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Estimating flow heterogeneity in natural fracture systems

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Abstract

Examples of small to medium scale fault systems have been mapped in Jurassic sedimentary rocks in north Somerset, England. These examples include contractional and dilational strike-slip oversteps as well as normal faults. These maps form the basis of calculations performed to investigate heterogeneity in natural fracture systems with the aim of predicting fluid flow localisation in different fault styles. As there is no way to measure fracture aperture directly, we use vein thickness to represent an integrated flow path or 'palaeo-aperture' from which we derive a representation of the flow distribution. Three different methods are used to estimate flow heterogeneity based on: (1) fracture density (the ratio of fracture length to area), (2) fracture aperture (fracture porosity) and (3) hydraulic conductance (fracture permeability normalised to the pressure gradient and fluid properties).

Our results show that fracture density and hydraulic conductance are poorly correlated and that fracture density does not fully represent the natural heterogeneity of fracture systems. Fracture aperture and hydraulic conductance indicate stronger degrees of flow localisation. Different types of structures also seem to display characteristic and predictable patterns of heterogeneity. Normal fault systems show the highest magnitude of localisation along the faults rather than in the relay ramps, while contractional and dilational strike-slip systems show very strong localisation in the faults and oversteps, respectively. In all cases the amount of damage in the oversteps can modify such patterns of heterogeneity.

Keywords: fault; fracture; fluid flow; fracture density; fracture aperture; hydraulic conductance; permeability

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1. Introduction

Faults and fracture networks occur in the brittle crust over a wide range of scales and lithologies. They can significantly modify the hydraulic behaviour of otherwise fairly homogeneous porous media, especially in very low permeability rocks. Depending on their degree of mineralisation, individual fractures may provide pathways that increase, decrease or block flow and thus, raise or lower the permeability of the rock. Fracture networks are not static systems and can behave differently as conditions change. Many crustal processes such as deformation, mineralisation or fluid migration in aquifers, hydrocarbon

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reservoirs (e.g. Aguilera, 1995) and geothermal systems (e.g. Gehlin and Hellstrom, 2003; Minissale et al., 2003) occur in fractured rock masses. These processes are often coupled and lead to highly localised flow (e.g. Sanderson and Zhang, 1999). Understanding flow heterogeneity in these systems is therefore important for fluid flow modelling, for example, in applied cases such as geothermal resource exploitation, waste disposal and monitoring, petroleum engineering and mineral exploration.

Although the geometry and characteristics of a fracture system depends on the stress field during fracturing, it has been shown (e.g. Barton et al., 1995; Zhang and Sanderson, 1996a) that the conductivity of a fracture network may change as a function of the orientation and magnitude of the maximum stress. This results from selective opening and closing of fractures, often in response to slip on others (Sanderson and Zhang, 1999). In this paper, the extent of the changes in conductivity that might be expected to result from variations in fracture aperture is investigated for some natural examples of metre-scale vein and fault systems.

A common assumption that is made in estimating the permeability of a rock mass with open fractures is that total permeability increases as a function of fracture density (e.g. Shimo and Long, 1987; Renshaw, 1997; Wei and Pringle, 1998; La Pointe, 2000; Wu and Pollard, 2002), where fracture density is the total length of fracture per unit area. In systems where the fracture network is homogeneous and isotropic this may be an adequate approximation, but a simple conceptual model can show how this might not always be the case. Fig. 1 depicts two rock blocks (A and B) of equal dimensions and equal strain. Block A contains a single fracture of aperture 1 unit, whereas block B contains two fractures of aperture 0.5 units. The fractures are approximated as prismatic tubes with smooth walls and cross-sectional areas given by the length (L) and aperture (a) of each fracture. The flows Q_A and Q_B, under a vertical pressure gradient, are orthogonal to the upper surface of each

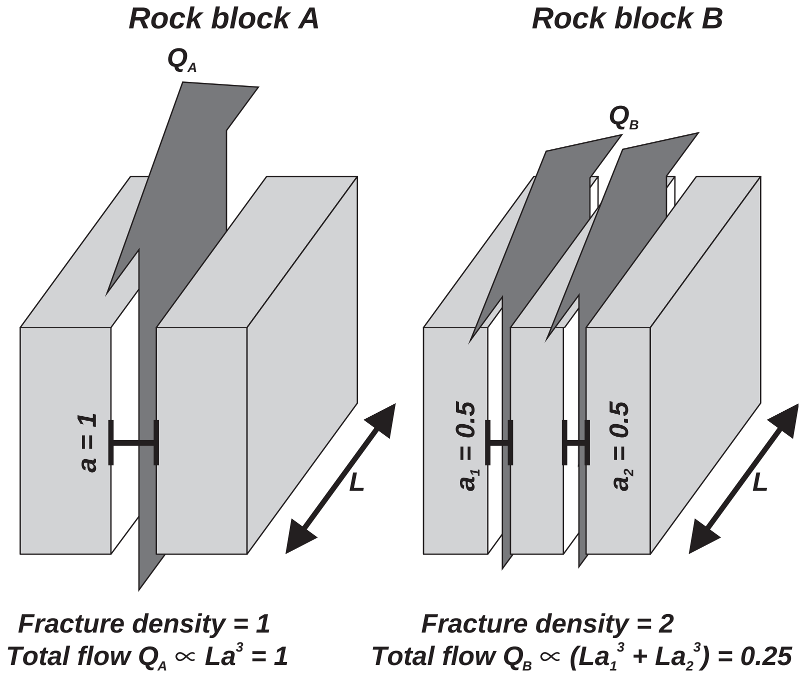

Fig. 1. Rock blocks A and B have equal dimensions and strain. Applying a simple flow law, such as the cubic flow law to the fractures in these blocks yields the result indicated in the figure: despite block B having a fracture density twice that in block A, fluid flow would in fact be four times greater in block A than in block B because of the larger aperture in block A. *(L)* is fracture length and *(a)* is fracture aperture.