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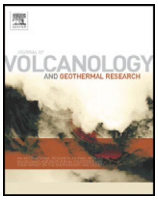

Permeability and porosity relationships of edifice-forming andesites: A combined field and laboratory study

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ABSTRACT

Permeability of the edifice is one of the key parameters governing eruptive style, magnitude, and frequency of active stratovolcanoes. This study presents a suite of density and permeability field measurements from 572 samples of edifice-forming andesite from Volcán de Colima, Mexico. The breadth of the density distribution of the rocks collected (corresponding to porosity values from 2.5 to 73%), and the increasing bimodality towards the vent, are indicative of the explosive–effusive behaviour that characterises active composite volcanoes. Measured field permeabilities are in the range of 10^{-16} to 10^{-11} m^2, encompassing values significantly greater than those generally assumed for fluid transport in magma, and thus emphasising the importance of host-rock permeability in facilitating outgassing of volatiles and, in turn, governing eruption dynamics. For any given porosity we observe up to four orders of magnitude in permeability. This range of scatter was found to be unaffected for the most part by meso-scale textural differences, oxidation, or alteration. A complementary laboratory and microstructural study reveals that the andesites collected are microstructurally diverse and complex. For example, anomalously high surface areas are measured in samples with significant inter-microlite microporosity. However, these micropores do not serve to significantly increase porosity or pore connectivity, resulting in underestimation of fluid pathway tortuosities using the Kozeny–Carman relation. Indeed, calculated tortuosity values highlight that the Kozeny–Carman relation poorly predicts connectivity and does not therefore capture the microstructural complexity of the studied volcanic rocks. A changepoint porosity value, where the permeability–porosity power-law exponent changes, is identified at around 14% porosity using a Bayesian Information Criterion analysis. Here we assume a change in the dominant microstructural element controlling fluid flow, i.e. from crack- to pore-dominated flowpath geometries. Microstructural analysis indicates that fluid flow in the low porosity andesites (<14%) of this study is governed by tortuous microcracks, while the more porous samples (>14%) display relatively large, interconnected pores. While the supposition that the power-law exponent changes at a distinct changepoint is a simplification, we find that it well describes permeability data from Volcán de Colima (from this study and those of previous authors). The exceptional heterogeneity of edifice-forming rocks is thought to have significant implications for lateral outgassing, eruption dynamics, as well as influencing regional edifice strength and stability.

1. Introduction

1.1. Permeability of a volcanic edifice

Permeability, quantifying the capacity of a material to transmit fluids, is fundamental in controlling a variety of processes in geological systems, and can vary over twelve orders of magnitude in natural rocks (Guéguen and Palciauskas, 1994). In volcanic settings, permeability is a key parameter controlling eruptive style and magnitude by influencing the capacity for a volcano to outgas (Jaupart, 1998; Edmonds et al., 2003; Costa, 2006; Taisne and Jaupart, 2008; Castro et al., 2014). As magma ascends, volatile species exsolve (degas) from the melt phase due to oversaturation; the relative ease by which these volatiles can then outgas depends on the permeability of the rocks forming the edifice (e.g., Jaupart, 1998), and the connectivity and mobility of bubbles in conduit magma (i.e. outgassing through a permeable network in the magma, e.g., Plail et al. (2014); Shields et al. (2014)). Efficiently degassed and outgassed magma tends to erupt effusively (e.g. Lev et al., 2012), constituting a hazard only in the immediate vicinity of a volcano. On the other hand, inefficient outgassing can result in volatile

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oversaturation and pressure build-up within the volcano, ultimately fostering catastrophic explosive eruptions, flank collapse, and pyroclastic density currents (e.g. Wallace and Anderson, 2000). In these latter cases, impacts may be widespread, long-lived, and lethal.

Stratovolcanoes comprise an edifice constructed by indiscriminate emplacement of explosive and effusive products, surrounding a central magma conduit or cluster of dykes (e.g., Biggs et al., 2010; Gudmundsson, 2012). Continual accumulation of these products results in a structure with spatially variable physical properties, with pervasive differences in porosity and permeability down to the intra-clast scale. Thus transport networks for magmatic volatiles are dependant not only on large-scale fault systems (which may not necessarily provide a direct pathway for volcanic gas species: see Varley and Taran (2003)), but also on the fluid transport properties of the constituent edifice-forming rocks.

Models of volcanic processes must be built on a foundation of observed or experimentally derived parameters; however, as we often wish to understand fluid flow in regions of the edifice that are difficult or indeed impossible to access, permeability cannot necessarily be determined in situ. It is thus of importance to relate transport properties of porous volcanic rocks to the governing physical properties, such as porosity. Though it is evident that the capacity for fluid transport through a porous rock is somewhat dependent on its connected pore space (porosity φ), it is nontrivial to define a precise relationship due to the microstructural complexity of the medium involved (e.g. Zhu and Wong, 1996; Bernabé et al., 2003). Generally, permeability k is estimated as some function of connected porosity, such that $k = f(\varphi)$, where f may include further parameters such as tortuosity (τ) or pore aperture radius. This relation then forms the basis of permeability modelling reliant on empirical or semi-empirical Kozeny–Carman equations (geometrical models), or network modelling (statistical models) (see Guéguen and Palciauskas (1994) for a review).

It is recognised that no all-encompassing theory exists to describe this relationship in all media, due primarily to the fact that some pore geometries may be more effective than others at transporting fluid (e.g. Bernabé et al., 2003). Nevertheless, models such as the Kozeny–Carman (see Kozeny (1927); Carman (1937)), or percolation theory (Sahimi, 1994) have been employed and modified in order to describe the behaviour of volcanic rocks (e.g. Klug and Cashman, 1996; Klug et al., 2002; Mueller et al., 2005; Costa, 2006). In turn, estimates of permeability can be included in numerical simulations of various volcanic processes, with the ultimate aim of predicting the behaviour of a given volcanic system (e.g. Lacey et al., 1981; Day, 1996; Clarke et al., 2002a, b; Reid, 2004; Collinson and Neuberg, 2012; Lavallée et al., 2013).

Previous experimental studies concerning the permeability and porosity of volcanic rocks (e.g. Eichelberger et al., 1986; Klug and Cashman, 1996; Tait et al., 1998; Saar and Manga, 1999; Blower, 2001; Klug et al., 2002; Melnik and Sparks, 2002; Sruoga et al., 2004; Mueller et al., 2005; Wright et al., 2006; Bernard et al., 2007; De Maisonneuve et al., 2009; Yokoyama and Takeuchi, 2009; Heap et al., 2014a,b; Gaunt et al., 2014; Okumura and Sasaki, 2014) have highlighted a vast range of measured values. Porosity of the various volcanic materials—as determined in these laboratory-based studies—has been shown to range between 3 and 90%, while permeabilities in the range of 10^{-17}–10^{-8} m^2 have been measured. The spatiotemporal variation of the physical properties of volcanic rocks necessitates the sampling of a statistically robust dataset (Kueppers et al., 2005; Bernard et al., 2015). In light of these factors, the research herein comprises a systematic field campaign assessing the permeability of edifice-forming rocks representative of a typical andesitic volcano. Combined with field-based density measurements and a complementary laboratory-based study, we further explore the microstructural processes governing permeability in volcanic rocks. While we focus herein on cooled, variably fractured rock, the incidence of fracturing in magma—for example due to strain localisation close to the conduit margins (e.g. Lavallée et al., 2013; Gaunt et al., 2014)—means that the following discussions and conclusions may also be extended to outgassing processes at the periphery of the conduit, as well as in the edifice.

1.2. Case study: Volcán de Colima

Volcán de Colima is situated at 19°30′45.82″N, 103°37′2.07″W on the Colima–Jalisco border at the south-western margin of the Trans-Mexican Volcanic Belt (Fig. 1). Along with the extinct Nevado edifice, the volcano comprises the Colima Volcanic Complex, marking the conjunction of the Colima rift zone and the Tamazula fault (Rodríguez-Elizarrarás, 1995; Norini et al., 2010). Overlying a Cretaceous basement consisting of deformed volcanic and sedimentary rocks (Rodríguez-Elizarrarás, 1995), Volcán de Colima forms a typical stratocone, with eruptive products varying little in bulk composition: crystal-rich andesites with SiO_2 contents typically between ~58 and 61 wt.% (Luhr, 2002; Mora et al., 2002; Valdez-Moreno et al., 2006; Reubi and Blundy, 2008; Savov et al., 2008). Historic volcanism has been characterised by periods of effusive activity (dome formation and lava flows, determined by magma ascent rates, topography, etc.), punctuated by frequent Vulcanian explosions and commonly culminating in voluminous Plinian eruptions (e.g. Luhr, 2002; Varley et al., 2010; James and Varley, 2012; Lavallée et al., 2012). The most recent period of sustained activity began in January 2013, consisting of dome extrusion, pyroclastic density current generation, and intermittent Vulcanian activity. As of April 2015, frequent explosive events were still ongoing.

Volcán de Colima exhibits many characteristics common to convergent margin volcanoes, such as Santa Maria (Guatemala), Ruapehu (New Zealand), Lascar (Chile), Mount Merapi (Indonesia), Citlaltépetl (Mexico), or Egmont Volcano (New Zealand): the steep conical edifice structure overlying a sedimentary basement (e.g. Carrasco-Núñez, 2000; Smyth et al., 2005; Gaylord and Neall, 2012) fosters frequent collapse events (e.g. Rose et al., 1977; Gardeweg et al., 1998; Gamble et al., 1999; Camus et al., 2000; Carrasco-Núñez, 2000), with cyclic eruptive behaviour interspersed with periods of dome effusion (e.g. Rose et al., 1977; Houghton et al., 1987; Gardeweg et al., 1998; Gamble et al., 1999; Camus et al., 2000; Carrasco-Núñez, 2000; Gaylord and Neall, 2012). Combined with its consistently intermediate composition, we maintain that Volcán de Colima can be viewed as generally representative of andesitic stratovolcanoes worldwide.

2. Methods

2.1. Field methods

We collected 572 hand samples from sites around the volcano, shown in Fig. 1, comprising over half a metric ton of andesitic edifice rock. The sites are debris-flow tracks, locally termed *barrancas*: La Lumbre, Montegrande, and El Zarco; as well as a site at El Playón, the area between the summit cone and the ancient caldera wall (Fig. 1). These sites were chosen due to their accessibility and because they all contain abundant loose surface material of a size suitable for our methods (i.e. approximately fist-sized clasts). The collected samples comprise a range of variably remobilised and reworked explosive and effusive products, representative of the edifice-forming materials. A portable air permeameter (Vindum Engineering TinyPerm II) was used to measure the permeability of each hand sample. By evacuating air from a rock, the TinyPerm II unit calculates a value based on the monitored response function of the transient vacuum at the nozzle-rock interface, which corresponds to the sample permeability. The relation between the given TinyPerm value and Darcian permeability is discussed in Appendix A.

The ability to make autonomous and rapid measurements is extremely useful when working in the field; as such these permeameters have seen increasing use in volcanology and related geoscience disciplines (e.g. Possemiers et al., 2012; Invernizzi et al., 2014; Vignaroli