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The effect of tectonic environment on permeability development around faults and in the brittle crust

D.R. Faulkner *, P.J. Armitage

Rock Deformation Laboratory, Geology and Geophysics, School of Environmental Sciences, University of Liverpool, UK

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ABSTRACT

Fluid flow in the brittle crust is strongly influenced by brittle deformation. The tectonic environment in which brittle deformation occurs will dictate both the orientation and magnitude of the resulting permeability tensor. The effect of the tectonic environment on permeability is considered conceptually, and triaxial deformation experiments showing microfracture permeability development in Westerly granite in the pre-failure region, prior to pervasive shear failure of the sample, are used to illustrate the concept. In the experiments, the permeability changes are greatest in a simulated extensional tectonic regime and smallest in a compressional tectonic environment. The results are most usefully considered in the context of effective mean stress (P) and differential stress (Q) space where permeability may be contoured to allow an indication of permeability development under any experimental loading path.

1. Introduction

Brittle damage in the upper crust typically results in dilatancy that provides enhanced pathways for fluid flow. Faults are structural features in the brittle crust that strongly concentrate fractures around them (Chester and Logan, 1986; Faulkner et al., 2010; Wibberley et al., 2008). The development of fracture networks in the brittle crust, and in particular surrounding faults, both in the long term and over the seismic cycle, will dictate the flux of fluids and influence crustal strength, earthquake nucleation and propagation, the migration of oil and gas, and the distribution of economically important mineral resources (Blanpied et al., 1992; Chester and Logan, 1986; Micklethwaite, 2009; Miller et al., 2004). Crustal permeability is also of vital importance when considering the long-term storage of hazardous materials or carbon dioxide sequestration (Armitage et al., 2013).

Fractures in the brittle crust occur on many different scales. Grain-scale damage (microfracturing) occurs at stresses above ~50% of the macroscopic failure strength (Brace, 1964; Scholz, 1968). When the macroscopic failure strength is reached, a shear or tensile fracture occurs. Macroscopic failure manifests itself as other types of damage, particularly in the top few kilometers of the crust, such as breccias (Sibson, 1986; Woodcock et al., 2006), pulverized rock (Dor et al., 2006; Mitchell et al., 2011) and pervasive, distributed fracturing, commonly seen in carbonate sequences, for example in the central Apennines in Italy (Aydin et al., 2010).

Faults in particular are regions where stresses become concentrated and consequently an enhanced concentration of fractures such as that outlined above results, often related systematically to the fault core. In a linear-elastic rock, stress perturbations reduce as $1/\sqrt{r}$ where r is the distance from a stress concentrator. Many sources for fracturing around faults have been suggested, from process zone yielding around the propagating tip of a fault (Cowie and Scholz, 1992), geometric irregularities ('wavy' faults; Chester and Chester, 2000) and dynamic earthquake damage (Bhat et al., 2007; Rice et al., 2005).

The distribution of microfractures surrounding faults generally shows an exponential decrease with distance from the fault core (Anders and Wiltschko, 1994; Mitchell and Faulkner, 2009; Vermilye and Scholz, 1998; Wilson et al., 2003), although some lithologies, such as porous sandstones, do not appear to show this relationship (Faulkner et al., 2010; Shipton and Cowie, 2001). Macroscopic fractures also show an exponential decrease with distance (Mitchell and Faulkner, 2009; Wilson et al., 2003). For porous sandstones, deformation bands appear to show a similar spatial relationship with the fault core (Berg and Skar, 2005; de Joussineau and Aydin, 2007).

Permeability has sometimes been suggested to be a 'toggle switch' in geological processes, with low-permeability rocks essentially having zero (or close to zero) permeability below failure, and connectivity and high permeability post-failure

* Corresponding author. Tel.: +44 151 794 5149.
E-mail address: faulkner@liv.ac.uk (D.R. Faulkner).

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(Miller and Nur, 2000). This 'elastic–plastic' view of fault zone properties discounts important rock property changes that occur in the sub-failure region (Barnhoorn et al., 2010; De Paola et al., 2009; Faulkner et al., 2006; Mitchell and Faulkner, 2008, 2012; Zoback and Byerlee, 1975). Regardless of the mechanism by which fracturing accumulates, if stress in any part of the brittle crust approaches the failure stress of the rock, then fractures would be expected even in what might typically be viewed as 'intact' rock.

The development and properties of fracture networks depend on the lithology in which damage is accumulated, and the depth (Faulkner et al., 2010). This aside, permeability in the brittle crust is controlled by the density, distribution and orientation of crack damage that is present. Permeability will be anisotropic wherever oriented and connected crack networks develop. In addition, the permeability will be strongly influenced by the stress field that acts on the crack network. The magnitude and orientation of the stress field will vary significantly as a result of the tectonic environment: extension, compression or strike–slip. Hence the overall permeability will be a product of some crack density tensor and the stress tensor that acts on it.

Here, we test the notion that permeability will develop differently under various loading conditions approximating to different tectonic environments in the Earth's crust. While the effect of the tectonic environment has previously been considered for the mechanical development of faults (e.g. Sibson, 1991, 1993), the effect of the tectonic environment on the development of the permeability has not been fully considered (but see, for example, Cox, 2010). Stress path variation and its effect on the permeability of porous rocks have been considered previously (e.g. Schutjens and De Ruig, 1997) but an extended suite of experiments has never been done.

We first develop the ideas conceptually, but also test these by performing triaxial deformation experiments where microfracture permeability is measured in samples of Westerly granite under different loading paths to failure. Although our experiments will not represent the overall permeability development, which will be also influenced by the presence of macrofractures, it captures the development of microfracture permeability and serves as an illustration of the importance of stress path on the permeability development.

2. The development of stresses in different tectonic environments

The development of stress on faults during the faulting cycle depends on the tectonic environment. In Andersonian faulting (Anderson, 1905) owing to the presence of the free surface, one of the principal stresses is always vertical and hence equal to the overburden. Depending on the tectonic environment, this vertical stress can be the maximum (σ_1), intermediate (σ_2) or minimum (σ_3) principal stress. In compressional tectonic environments, where thrust faulting is expected, the vertical stress is the least principal stress, and is fixed ($\sigma_v=\sigma_3$). Hence for failure to occur, one of the horizontal principal stresses must increase. In this case, the mean stress (($\sigma_1+\sigma_2+\sigma_3$)/3) increases as failure is approached, and the differential stress (σ_1–σ_3) is large. Conversely, during extensional faulting, the fixed vertical stress is the greatest principal stress and failure is achieved by reduction of one of the horizontal stresses. In this case, the mean stress decreases as failure is approached and, although the differential stress also increases, it is necessarily much smaller than failure in compressional tectonic environments. There is a special case in wrench (strike–slip) faulting here referred to as 'direct shear', where the intermediate stress is the vertical stress and the largest horizontal stress (σ_1) increases at twice the rate at which the least principal stress decreases. In this case, the mean stress as failure is approached is constant. These concepts and ideas are illustrated in Fig. 1. In all these cases the pore fluid pressure is constant and consequently the effective mean stress (the mean stress minus the pore fluid pressure) is unaffected by pore fluid pressure variations. In nature, changes in the pore fluid pressure will likely play an important role as rock approaches failure.

The consequences of different tectonic environments on the mechanics of faulting have been explored previously (Sibson, 1991, 1993). Sibson termed extensional faulting 'load weakening' because the normal stress on the fault decreases at the same time the shear stress increases as failure is approached. Compressional faulting is termed 'load strengthening' as, in this case, the normal stress increases as the fault is loaded. This treatment also assumes pore pressure does not vary, as scenarios can be envisaged where an increase in pore fluid pressure during compressional loading, for example, could result in a load-weakening stress path. Clearly, both the *development* of crack networks as well as their *properties* will be strongly affected by the variations in differential stress, that might be expected to widen or lengthen existing cracks, and the effective mean stress, that will serve to close existing cracks. The micromechanics of the rock during deformation is not considered in detail here; it is the concept and exploration of the concept with experiments that is the aim.

In previous triaxial experimental studies of the permeability development during loading the confining pressure ($\sigma_2=\sigma_3$) is fixed and the axial stress (σ_1) is increased to failure (Zoback and Byerlee, 1975; Mitchell and Faulkner, 2008; De Paola et al., 2009). The experiments thus approximate to the development of permeability in the direction of σ_1 in a compressional tectonic regime. In this study we control confining pressure, pore pressure, and axial stress to produce failure approximating to a number of tectonic scenarios. These ideas are explored further by a series of experiments the results of which are presented in Section 3.

The variation in the orientation of the stress tensor between different tectonic environments will produce variations in the orientation of the permeability tensor. Fig. 2 illustrates that mode I microfractures and shear fractures will likely intersect close to the direction of the intermediate principal stress, and this will be the principal axis of the permeability tensor, owing to the greatest fracture connectivity (Cox, 2005). In compressional tectonic environments where other structures such as folds may occur, this principal permeability direction will only be reinforced by hinge-parallel fluid flow (Sibson, 2005). Consequently, the orientation of the permeability tensor produced by fracturing will vary between tectonic environments. For normal faulting, the principal permeability direction will be horizontal, with the intermediate permeability direction oriented vertically. The lowest permeability will be horizontal, oriented normal to the strike of the fault. For a compressional tectonic environment, the two major permeability tensor axes will be horizontal, implying that vertical fluid flow will likely be inhibited in this tectonic regime. For strike–slip faulting, the principal permeability direction will be vertical.

3. Experimental results showing the development of permeability under different loading conditions

3.1. Experimental methods

Fig. 3 illustrates the sample arrangement used for the experiments. 20 mm diameter cores were prepared to 50 mm length to ensure a sample diameter–length ratio of 2.5 (Paterson and Wong, 2005). The sample ends were ground to a squareness better than 0.2 μm. The oven-dried samples were jacketed in a 2.5 mm wall thickness PVC jacket prior to insertion into the sample assembly.