Geophysical Research Abstracts
Vol. 18, EGU2016-9264, 2016
EGU General Assembly 2016

Scale-dependent permeability of fractured andesite

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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 m2. Following fracture formation, the permeability of the samples (the effective permeability) falls within a narrow range regardless of their initial porosity: 2-6 × 10-11 m2. However, laboratory measurements of fractured samples likely overestimate the effective permeability due to the inherent scale-dependence of permeability. To better understand 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 2.3 × 10-9 m2) than those in high-porosity samples (as low as 3.0 × 10-10 m2), a difference that can be explained by an increase in fracture tortuosity with porosity. We then use our fracture permeability data to model the effective permeability of rock with different host rock permeabilities (10-17 to 10-11 m2) populated by tensile fractures over a wide range of lengthscale. We find that the effective permeability of fractured andesite depends heavily on the initial host rock permeability and the scale of interest. At a given lengthscale, the effective permeability of high-permeability rock (10-12 to 10-11 m2) is essentially unaffected by the presence of numerous tensile fractures. By contrast, a single tensile fracture increases the effective permeability of low-permeability rock (< 10-15 m2) by many orders of magnitude. We also find that fractured, low-permeability rock (e.g. 10-17 m2) can have an effective permeability higher than that of similarly fractured rock with higher host rock permeability (e.g. 10-15 m2) due to the low-tortuosity of fractures in low-porosity andesite. Our modelling outlines the importance of fractures in low-porosity, low-permeability volcanic systems. While our laboratory measurements show that, regardless of the initial porosity, the effective permeability of fractured rock on the laboratory scale is 2-6 × 10-11 m2, the effective permeability of low-permeability rock is significantly reduced as the scale of interest is increased. The role of lengthscale on effective permeability diminishes for high-permeability rocks. In summary, due to the scale-dependence of permeability, laboratory measurements on pristine rocks significantly underestimate the effective permeability of a fractured volcanic system, and measurements on fractured rocks can significantly overestimate the effective 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.