Earth and Planetary Science Letters 447 (2016) 139–150

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Exploring the scale-dependent permeability of fractured andesite

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ARTICLE INFO

Article history:
Received 21 November 2015
Received in revised form 10 March 2016
Accepted 3 May 2016
Available online 19 May 2016
Editor: T.A. Mather

Keywords:
volcano
outgassing
porosity
equivalent permeability
upscaling

ABSTRACT

Extension fractures in volcanic systems exist on all scales, from microscopic fractures to large fissures. They play a fundamental role in the movement of fluids and distribution of pore pressure, and therefore exert considerable influence over volcanic eruption recurrence. We present here laboratory permeability measurements for porous (porosity = 0.03–0.6) andesites before (i.e., intact) and after failure in tension (i.e., the samples host a throughgoing tensile fracture). The permeability of the intact andesites increases with increasing porosity, from 2×10^{-17} to 5×10^{-11} m^2. Following fracture formation, the permeability of the samples (the equivalent permeability) falls within a narrow range, $2–6 \times 10^{-11}$ m^2, regardless of their initial porosity. However, laboratory measurements on fractured samples likely overestimate the equivalent permeability due to the inherent scale-dependence of permeability. To explore this scale-dependence, we first determined the permeability of the tensile fractures using a two-dimensional model that considers flow in parallel layers. Our calculations highlight that tensile fractures in low-porosity samples are more permeable (as high as 3.5×10^{-9} m^2) than those in high-porosity samples (as low as 4.1×10^{-10} m^2), a difference that can be explained by an increase in fracture tortuosity with porosity. We then use our fracture permeability data to model the equivalent permeability of fractured rock (with different host rock permeabilities, from 10^{-17} to 10^{-11} m^2) with increasing lengthscale. We highlight that our modelling approach can be used to estimate the equivalent permeability of numerous scenarios at andesitic stratovolcanoes in which the fracture density and width and host rock porosity or permeability are known. The model shows that the equivalent permeability of fractured andesite depends heavily on the initial host rock permeability and the scale of interest. At a given lengthscale, the equivalent permeability of high-permeability rock (10^{-12} to 10^{-11} m^2) is essentially unaffected by the presence of numerous tensile fractures. By contrast, a single tensile fracture increases the equivalent permeability of low-permeability rock ($<10^{-15}$ m^2) by many orders of magnitude. We also find that fractured, low-permeability rock (e.g., 10^{-17} m^2) can have an equivalent permeability higher than that of similarly fractured rock with higher host rock permeability (e.g., 10^{-15} m^2) due to the low-tortuosity of fractures in low-porosity andesite. Our modelling therefore outlines the importance of fractures in low-porosity, low-permeability volcanic systems. While our laboratory measurements show that, regardless of the initial porosity, the equivalent permeability of fractured rock on the laboratory scale is $2–6 \times 10^{-11}$ m^2, the equivalent permeability of low-permeability rock is significantly reduced as the scale of interest is increased. Therefore, due to the scale-dependence of permeability, laboratory measurements on pristine, low-permeability rocks significantly underestimate the equivalent permeability of fractured volcanic rock. Further, measurements on fractured rock samples can significantly overestimate the equivalent permeability. As a result, care must be taken when selecting samples in the field and when using laboratory data in volcano outgassing models. The data and modelling presented herein provide insight into the scale-dependence of the permeability of fractured volcanic rock, a prerequisite for understanding outgassing at active volcanoes.

1. Introduction

Extension fractures (tensile fractures and hydrofractures) are ubiquitous in volcanic systems, a consequence of the mechani-

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http://dx.doi.org/10.1016/j.epsl.2016.05.004

cal (e.g., Heiken et al., 1988) and thermal stresses (e.g., Aydin and DeGraff, 1988) inherent to these environments and the low tensile strength of rock (strength in tension is typically an order of magnitude lower than compressive strength; Jaeger et al., 2007). Extension fractures commonly seen within volcano environments include: microscopic cooling fractures (e.g., Heap et al., 2014), macroscopic polygonal cooling fractures in lavas and lava domes (e.g., Aydin and DeGraff, 1988; Spörli and Rowland, 2006), hydrofractures and tuffisites (e.g., Knapp and Knight, 1977; Heiken et al., 1988; Stasiuk et al., 1996; Sparks, 1997; Tuffen and Dingwell, 2005; Kolzenburg et al., 2012; Castro et al., 2014), crease structures (e.g., Anderson and Fink, 1992), lava dome fractures that form due to a combination of subsurface overpressures and regional stresses (such as that formed following the 2013 explosion at Mt. Merapi, Indonesia; Walter et al., 2015), and large crevasses/fissures (e.g., Gudmundsson, 2011; Fitzgerald et al., 2014). In many cases, magma fragmentation in conduits is dominated by extension fractures with a wide range of orientations (Kennedy et al., 2005). Extension fractures form due to the high overpressures generated by exsolving magmatic fluids, the thermal expansion of pore fluids, and/or the magmatic stresses (hydrofractures; e.g., Knapp and Knight, 1977; Heiken et al., 1988; Benson et al., 2012) or simply as a result of the tensile stresses exceeding the local tensile strength (tensile fractures; e.g., see the experiments presented in Lavallée et al., 2012). Both mechanisms require that, if the temperature exceeds the glass transition of the melt phase *Tg*, strain rates are high enough to exceed the structural relaxation timescale of the melt (Dingwell and Webb, 1990).

The extension fractures outlined above occur on a wide range of scale, from the microscale (Fig. 1a shows a back-scattered scanning electron photomicrograph of a cooling microcrack within one of the andesite samples of this study) to the hand sample or laboratory-scale (Fig. 1b shows a photograph of a block collected from Volcán de Colima (Mexico) containing a tensile fracture; inset shows a cylindrical laboratory sample (20 mm in diameter and 40 mm in length) prepared from the block) to the meso- or outcrop-scale (Fig. 1c shows columnar cooling fractures at Mt. Ruapehu, New Zealand) to, finally, the macroscale (Fig. 1d shows the fissure exposed following the 2012 eruption from the Te Maari vent at Mt Tongariro, New Zealand). Once formed, extension fractures principally perform two functions at active volcanoes: (1) they reduce the structural stability of the volcano and lava dome (e.g., Voight, 2000) and, (2) they act as pathways for fluids. The ease with which exsolved magmatic gases can escape the conduit—governed by the permeability of the rock and magma—is thought to impact volcanic explosivity (as discussed by many authors, e.g., Eichelberger et al., 1986; Sparks, 1997; Mueller et al., 2005; Melnik et al., 2005; Edmonds and Herd, 2007; Lavallée et al., 2013; Castro et al., 2014). Extension fractures in particular are considered to be a key component in facilitating the outgassing of the conduit magma (e.g., Castro et al., 2014). Indeed, overpressure-driven fractures can propagate to considerable distances and are thought to form efficient fluid pathways (Heiken et al., 1988; Gudmundsson et al., 2002).

Laboratory studies designed to measure the impact of tensile fracture formation on permeability are few, especially for volcanic rocks. Well-constrained laboratory measurements have shown that sample-scale tensile fractures increase permeability of very low-porosity basalt (porosity <0.05) and porous andesite (porosity = 0.17–0.18) by many orders of magnitude (Nara et al., 2011) and by a factor of almost two (Heap et al., 2015a), respectively. The few number of studies, and the discrepancy between measurements performed on rock with different porosity (Nara et al., 2011; Heap et al., 2015a), highlight the need for systematic laboratory studies to better understand the influence of tensile fractures on the permeability of variably-porous volcanic rock. How-

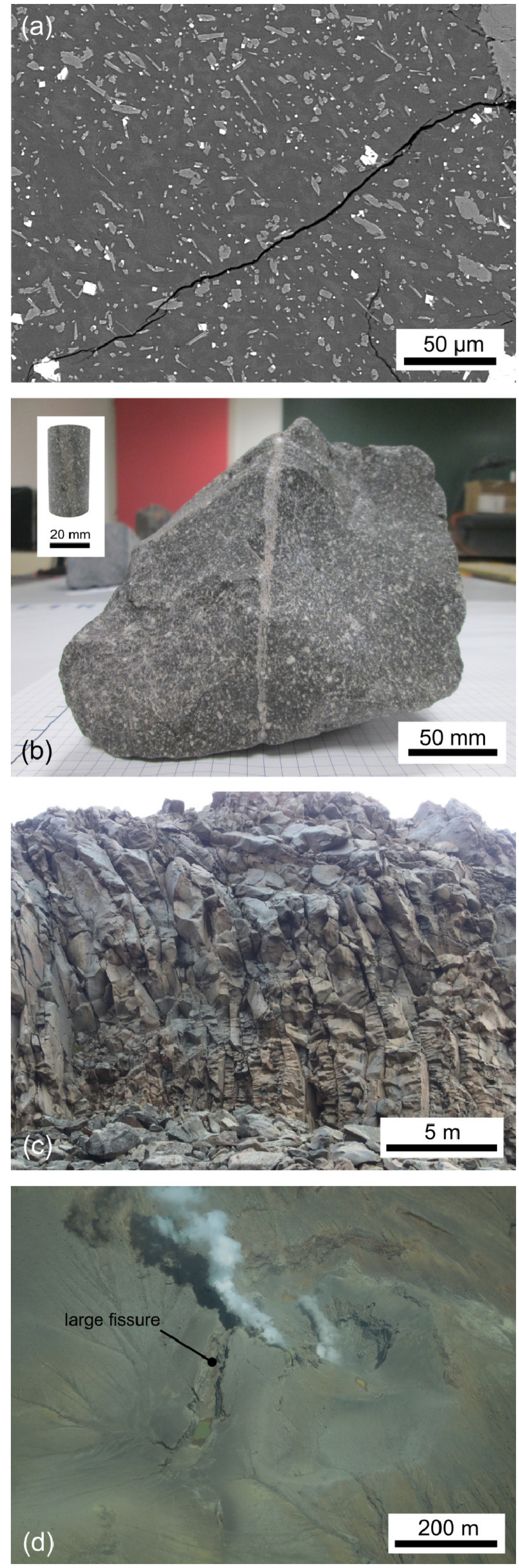

Fig. 1. A voyage through scales. (a) A microscopic cooling fracture in one of the andesites of this study (sample R10). The fracture, seen here to cut through a glassy groundmass containing microlites, is only a few microns wide. (b) A hand- or laboratory-scale block (roughly 20 × 20 × 20 cm) of andesite from Volcán de Colima (Mexico) containing a fracture. The fracture is a couple of mm wide. Inset shows a cylindrical laboratory sample cored from the block shown (20 mm in diameter and 40 mm in length). (c) Macroscopic polygonal columnar cooling fractures in an outcrop at Mt. Ruapehu (New Zealand). Photo credit: Ben Kennedy. (d) Aerial photograph of the large fissure formed following the 2012 eruption from the Te Maari vent at Tongariro (New Zealand). Photo credit: Tetsuo Kobayashi.