Permeability of tensile fractures in andesites

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ABSTRACT

Fractures play a fundamental role in the movement of fluids and the distribution of pore pressure within a reservoir. We present here laboratory permeability measurements for variably porous andesite samples before and after failure in tension. We find that tensile fractures increase sample permeability. Increases are large and small for samples with low and high initial permeabilities, respectively. We use these data to explore the scale dependence of the permeability of fractured andesite using a model that considers flow in parallel layers. The scale-dependence of the permeability of fractured rock is important to improve estimates of the equivalent permeability of geothermal systems. (The research reported here is published as Heap and Kennedy, 2016).

1. INTRODUCTION

Fractures at all scales are ubiquitous in actively utilised geothermal systems (e.g., Massiot et al., 2015; McNamara et al., 2016). They play a crucial role in the movement of fluids and the distribution of pore pressure within a reservoir, and therefore control the productivity of a particular geothermal resource. Laboratory studies focussed on measuring the permeability of samples containing fractures are scarce, especially for volcanic lithologies (Nara et al., 2012; Heap et al., 2015). Here therefore we present a systematic experimental study in which we measure the permeability of samples of andesite—a rock type of particular importance for the geothermal systems of New Zealand (such as the Rotokawa Geothermal Field; Siratovich et al., 2014; 2016; McNamara et al., 2016)—before and after fracture in tension. However, laboratory measurements of permeability will under- and overestimate the permeability of pristine (fracture-free) and samples containing one lengthscale fracture, respectively. The extrapolation of laboratory permeability data for fractured volcanic rock to larger scales is currently hampered by the paucity of well-constrained laboratory data. We aim here therefore to provide a new and systematic dataset so we can explore permeability upscaling. A grasp of the scale-dependence of the permeability of fractured rock is important for better understanding the permeability of a geothermal system.

2. MATERIALS AND METHODS

A suite of variably porous (porosity = 0.03 – 0.6; measured using a helium pycnometer) andesites from Mt. Ruapehu (New Zealand) was selected for this study. Cylindrical samples (20 mm in diameter and 20 mm in length) were prepared from the blocks. Their intact (initial) permeability was then measured using a steady state gas (nitrogen) permeameter (Figures 1a and 1b) under a confining pressure of 1 MPa.

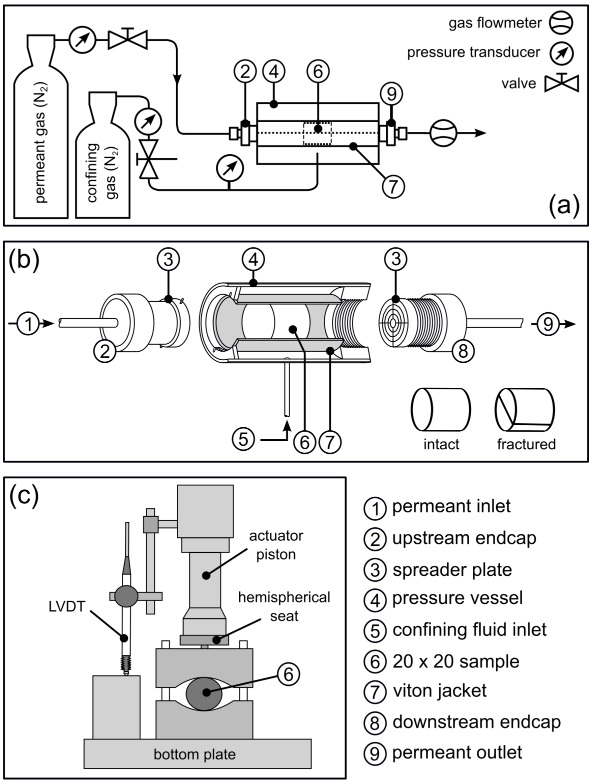

Figure 1: Schematic diagrams (not to scale) of the experimental equipment used in this study. (a and b) The benchtop steady-state permeameter. (c) The uniaxial press used to fracture the rocks in tension. Taken from Heap and Kennedy (2016).

Flow rate measurements were taken (using either a low- or high-flow gas flowmeter, depending on the permeability of the sample) under several pressure gradients (typically from 0.05 to 0.2 MPa, equating to flow rates between 0.2 and 400 ml/min) to determine the permeability using Darcy's law and to assess the need for the Klinkenberg or Forchheimer corrections, which were applied on a case-by-case basis (see also Farquharson et al., 2015; Kushnir et al., 2016). The samples were then double-wrapped in tape and loaded diametrically in compression (at a constant displacement rate of 0.004 mm/s) until tensile failure using a servo-controlled uniaxial load frame (Figure 1c). The samples were unloaded following the formation of the first macrofracture (a throughgoing tensile fracture in each case) and their post-fracture permeability was measured using the same procedure described above. The plane of the throughgoing fracture was oriented parallel to the direction of fluid flow (see inset in Figure 1b).

3. RESULTS

Measured values of intact (pre-fracture) permeability are plotted as a function of connected porosity in Figure 2a. Intact permeability increases as connected porosity increases (Figure 2a).

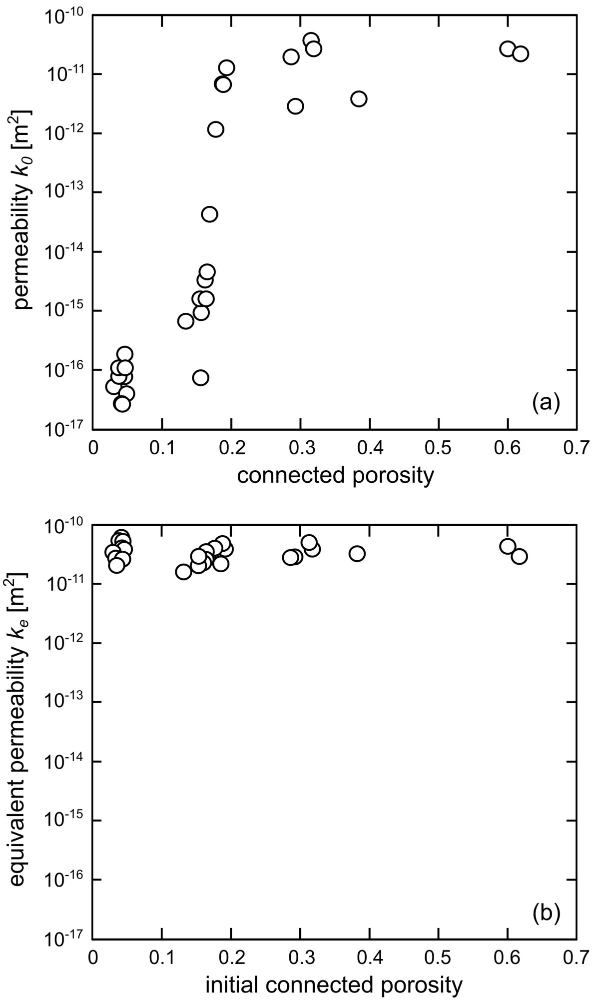

Figure 2: (a) Permeability as a function of initial connected porosity. (b) Equivalent permeability as a function of initial connected porosity. Taken from Heap and Kennedy (2016).

The permeability of the samples following the formation of a macroscopic tensile fracture—termed here the equivalent permeability—is plotted as a function of initial connected porosity in Figure 2b. The equivalent permeabilities of all the fractured samples fall within a narrow range regardless of the initial porosity (Figure 2b).

3. DISCUSSION

If we consider the permeability of a sample containing a fracture as an equivalent permeability, we can extract the fracture permeability using a two-dimensional model that considers flow in parallel layers (using the equivalent permeability, the host rock permeability, the area of intact rock, and the area of the fracture) (Figure 3). For more details see Heap and Kennedy (2016).

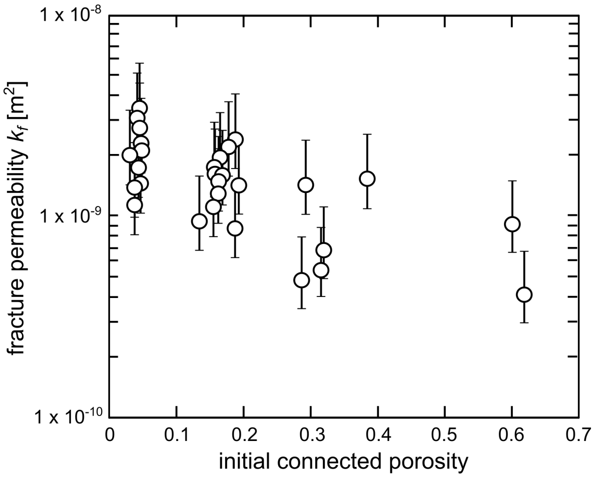

Figure 3: (a) Fracture permeability as a function of initial connected porosity. Error bars represent the anticipated variability of the fracture width at a confining pressure of 1 MPa (0.25 ± 0.1 mm). Taken from Heap and Kennedy (2016).

Using our fracture permeability data (Figure 3), we can model the equivalent permeability of a given length of rock (with chosen host rock permeability) containing 0.25 mm-wide tensile fractures using a one-dimensional relation that considers flow in parallel layers (for more details see Heap and Kennedy, 2016). We can now therefore explore the influence of lengthscale on the equivalent permeability of fractured andesitic rock.

If we consider a 10 m length of rock (Figure 4), we find that the increase in equivalent permeability with number of tensile fractures (i.e., fracture density) depends heavily on the permeability of the host rock. We also highlight that these modelled equivalent permeabilities differ considerably from the laboratory measurements of equivalent permeability, which were all in the range 2-6 × 10^{-11} m^2 (Figure 2b). The modelled curves in Figure 4 show that the equivalent permeability of a 10 m length of rock is essentially unaffected by fractures when the host rock permeability is between 10^{-13} and 10^{-11} m^2; by contrast, the addition of a single tensile fracture in low-permeability rock (between 10^{-15} and 10^{-17} m^2) increases the equivalent permeability by many orders of magnitude.

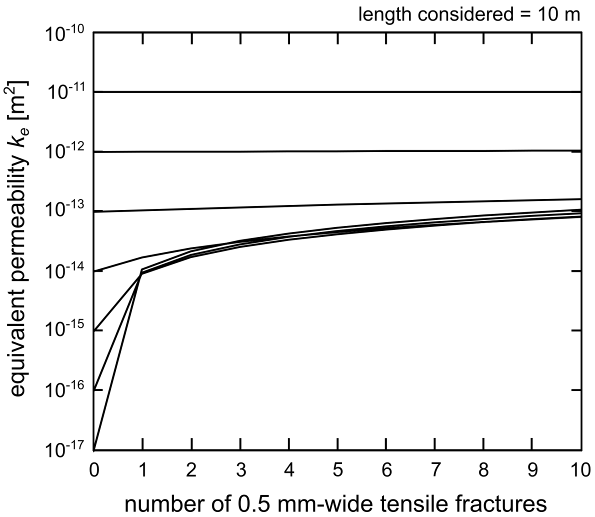

Figure 4: Equivalent permeability of a 10 m length of rock with host rock permeabilities from 10^{-17} to 10^{-11} m^2 as a function of the number of tensile fractures. Each fracture is 0.25 mm wide. Taken from Heap and Kennedy (2016).

The approach here demonstrates how laboratory-measured permeabilities can be used to better approximate equivalent (i.e., "upscaled") permeabilities. To emphasise, if we imagine a reservoir (host rock permeability = 1.0×10^{-17} m^2) that contains 15 fractures (0.25 mm-wide) over a length of 10 m, the equivalent permeability of that length of the reservoir, using a fracture permeability of 2.18×10^{-9} m^2 (determined using the power law relationship between the initial permeability and fracture permeability), is estimated using the model presented herein to be 8.2×10^{-13} m^2. Core samples taken from a borehole for laboratory measurements of permeability would therefore yield an underestimate of the permeability is the sample is pristine (the permeability of this sample would be 1.0×10^{-17} m^2) or an overestimation if the sample (length = 0.02 m) contains one throughgoing fracture (the equivalent permeability of this sample would be 2.7×10^{-11} m^2). As a result, care must be taken when using laboratory measurements of permeability to infer reservoir permeabilities.

We highlight that our modelling approach can be used to estimate the equivalent permeability of any length of andesitic geothermal reservoir for which the fracture density and width (from borehole image logs, for example) and the host rock porosity or permeability are known (wireline logging or core analysis).

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