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Effects of overpressure variations on fracture apertures and fluid transport

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ABSTRACT

For an isolated rock fracture in a homogeneous, isotropic rock subject to constant internal fluid overpressure or constant external driving stress, the ideal opening-displacement (aperture) profile or variation is that of a flat ellipse. For many mineral veins, dykes, tension fractures, normal faults, and other rock fractures, however, the opening-displacements show irregular aperture (thickness) variations very different from that of a flat ellipse. Here we present field data on typical fracture-aperture variations, as well as new numerical and analytical models to explain these data. We present the overpressure variation by Fourier cosine series, a very flexible method that can be used to model abrupt overpressure and driving-stress variations in vertical and lateral sections for fractures of various sizes and types. We calculate the opening-displacements of typical hydrofractures, and discuss the results with reference to mineral veins and dykes. We also present numerical models showing that when a fracture dissects layer, or parts of a single layer (such as a lava flow), with different stiffnesses (Young's moduli), the opening-displacement may show irregular variation even when the overpressure is constant. From the cubic law, the volumetric flow rates in the large-aperture segments of the mineral veins and dykes discussed in the paper may have been as much as 3–5-times the flow rates in the small-aperture segments. We propose that differences in volumetric flow rates are related to irregular opening-displacement variations in feeder-dykes is one principal reason for the development of crater cones, a universal feature of volcanic fissures.

1. Introduction

Much fluid transport in the crust occurs through rock fractures. This applies, for example, to the transport of ground water, geothermal water, gas, oil, and magma. The volume of fluid transported per unit time, the volumetric flow rate, through a fracture depends not only on its size, that is, its strike dimension (length) and its dip dimension (height), but also on its aperture (opening). In particular, the volumetric flow rate is a function of the aperture in the third power, an observation referred to as the "cubic law" in hydrogeology and related fields (Bear, 1993; De Marsily, 1986; Lee and Farmer, 1993). Because of this law, which applies to general laminar flow between comparatively smooth, parallel plates and is widely used to model fluid transport in rock fractures (Bear, 1993; Gudmundsson, 2011; Singhal and Gupta, 1999), it is important to understand the factors that determine the aperture changes or variations along the fracture strike and dip dimensions.

Fracture aperture depends partly on the host-rock properties and the fracture type. Mechanically, there are two main types of fractures: extension fractures and shear fractures. As is discussed below (Section 3), in fracture mechanics, extension fractures are modelled as mode I (opening or tensile mode) cracks, whereas shear fractures are modelled as either mode II (in-plane or forward shear mode) or mode III (anti-plane or transverse shear mode) cracks (Atkins and Mai, 1985; Broberg, 1999). Shear fractures include all faults and some joints. For shear fractures there is not a simple relationship between aperture and stress because the relative displacement across the fracture plane is parallel with the fracture. Extension fractures are of two basic subtypes: tension fractures and fluid-driven fractures, that is, hydrofractures. For uniform loading, there is a simple relationship between stress or pressure and the extension-fracture aperture, provided the host rock is isotropic and homogeneous. Here loading refers to the stresses, pressures, and displacements applied to the rock and external to its material (Gudmundsson, 2011). The simple relationship is that an extension fracture under a constant tensile stress (for a tension fracture) or fluid overpressure (for a hydrofracture) opens into a flat ellipse (Sneddon and Lowengrub, 1969; Tada et al., 2000).

The apertures of some extension fractures approach the ideal elliptical geometry, but many fractures show irregular and abrupt aperture variations (Figs. 1 and 2). Many mineral veins with strike dimensions up to several metres show this kind of irregular aperture variations

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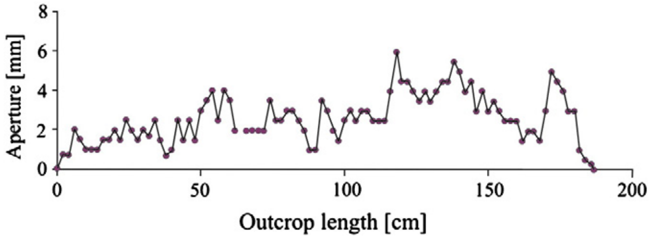

Fig. 1. Aperture variation, measured as mineral-filling thickness, of a vein in gneiss in West Norway. The vein is close to 190 cm long, with a maximum aperture (thickness) of 6 mm, the filling being quartz.

(Figs. 1 and 2). But large tension fractures and normal faults, with strike dimensions from a few hundred metres to many kilometres, show similar, irregular variations (Burgmann et al., 1994; Gudmundsson, 1987a, 1987b; Martel and Shacat, 2006). Generally, the irregular, and commonly abrupt, aperture variations are too large to be explained in terms of inaccuracy in measurement. When there are large variations in aperture over comparatively short distances along the fracture plane, the cubic law implies that much of the fluid transport may become confined or channelled to the parts or segments of the fracture with the largest apertures. This results in flow channelling (Tsang and Neretnieks, 1998) whereby much of or all the fluid transport through a fracture is confined to the large-aperture parts of the fracture. Flow channelling may be one reason for the formation of crater cones along volcanic fissures, as described below, and is also well known from tunnelling and fractured reservoirs of various types (Tsang and Neretnieks, 1998).

This paper has two main aims. The first is to present field data on fracture-aperture variations from different rock types. Most of the fractures are hydrofractures, that is, mineral veins and dykes, but for comparison we also show aperture variations along large tension fractures and normal faults exposed at the surface of the active rift zone in Iceland (Angelier et al., 1997; Sonnette et al., 2010). The fractures discussed in the paper are hosted by basaltic lava flows in Iceland, gneiss in Norway, and limestone in Britain, thereby including igneous, metamorphic, and sedimentary rocks. The second aim is to provide analytical and numerical models to explain general aperture variations of rock fractures, such as the examples here, and their effects on volumetric fluid-flow rates. The results are applied to volumetric flow rates through the types of fractures that eventually become mineral veins and dykes, in particular feeder dykes.

2. Field data

A typical irregular variation in aperture along mineral veins is seen in Figs. 1 and 2. The strike dimension of both veins is about 2 m, the mineral filling is quartz, the host rock is gneiss, and the location is Vaksdal in West Norway (Simmenes, 2002). The maximum vein aperture, measured as thickness of the mineral filling, is about 6 mm in the vein in Fig. 1 and 9 mm in the vein in Fig. 2. The aperture varies irregularly along the vein length, commonly by 20–50% of the

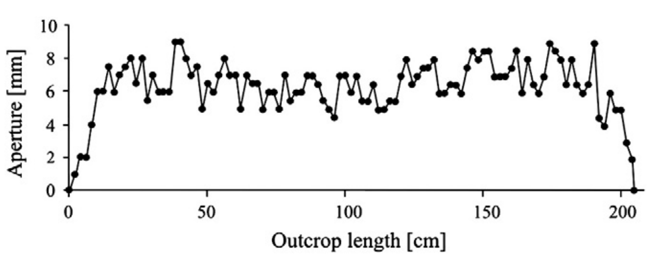

Fig. 2. Aperture variation, measured as thickness of the mineral filling, of a vein in gneiss in West Norway. The vein is about 205 cm long, with a maximum aperture (thickness) of 9 mm, the filling being quartz.

maximum vein thickness. The veins are non-restricted, that is, they thin out at their lateral ends (tips) and do not end in other veins or structures.

Very similar thickness variations occur in non-restricted mineral veins in basaltic lava flows in North Iceland (Berg, 2000; Gudmundsson et al., 2002; Lyslo, 2002; Skurtveit, 2000). The mineral filling is mostly zeolites, quartz and calcite. Some of the veins reach maximum thicknesses of 10–15 mm, others reach 20–25 mm. The thickness variation is irregular, similar to that in Figs. 1 and 2, and is generally larger for the thicker veins. Thus, while for the thin veins the irregular variation is commonly about 5 mm, for the thickest veins it reaches up to 10–15 mm. Generally, the thickness variation is mostly 20–50%, but in places as much as 60–70%, of the maximum vein thickness.

Irregular thickness variations, although much larger, also occur in dykes. For example, Gudmundsson (1983) measured the thickness variation along two basaltic dykes hosted by basaltic lava flows and, in between, thin scoria and soil layers, in the East Iceland (Fig. 3). Both dykes are many kilometres long, but the lengths of the studied parts are 2–2.5 km. Each dyke has a maximum thickness of 9–10 m, shows irregular thickness variations of mostly 2–3 m and, in places, 4–6 m. Thus, the dykes vary in thickness by 30–50% of their maximum thicknesses. Similar, although somewhat smaller, thickness variations were observed in dykes in New Mexico, USA, hosted by shale, where a 200-m-long segment shows irregular thickness variations of about 30% of a maximum thickness of around 3 m (Delaney and Pollard, 1981).

Thickness variations of dykes along their heights (dip dimensions) are also well known. For example, many well-exposed feeder and non-feeder dykes in the subvertical caldera walls of the Miyakejima Volcano in Japan show irregular variations in the thickness as they dissect layers with different stiffnesses (Geshi et al., 2010). Thus, some of the dykes show an abrupt thickness increase where they dissect soft (compliant) scoria and tuff layers and a thickness decrease where they dissect stiff lava flows.

The dykes and mineral veins are primarily driven open by their internal fluid overpressure (driving pressure) and are thus hydrofractures. For any particular point(s) of reference on the fracture walls (surfaces), overpressure is defined as the difference between the total fluid pressure inside the fracture and the normal stress at that point. For a pure extension fracture, the stress acting perpendicular to the fracture walls is the minimum principal compressive (maximum tensile) stress, σ_3. Dykes and mineral veins are hydrofractures, but similar variations in aperture are seen for many large tension fractures and normal faults in rift zones (Fig. 4). The opening (aperture) of tension fractures and shear displacements on normal faults are primarily related to driving stress, defined as the difference between the remote applied (tensile or shear) stress and the residual (tensile or shear) strength on the fracture walls

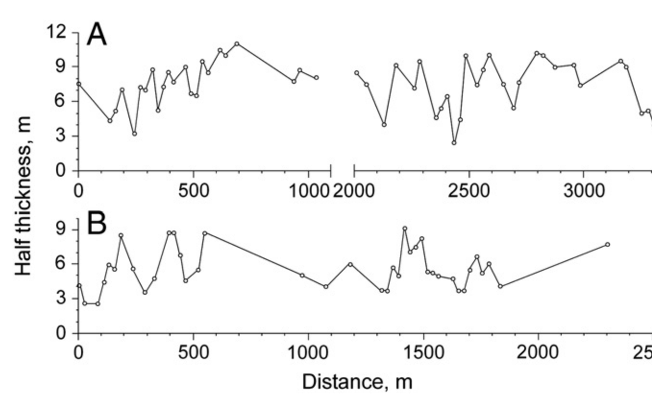

Fig. 3. Aperture variation (measured as half thickness) in two segments of regional, basaltic dykes in East Iceland (data from Gudmundsson, 1983). A) This dyke segment cuts through a basaltic lava pile with numerous red, soft soil and scoria layers in between the lavas. Many of the thickness changes are related to stiffness differences between the lava flows and the soil/scoria layers. B) This dyke segment cuts fewer scoria/soil layers, which may be one reason for less variation in aperture/thickness.