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Effects of rock stiffness and loading conditions on aperture variations of rock fractures and associated fluid flow rates

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Fracture aperture depends on the host-rock properties, particularly the stiffness (Youngś modulus), the loading conditions (fluid pressure, driving stress), and the fracture type. Mechanically, there are two main types of fractures: extension fractures (tension fractures and fluid-driven fractures or hydrofractures) and shear fractures (faults). For shear fractures there is not a simple relationship between aperture and driving stress because the displacement is parallel with the fracture. In the case of extension fractures, a constant tensile stress or a constant fluid overpressure give rise to a simple relationship between stress or overpressure and fracture aperture, provided the host rock is isotropic and homogeneous. Here overpressure is defined as the difference between the total fluid pressure inside the fracture and the stress acting perpendicular to the fracture walls whereas driving stress is the difference between the remote applied (tensile or shear) stress and the residual strength (tensile or shear) on the fracture surface after opening or sliding. Thus, an extension fracture under a constant driving stress or fluid overpressure opens into a flat ellipse. However, the aperture of rock fractures, when measured along fracture lengths (strike dimensions), commonly shows irregular variations. This applies, for example, to many mineral veins, ranging in strike dimensions from a few tens of centimetres to many metres. But it applies equally well to large tension fractures and normal faults ranging in strike dimensions from a few hundred metres to many kilometres. For all the fractures, the aperture variations are too large to be explained in terms of inaccuracy in measurement.

Here we present field data on typical fracture-aperture variations, as well as new numerical and analytical models to explain these data. In the analytical models we focus on how any variation in stiffness along the fracture results in variations in overpressure (for a hydrofracture) and driving stress (for a tension fracture or a fault). We present the overpressure variations by Fourier cosine series, calculate the apertures of typical hydrofractures, and discuss the results with reference to mineral veins and dykes. The results indicate that this analytical method is very flexible and can be used to model abrupt overpressure and driving-stress variations in vertical and lateral sections for fractures of various sizes and types. We also present numerical models showing that any variation in stiffness along a fracture path, even if the applied loading is constant, results in variation in aperture. In particular, the results indicate that when fluid overpressure is the only loading, hydrofractures such as dykes and mineral veins tend to have larger apertures in the low-Young's modulus (compliant) layers. We explore the aperture-variation results using analytical models for volumetric flow rates, based on the cubic law. The results indicate that, for the mineral veins and dykes discussed in the paper, the volumetric flow in the large-aperture segments may have been as much as 3-5-times the flow rate in the small-aperture segments. This has implications for fluid transport in fractured reservoirs of oil, gas, magma, geothermal water, and ground water.