores and a phenocryst cargo (Fig. 1). The porosity within these andesites comprises a combination of microcracks and pores (Fig. 1) [Kendrick et al., 2013; Heap et al., 2014a, 2015]. As evident in the scanning electron microscope (SEM) images of Fig. 1, the andesites contain a microcrack network that is both pervasive and tortuous. Indeed, microcrack densities range between 35 and 45 mm^{-1} [Heap et al., 2014a]. The microcracks are typically thin (no more than a few microns) and are usually no longer than 0.5 mm in length (Fig. 1). The andesites also contain high pore number densities, between 3.3 and 8.1 mm^{-2} [Heap et al., 2014a]. The pores are often far from spherical (Fig. 1) and are, in the case of the lowest porosity sample (B5), coated with cristobalite crystals (Fig. 1a). All of the andesites show a wide range of pore diameters, from 1 to 2 mm to a few tens of microns [Heap et al., 2014a].

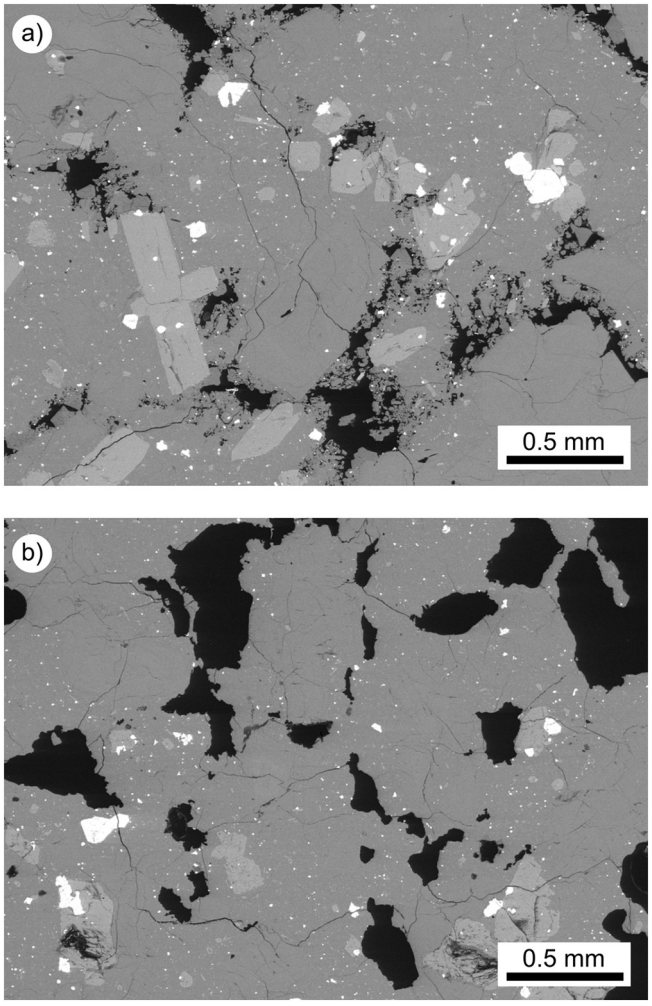

Fig. 1. (a) Backscattered scanning electron microscope image of andesite sample B5 (from Volcán de Colima, Mexico). (b) Backscattered scanning electron microscope image of andesite sample C8 (from Volcán de Colima). Both samples are characterised by a complex microstructure containing both pores and microcracks (see text for details).

The basalt from Mt. Etna has porphyritic texture consisting of a completely crystallised groundmass containing pores and a phenocryst cargo (Fig. 2). This basalt has been the focus of a number of studies in the last ten years [e.g., Vinciguerra et al., 2005; Stanchits et al., 2006; Heap et al., 2011; Zhu et al., 2016]. The porosity within the basalt comprises a combination of microcracks and pores (Fig. 2). Qualitatively, the microcracks in the basalt are typically much longer (often several mm) than those in the andesites (Figs. 1 and 2). The microcracks within the basalt often traverse through both the crystallised groundmass and the large phenocrysts present within the sample (Fig. 2a). The pores within the basalt are not distributed throughout the sample, but are present in pockets (Fig. 2b). The pores within these porous pockets represent the volume between microlites where the groundmass is absent, a texture termed diktytaxitic [see, for example, Kushnir et al., 2016]. The pores are typically <100 μm in diameter (Fig. 2b).

3. Experimental methods

Cylindrical samples (20 mm in diameter and precision-ground to a nominal length of 40 mm) were prepared from the five blocks of andesite (A5, B4, B5, C8, and LAH4) and the block of basalt. These samples were then dried in a vacuum oven at 40 °C for at least 48 h. Before measuring their permeability, the prepared 20 mm-diameter samples were first investigated in terms of their connected porosity (using helium

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