Influence of Normal and Shear Stress on the Hydraulic Transmissivity of Thin Cracks in a Tight Quartz Sandstone, a Granite, and a Shale

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Abstract Transmissivity of fluids along fractures in rocks is reduced by increasing normal stress acting across them, demonstrated here through gas flow experiments on Bowland shale, and oil flow experiments on Pennant sandstone and Westerly granite. Additionally, the effect of imposing shear stress on the hydraulic transmissivity of thin cracks is demonstrated experimentally in Pennant sandstone and Westerly granite. The results shown here cast doubt on the commonly applied presumption that cracks with high resolved shear stress are the most conductive. In the case of Bowland shale, crack transmissivity is commensurate with matrix permeability, such that shales are expected always to be good seals. For the sandstone and granite, unsheared crack transmissivity was respectively 2 and 2.5 orders of magnitude greater than matrix permeability. For these rocks crack transmissivity can dominate fluid flow in the upper crust, potentially enough to permit maintenance of a hydrostatic fluid pressure gradient in the upper crust.

Plain Language Summary Few direct experimental determinations have been made of how shear and normal stresses affect hydraulic transmissivity of rocks, and the importance of flow through cracks in deep waste disposal, geothermal energy, and stimulation of hydrocarbon recovery. Here we measure crack flows in lab experiments, comparing granite, sandstone, and shale and show that small shear displacements greatly reduce crack conductivity. Cracks in granite and sandstone greatly enhance flow compared to porous rocks, but this is not so for shales, which even in the cracked state form very effective, long-term sealing layers for oil, gas, and water.

1. Introduction

Fluid flow through rocks takes place via cracks and faults in addition to flow through the rock matrix. In low permeability rocks, fracture flow can be the dominant process, even though the cross-sectional area presented by the fractures may be small, provided crack hydraulic transmissivity is sufficiently high compared to the matrix permeability. It is well established that flow through natural or hydraulically induced fractures is of particular importance to the production of oil, natural gas, water, and geothermal energy, and understanding crack flow is vital in connection with waste fluid disposal by deep injection, CO2, and natural gas storage underground, and in radioactive wastes containment (Davies et al., 2013; Green et al., 1988; McGarr, 2014; Rutter & Mecklenburgh, 2017; Wilson et al., 2015). Its importance has long been recognized in connection with the hazard of induced earthquakes (Fang et al., 2017; Guglielmi et al., 2015; Healy et al., 1968; McGarr et al., 2015; Rubinstein & Mahani, 2015). Townend and Zoback (2000) recognized the importance of cracks in permitting sufficient fluid interconnectivity in otherwise low matrix permeability rocks such that a hydrostatic fluid pressure distribution can be maintained at least to midcrustal depths, in order to satisfy the constraints of in situ stress determinations in deep boreholes.

Through laboratory tests and in situ experiments on various strong, brittle rocks (Co & Horne, 2014; Gale et al., 1990; Hakami & Barton, 1990; Jung, 1989; Tokunaga & Wan, 1997; Waite et al., 1999) it has been established that increasing normal stress across crack faces reduces the hydraulic transmissivity of fractures. Some studies have also included the effects of shear offsets across crack walls, as a result of applying a combination of normal (σn) and shear (τ) stresses (Yeo et al., 1998). For example, in experiments up to 3 MPa normal stress Lee and Cho (2002) showed that fracture transmissivity increased by 2 orders of magnitude during shear...
offsets between 1 and 15 mm, after the first 1 mm of slip, as predicted by an analytic model (Barton et al., 1985). Auradou et al. (2006) also found that fluid flow on the slip plane in a direction normal to shear displacement direction became increased by more than flow parallel to it. From studies like these has emerged a dominant view that onset of shear displacements increases the hydraulic transmissivity of cracks in rocks.

In shales, most interest has naturally focused on the shape and hydraulic transmissivity of opening-mode cracks induced by hydraulic fracturing, and especially the ability of proppant sand grains to maintain flow when fluid pressure is released and fractures attempt to close under the influence of normal stress. For example, Zhang et al. (2013, 2015) used a standardized hydraulic flow cell to measure the normal stress dependence of fracture transmissivity over the range of reservoir pressures and temperatures and demonstrated the transmissivity-enhancing role of sand proppants (American Petroleum Institute industry-standard; API RP 61, 1989; API RP 60, 1995).

The influence of the additional application of shear stress on shale fracture transmissivity was expected to enhance transmissivity in the same way as reported for other silicic rock types (Johri & Zoback, 2013). Relatively few experimental studies have been performed, usually at low stresses but to large shear offsets (e.g., Cuss et al., 2011; Gutierrez et al., 2000). However, Rutter and Mecklenburgh (2017) reported experimental data for flow through bedding-parallel cracks in shale at effective normal stresses (total normal stress minus pore fluid pressure, also known as Terzaghi effective pressure) up to 90 MPa and found that the initiation of shearing caused dramatic reduction in hydraulic transmissivity.

This paper reports the results of experiments comparing the transmissivity of thin cracks in three low permeability but otherwise markedly different rock types. The behavior of a tight quartz sandstone and a granite are compared with the results for the shale studied using the same methods by Rutter and Mecklenburgh (2017). The crack-normal pressure was varied up to that corresponding to about 3 km depth of burial. Additionally, shear stress was increased while keeping the effective normal stress across the fracture constant, up to the initiation of permanent slip. The transmissivity to gas or liquid was measured after each shear stress increment. The permeability of the rock matrix was also measured to provide a reference for comparison with flow through a crack.

2. Test Materials and Experiments Performed

In order to minimize fluid transport through the rock matrix compared to flow through the crack, it is important to use a relatively low permeability host rock, or otherwise to ensure that the rock matrix does not present a “short-circuit” route for fluid flow. The three different rock types used met this requirement. All samples were tested after oven drying to constant weight at 60°C to avoid damage to clay mineral grains and the likelihood that any residual moisture would affect mechanical behavior or permeability measurements.

1. Pennant sandstone is a gray, durable, quartz sandstone of upper Carboniferous age from South Wales (Kelling, 1974). A large, homogeneous block was obtained from a monumental mason. Samples from the same block were used in rock mechanics studies by Hackston and Rutter (2016) and Rutter and Hackston (2017). Pennant sandstone displays a weak grain shape orientation parallel to bedding (Figure 1), but the bedding orientation is not well defined by microstructural layering or inhomogeneities. Effective porosity determined by helium pycnometry is 4.6% ± 0.6. From chemical mapping on the scanning electron microscope (SEM), modal composition is 70 vol% quartz plus 15 vol% feldspar of mean grain diameters 200 ± 90 μm. The sand grains show indentation by pressure solution and are partially cemented by quartz overgrowths. The remaining interstitial spaces (12 vol%) are largely filled by muscovite, oxides, and clay minerals.

2. Westerly Granite is a near-isotropically textured microgranite from a quarry in Rhode Island, USA. Rocks from this source have been extensively used in rock mechanical investigations for many years (e.g., Tullis & Yund, 1977; Wong, 1982). It consists of feldspars (67 vol%), quartz (24%), biotite (5%), and hornblende (1%) (Figure 1). The mean grain size of the feldspars is under 1 mm, and the texture is near isotropic, with a very weak orientation of laths of feldspar. Effective porosity by helium pycnometry is 0.95% ± 0.37.

3. Bowland shale is a foliated mudstone of middle Carboniferous age from a vertical borehole (normal to bedding) at a depth of 2.5 km near Manchester, England. This rock was used in a preliminary study of crack transmissivity by Rutter and Mecklenburgh (2017), and these previously reported results are here
compared results for the other two rock types. The shale sample displays a marked lamellar structure defining the bedding (Figure 1). From X-ray diffraction and SEM analysis it is a siliceous mudstone with dispersed silt-sized quartz grains and a matrix of mud-sized quartz of about 20 μm grain size and smaller together with detrital muscovite and kaolinite, with only traces of carbonate. Pyrite occupies 1 to 2 vol%, and there is approximately 4 vol% organic matter. Effective porosity by helium pycnometry is 1.9% ± 0.4.

Experiments were performed as follows:

1. The rock matrix permeability of each of the starting materials was measured as a function of effective hydrostatic confining pressure. This was done in all cases using argon gas as the permeating fluid.
2. The resistance to frictional sliding along the crack surface was measured as a function of effective normal stress. This was usually done as rock-on-rock sliding, but for comparison with previous work, some measurements were made on Westerly granite with a thin layer of fault gouge of crushed granite placed between the sliding surfaces.
3. The transmissivity along the saw cut surfaces was measured as a function of effective normal stress, first with zero shear stress and then after progressively increasing shear stress at each of three constant effective normal stresses, until frictional sliding began.

The low transmissivity of the shale cracks required the use of argon gas as the permeating fluid, but the much higher transmissivities of the sandstone and the granite cracks required the use of a more viscous oil. The same oil (dioctyl sebacate synthetic ester, Reolube DOS®) was employed that was used as the confining pressure fluid.

2.1. Apparatus Used and Specimen Assembly

Experiments were carried out in the same conventional triaxial testing machine as used for the previous study of crack transmissivity in shale reported by Rutter and Mecklenburgh (2017). Machine specifications are given.

Figure 1. (a) Pennant sandstone backscattered electron image. Gray, near equant, partially sutured grains are quartz, with intergranular spaces largely filled with clay minerals, detrital micas, and small oxide (bright) grains. (b) Optical micrograph (plane-polarized light) of Bowland shale, with dispersed silt grains and oriented clusters of clay minerals and detrital micas that define bedding planes. Organic grains are black. (c) Optical micrograph (crossed polars) of Westerly granite, dominated by alkali feldspars that are partially clouded, clear quartz grains, and a small proportion of biotite mica.
in that paper. Upstream pore fluid pressure was controlled using one of two servo-controlled pore volumometers, according to whether argon gas or oil was being used as a pore fluid. Pore pressure measurements were made to a resolution of ±0.02 MPa using standard electronic pressure transducers.

Samples were prepared from 25.4 mm diameter cores cut normal to bedding in the case of the sandstone and in an arbitrary common orientation in the case of the granite. A simulated planar crack was made at 45° to the rock cylinder axis with a diamond saw (Figure 2). This was done to maintain a degree of morphological consistency between samples of a given rock type and between rock types. It was not feasible to fabricate samples of shale with the saw cut parallel to the bedding planes because the borehole core sample supplied was too small to permit coring at 45° to bedding. Therefore, 3 mm thick bedding-parallel slabs were cut and glued with epoxy cement to 45° saw cuts made in 25.4 mm diameter aluminum cylinders to act as forcing blocks, in the manner employed by Rutter and Mecklenburgh (2017). The surfaces of the 45° saw cuts were finished by grinding on abrasive paper of 220 grit (60 μm particle size).

In all cases pore fluid was given access to the “crack” surfaces via nominally 1 mm diameter holes connecting the centers of the specimen ends to positions near the elliptical periphery of the crack surface as illustrated in Figure 2. These would allow fluid injection and withdrawal respectively parallel to the long and short axes of the ellipse, that is, parallel and perpendicular to the slip direction when the crack was loaded in axial shortening, also termed respectively downdip and along-strike flow configurations. Copper wire inserts were used in the holes to reduce pipework volume and the risk of gouge particles produced on the shear surfaces being forced into the pipework, but the latter was further inhibited by using 2 mm thick porous stainless steel filter plates (17% porosity) at each end of the cylindrical forcing blocks. For the matrix permeability measurements made on intact rock cylinders, the 2 mm thick filter plates served to spread the pore fluid over the entire circular ends of the specimens.

Figure 2. (a) Schematic longitudinal section through a cylindrical sample specimen configuration as used for downdip flow, parallel to shear direction. (b) Shows the two alternate fluid injection and withdrawal hole combinations for along-strike and downdip flows on the elliptical slip surface. Compression direction (σ1) for shear loading is vertical. At each end of the specimen assembly a 25.4 mm diameter porous steel disk, 2 mm thick, was placed to inhibit flushing of rock particles into the pore fluid system.
A 1 mm wall thickness tube of neoprene rubber was placed immediately around the sample to prevent pore fluid flow around the outer periphery of the saw cut, and an outer jacket of heat shrink tubing sealed the sample assembly to the loading pistons. The inner tubing also served to prevent the sharp leading edge of the saw cut specimens from puncturing the outer, thinner jacket when frictional sliding started. The jackets did not have any significant axial load bearing capacity (0.1 MPa differential stress or less).

Despite the crack surfaces being similarly ground before use, the surface finishes were quite different, in accordance with their different mineralogies and the way that they respond to grinding. Frictional sliding also modified the surface morphology of the different rocks to different degrees, always causing roughening. Figure 3 compares the surface morphologies of the rocks as measured by profilometer with each other and before and after frictional sliding. The standard deviations of the profilometer measurements about the mean values were used as an index of relative roughness of the surfaces (Figure 3). As might be expected, the shale surface was always smoothest and all initial surfaces were always less rough than the nominal particle size of the abrasive particles used.

Before hydraulic transmissivity measurements were made under resolved shear stress along the rock/rock interface, measurements of transmissivity were made without shear stress but with increasing amounts of effective normal stress up to a maximum of 96.5 MPa, equal to the applied hydrostatic confining pressure minus the pore pressure. Thus, all specimens were initially taken to this effective normal stress, irrespective of subsequent combinations of normal and shear stress used.

Except for some of the frictional sliding determinations, all samples were compressed parallel to the cylindrical specimen axis at 20°C to give rise to a resolved shear stress along the crack surface. Servo control of the axial load and separately from the confining pressure was used to permit resolved shear stress on the crack plane to be increased while keeping constant the resolved normal stress across the plane (Rutter & Mecklenburgh, 2017). For a 45° saw cut as used in this study, this results in the confining pressure having to be decreased by an amount equal to the resolved shear stress.

Water was not used as a pore fluid. This was to prevent possible water-weakening effects relative to tests on the dry rock and to avoid clay expansion effects in the shale and sandstone. Weakening effects of water on some sandstones have previously been described (e.g., Baud et al., 2000; Colback & Wiid, 1965; Duda & Renner, 2013; Hadizadeh & Law, 1991). There is, however, some evidence that oil saturation reduces the friction coefficient for rock-on-rock sliding. A mean pore pressure of 10.0 MPa and an axial loading rate of 0.05 mm/min was used in all experiments. The previous results of Rutter and Hackston (2017) showed that under these conditions, the effective pressure law applies to Pennant sandstone without dilatancy hardening effects becoming apparent. Rutter and Mecklenburgh (2017) found that the same was true of Bowland shale when argon gas was used as pore fluid.

### 2.2. Fluid Flow in a Crack and the Measurement of Hydraulic Transmissivity

The flow of a viscous fluid through a permeable matrix or through a more conductive crack are respectively analogous to the flow of electric current through a resistive solid or through a thin, resistive sheet embedded within an insulating medium. The analogy is described in Appendix A, and the equations necessary to obtain permeability or crack transmissivity are derived. Transmissivity of a crack has dimensions of cubic millimeters. It can be viewed as the product $kt$ of the permeability ($m^2$) of the material within the crack (greater than that of the matrix) with the effective thickness of the crack ($m$) (Rutter & Mecklenburgh, 2017). The measurement method used gives the product directly, and it is not necessary to know the crack thickness. It can be useful to compare the fluid transport capacity of a crack with

![Figure 3. Surface roughness profiles 10 mm long for each of the rock types used in this study, both as prepared (ground) and after shearing. Standard deviation ($\mu m$) of the data of each profile about the mean value is shown to the right of each profile and can be used as an index of relative roughness.](image)
that of flow through the matrix permeability \( k_{\text{m}} \), given that permeability is in effect the transmissivity of a meter thick layer of matrix material.

This approach avoids the need to model the flow of fluids through cracks starting with the well-known “cubic” law for the flow of a viscous fluid between stationary parallel plates (Brown, 1989; Chen et al., 2015; Germanovich & Astakhov, 2004; Renshaw, 1995; Tsang & Witherspoon, 1983; Witherspoon et al., 1980; Zimmerman & Bodvarsson, 1996). That approach requires the effects of tortuosity and variations in effective crack width arising from the irregular arrangement of contact points that bear the contact loads across the crack to be incorporated (e.g., Cappa & Rutqvist, 2011; Chivers, 2002; Dimadis et al., 2014; Elsworth & Goodman, 1986; Neuzil & Tracy, 1981; Pyrak-Nolte & Morris, 2000; Renshaw, 1995; Sisavath et al., 2003; Witherspoon et al., 1980; review by Zimmerman & Bodvarsson, 1996).

Rock permeability can be measured using a steady state method, in which the flow rate of a fluid through a sample is measured for a known hydraulic pressure gradient. When permeability is low, however, a long time may be required to establish a steady state; therefore, a transient flow method is commonly employed, such as the pulse transient decay method (Brace et al., 1968) or the oscillating pore pressure method (Bernabé et al., 2006; Faulkner & Rutter, 2000; Fischer, 1992; Kranz et al., 1990; Song & Renner, 2007). Both of these latter methods have been used in the present study. In these experiments the crack is an elliptically shaped interface. Fluid is injected into and withdrawn from the interface via two small holes of radius \( r_o = 0.5 \) mm, separated by distance \( 2a = 17 \) mm or 26 mm, for flow normal or parallel to the shear direction (along strike or downdip), respectively. The form of the flow lines and isopotential lines for the downdip case is shown in Figure A1.

When using transient flow rate methods to determine matrix permeability and crack transmissivity account must be taken of the storage capacity of the downstream volume and also of the specimen itself (Appendix A). The downstream volumes were determined from measurements change of pore fluid pressure in response to a known volume change applied by the pore volumometer. The downstream storage capacity \( \beta_d \) is the product of downstream volume \( V_d \) with fluid compressibility \( K \). The upstream volume is unimportant, because the servo control of the upstream pore pressure makes the volume effectively infinite. Using oil as a pore fluid a downstream volume of 38.9 cm\(^3\) was used and the oil compressibility at 10 MPa pressure was measured to be \( 4.71 \times 10^{-10} \text{Pa}^{-1} \). The oil viscosity \( \mu \) at 0.1 MPa is given as 0.023 Pa s by the manufacturer, and its variation with pressure \( P \) (up to 200 MPa) is given (Dorinson & Ludema, 1985) as

\[
\log_{10} \mu (\text{Pa s}) = -1.64 + 5.7 \times 10^{-3} P (\text{MPa}).
\]

Gosman et al. (1969) provide data from which the compressibility of argon can be calculated as a function of pressure. Behavior of argon at 10 MPa and 20°C is near to ideal, and compressibility is increased by only 2.9% above that of an ideal gas. The argon gas viscosity as a function of pressure was reported by Michels et al. (1954).

At 10 MPa gas pore pressure also there is no significant enhancement of apparent permeability through the Klinkenberg effect (McKernan et al., 2017). The downstream volume measured for the matrix permeability measurements using gas on intact rock was 319 mm\(^3\) and for the tests on the faulted samples was 440 mm\(^3\). For crack tests using either oil or gas as pore fluid the sample storativity was negligibly small.

### 2.3. Experimental Procedures

Matrix permeability of the each of the rock types was measured on cylindrical samples, oriented for flow parallel to bedding in the case of the shale, normal to bedding for the sandstone, and in an arbitrary orientation for the granite, and using the procedure of Bernabé et al. (2006). Measurements were made at total confining pressures up to 100 MPa and always at a constant mean pore pressure of 10 MPa. The total confining pressure was cycled over the whole pressure range until the permeability variation with effective pressure became constant, implying elastic behavior.

The characteristics of dry rock-on-rock frictional sliding were measured by increasing differential stress until sliding started at each of several different confining pressures. In the case of the shale, samples were tested for friction with two different surface finishes, at 60 \( \mu \)m and at 25 \( \mu \)m grinding powder sizes but without any pore fluid, but all crack hydraulic transmissivity measurements used samples with 25 \( \mu \)m surfaces finishes. For
the sandstone and granite a single 220 grit surface finish (60 μm abrasive particle size) was used but in both cases the rocks were tested saturated with oil at zero pressure. In addition to friction measurements on the granite on bare rock-on-rock surfaces, tests were also run with a thin layer of fault “gouge” of finely ground granite powder introduced to the sliding interface.

Crack transmissivity measurements were made at zero shear stress for each rock type at each of three different applied effective interfacial normal pressures, nominally at 24, 58, and 93 MPa or close to these values. Downdip (shear direction-parallel) and along-strike (normal to shear direction) flow paths were used. The shear stress was increased in steps at these constant resolved effective normal stresses until the start of frictional sliding. At each combination of normal and shear stress, crack transmissivity was measured.

3. Experimental Results

3.1. Host Rock Permeability

Test conditions and results for each rock type are summarized in Table 1 and Figure 4. In all cases application of the first cycle of increasing effective confining pressure led to a permanent decrease in permeability, whereas for subsequent pressure cycles the rocks behaved elastically. Between the three rock types, permeability varied by ~1 to almost 3 orders of magnitude over more than 80 MPa of effective pressure variation, according to

$$\log_{10} k = -17.73 - 0.028 P_e$$ for Bowland shale,

$$\log_{10} k = -18.2 - 0.011 P_e$$ for Pennant sandstone and

$$\log_{10} k = -19.49 - 0.018 P_e$$ for Westerly granite.

Permeability $k$ is in square meters, and $P_e$ is Terzaghi effective confining pressure in MPa.

| Sample | Log$_{10}$ permeability ($m^2$) | $P_e$ (MPa) | Sample | Log$_{10}$ permeability ($m^2$) | $P_e$ (MPa) | Sample | Log$_{10}$ permeability ($m^2$) | $P_e$ (MPa) |
|--------|---------------------------------|------------|--------|---------------------------------|------------|--------|---------------------------------|------------|
| G7a0   | -17.13                          | 10.7       | Pen35a1| -17.34                          | 10.7       | WGP4a  | -18.19                          | 3.8        |
| G7a1   | -17.54                          | 24.5       | Pen35a2| -18.36                          | 31.4       | WGP4b  | -18.44                          | 17.6       |
| G7a2   | -18.16                          | 45.2       | Pen35a3| -18.88                          | 52.1       | WGP4c  | -18.72                          | 31.4       |
| G7a3   | -18.70                          | 59         | Pen35a4| -19.26                          | 72.8       | WGP4d  | -18.87                          | 45.2       |
| G7a4   | -19.24                          | 79.7       | Pen35a5| -19.08                          | 31.4       | WGP4e  | -19.13                          | 59.0       |
| G7a5   | -19.22                          | 59         | Pen35a6| -18.47                          | 10.7       | WGP4f  | -19.59                          | 72.8       |
| G7a6   | -19.07                          | 45.2       | Pen35b1| -19.32                          | 72.8       | WGP5a  | -19.65                          | 86.6       |
| G7a7   | -18.69                          | 24.5       | Pen35b2| -18.89                          | 12.8       | WGP5b  | -19.02                          | 17.6       |
| G7a8   | -17.85                          | 10.7       | Pen35b3| -18.94                          | 32.8       | WGP5c  | -19.25                          | 17.6       |
| G7a21  | -18.04                          | 10.7       | Pen35c1| -19.24                          | 52.8       | WGP5d  | -18.89                          | 3.8        |
| G7a22  | -18.82                          | 31.4       | Pen35c2| -19.46                          | 72.8       | WGP5e  | -19.50                          | 30.0       |
| G7a23  | -19.52                          | 59         |        |                                 |            | WGP5f  | -19.96                          | 45.2       |
| G7a24  | -20.22                          | 79.7       |        |                                 |            | WGP5g  | -20.11                          | 59.0       |

Note. Mean pore pressure = 10.0 MPa.
3.2. Sliding Friction

Dry rock-on-rock frictional sliding measurements were made at zero pore pressure on each rock type up to nominally 100 MPa confining pressure on rock surfaces, mostly at 45° to the axial loading direction, at a constant axial shortening rate of 0.05 mm/min. Frictional sliding begins after initially elastic behavior and was permitted to a permanent shear offset of only 1 to 2 mm. Resolved stresses on the crack surfaces were corrected for change in contact area with displacement, but this small offset minimizes errors in stress measurement arising from inevitable elastic flexing of the axial column and minimizes generation of fault gouge.

Nearly all of the friction tests were carried out in axisymmetric compression ($\sigma_1 > \sigma_2 = \sigma_3$, where $\sigma_1$, $\sigma_2$, and $\sigma_3$ are principal stresses) except for three on Westerly granite (tests wg3fb, wg4fc, and wg4fa, Table 2 and Figure 5) and one on Bowland shale (test B9a4, Table 2) that were performed in axisymmetric extension ($\sigma_1 = \sigma_2 \geq \sigma_3$). Friction coefficient for the neither the granite nor the shale was affected by loading in axisymmetric compression versus axisymmetric extension. Frictional sliding in the Pennant sandstone samples was stable, without stick-slip and the friction coefficient ($\mu$) = 0.665 ± 0.005 (1 standard error) (Figure 5). Hackston and Rutter (2016) previously showed this to be the same as the friction coefficient on freshly faulted surfaces.

Frictional sliding data for dry Westerly granite is also shown in Figure 5. There is a large difference in behavior for sliding on a slip surface bearing a 0.5 mm thickness of fault gouge, produced by grinding Westerly granite to a powder of approximately 10 $\mu$m grainsize. Here $\mu$ = 0.74 ± 0.01, commensurate with what has previously been reported for Westerly granite (Byerlee, 1978; Passelègue et al., 2016; Wong, 1982). Initiation of sliding on
gouge-free surfaces produced a much lower $\mu = 0.35 \pm 0.02$, accompanied by stick-slip events. This is similar to the findings of Engelder (1976) for sliding on ground surfaces of Westerly granite. Friedman et al. (1974) and more recently Hayward et al. (2016) reported the occurrence of localized patches bearing small tendrils of glass produced by high-speed frictional melting (e.g., during stick-slip events) in high temperature experiments on sandstones at normal stress conditions overlapping with those used in the present experiments. From microscopic examination of the slip surfaces we did not find any evidence of such occurrences, but this does not preclude the possibility that frictional melting may have developed locally.

Steady frictional sliding occurred in Bowland shale without stick-slip, and with a very slow rate of displacement hardening (Rutter & Mecklenburgh, 2017). For a surface ground to 60 $\mu$m surface finish $\mu = 0.59 \pm 0.005$ (Figure 5) but was 0.45 $\pm$ 0.007 with 25 $\mu$m surface finish. Visible smearing of organic material, observed to produce a reflective polished black slip surface in the smoother surface finished samples, was inferred to cause the observed decrease in friction, given the very low friction coefficient of organic carbon (0.1 to 0.2) (Rutter et al., 2013).

### 3.3. Crack Transmissivity—Influence of Normal Stress

The data from crack transmissivity measurements, made for flows both parallel and normal to the long axis of the elliptical surface for each rock type, are given in summary form in Table 3 and shown graphically in Figure 6. The complete data set for all the experiments on sandstone and granite is available in supporting information Data Set S1 and includes also for comparison the shale data previously reported by Rutter and Mecklenburgh (2017).

The pore fluid used was argon gas for the shale but was oil for the granite and sandstone (unlike for the matrix permeability tests). Each sample was subjected initially to the same confining pressure history, with 96.5 MPa effective normal stress applied before lowering it to the desired test pressure. Mean pore

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**Table 2**

| Test | Bowland shale | Pennant sandstone | Westerly granite |
|------|---------------|-------------------|-----------------|
|      | Normal stress (MPa) | Shear stress (MPa) | Friction coefficient | Normal stress (MPa) | Shear stress (MPa) | Friction coefficient | Normal stress (MPa) | Shear stress (MPa) | Friction coefficient |
|      | B1b           | 68.92             | 39.27            | 0.58              | pen4            | 75.44             | 42.34            | 0.56              | WDf1a1          | 74.8              | 22.58            | 0.30              |
|      | B1a           | 33.27             | 19.36            | 0.58              | pen5            | 52.28             | 37.08            | 0.71              | WDf1a2          | 62.35             | 23.24            | 0.37              |
|      | GFSa1         | 40.35             | 23.85            | 0.59              | pen6            | 39.00             | 32.91            | 0.84              | WDf1a3          | 36.15             | 13.11            | 0.36              |
|      | GF1c          | 40.35             | 23.85            | 0.59              | pen8            | 21.94             | 19.87            | 0.91              | WDf1a4          | 24.8              | 8.3              | 0.33              |
|      | GFSa2         | 70.16             | 40.56            | 0.59              | pen10           | 68.65             | 47.68            | 0.69              | WDf1a5          | 7.6               | 4.32             | 0.57              |
|      |               |                   |                  |                   | pen23           | 75.00             | 60.62            | 0.81              | wg3fb(Ext)      | 86.5              | 31.13            | 0.36              |
|      |               |                   |                  |                   | BN1             | 7.24              | 8.36             | 1.15              | wg4fc(Ext)      | 52                | 14.48            | 0.28              |
|      |               |                   |                  |                   |                 |                   |                  |                   |                 |                   |                   |                   |
| 60 micron surface finish, dry | 95.67           | 39.32            | 0.58              | 22.16           | 9.11             | 0.41              | 34.4              | 22.40            | 0.65              | With gouge, oil wet |
| 25 micron surface finish, dry | 36.82           | 18.59            | 0.5               | 42.32           | 18.95            | 0.45              | 71.1              | 43.30            | 0.62              |                      |
|      | B8b1          | 95.67             | 39.32            | 0.58              | Pa1a2          | 71.1              | 43.30            | 0.62              |                      |
|      | B8b2          | 36.82             | 18.59            | 0.5               | Pa1b2          | 34.4              | 22.40            | 0.67              |                      |
|      | B9a1          | 22.16             | 9.11             | 0.41              | Pa2a1         | 34.4              | 22.40            | 0.67              |                      |
|      | B9a2          | 42.32             | 18.95            | 0.45              | Pa2a1a        | 34.4              | 22.40            | 0.67              |                      |
|      | B9a3          | 56.43             | 25.57            | 0.46              | Pa2a1b        | 183.5             | 114.00           | 0.62              |                      |
|      | B9a4 (ext)    | 54.75             | 24.32            | 0.44              | Pa2a2         | 52.9              | 31.50            | 0.60              |                      |
|      | B9a6          | 71.09             | 34.19            | 0.48              | Pa2a3         | 21.3              | 12.80            | 0.60              |                      |
|      |               |                   |                  |                   | Pa3           | 69.3              | 44.00            | 0.63              |                      |
|      |               |                   |                  |                   | Pen2          | 70                | 35.00            | 0.70              |                      |
|      |               |                   |                  |                   | Pen2a         | 100               | 68.50            | 0.69              |                      |
|      |               |                   |                  |                   | Pen2b         | 150               | 104.25           | 0.70              |                      |
|      |               |                   |                  |                   | Pen13         | 50                | 33.83            | 0.68              |                      |
|      |               |                   |                  |                   | Pen13b        | 100               | 68.60            | 0.69              |                      |
|      |               |                   |                  |                   | Pen13d        | 75.44             | 42.34            | 0.56              |                      |
|      |               |                   |                  |                   | Pen11g        | 21.94             | 19.87            | 0.91              |                      |
|      |               |                   |                  |                   | Pen11b        | 68.65             | 47.68            | 0.69              |                      |
|      |               |                   |                  |                   | Pen11         | 75.00             | 60.62            | 0.81              |                      |

Table 2: Frictional Sliding Data on Saw Cut Surfaces (All Rock Types), Plus With Faulted Surfaces (Pennant Sst) and With 0.5 mm Gouge Layer (Westerly Granite) (ext) = Axisymmetric Extension Test, Otherwise Axisymmetric Compression.
pressure was always 10 MPa and pore pressure upstream oscillation amplitudes were 1, 0.5, or 0.3 MPa. These pressure gradients, although small, are much greater than gravitational pressure gradients across the length of the sample, so that the latter can be ignored. These oscillation amplitudes will result in pore pressure gradients that are not expected to produce departures from Darcian flow (Zimmerman & Bodvarsson, 1996). Pore pressure oscillation periods were varied between 50 s and 3,000 s.

Crack transmissivity was first measured over the full range of effective normal stresses but at zero shear stress for each specimen assembly (Figure 6). Increasing normal stress decreased transmissivity for all three rock types, by about 100 times for the shale and granite, but only 10 times for the sandstone. For the shale and the sandstone there was no systematic difference in behavior between the two flow paths, but the granite showed more nonlinear behavior for flow along the ellipse long axis.

The initial pressure cycling over the full range of confining pressure on a given specimen assembly resulted in repeatable transmissivities and implied elastic behavior of the interface from the start. Between different specimen assemblies, however, there was often a substantial difference of mean transmissivity. This is to be expected, because the initial clamping of the two surfaces together determines the interface geometry and hence fluid pathway geometry, which is not expected to be identical for successive assemblies.

### 3.4. Crack Transmissivity—Influence of Shear Stress and Frictional Sliding

Transmissivities were measured as shear stress was increased at three constant Terzaghi effective normal stresses lying between 23 and 93 MPa.

Figure 7 shows the influence of increasing shear stress on crack transmissivity for the three rock types, as plots of log transmissivity versus the ratio of shear stress to Terzaghi effective normal stress. This ratio becomes the friction coefficient when sliding on the crack surface begins. Constant displacement rate loading was stopped so that each transmissivity measurement could be made, and these hold periods were
necessarily longer for lower crack transmissivities. At all normal stresses for all rock types, increasing shear stress caused very little change in transmissivity until steady sliding or stick-slip events started (Figure 7). Successive slip increments resulted in further substantial decreases in transmissivity, and most rapidly as slip events occurred in the granite and sandstone. Shear deformation typically resulted in a total reduction

| Sample       | Test type | Effective normal stress (MPa) | Shear stress (MPa) | Friction coefficient | Log_{10} crack transmissivity (m^3) |
|--------------|-----------|------------------------------|-------------------|----------------------|-------------------------------------|
| Bowland shale, along strike flow | B8a1 | Hydro only | 24.5 | 0 | -19.78 |
|               | B8a2 | Hydro only | 24.5 | 0 | -19.83 |
|               | b5  | Hydro only | 31.4 | 0 | -20.88 |
|               | b5  | H + shear | 31.4 | 14.5 | 0.46 | -22.22 |
|               | B8a3 | Hydro only | 59 | 0 | -20.73 |
|               | b3  | Hydro only | 59 | 0 | -21 |
|               | b3  | H + shear | 59 | 25.2 | 0.43 | -22.27 |
|               | B8a4 | Hydro only | 76.2 | 0 | -21.04 |
|               | B8a5 | Hydro only | 93.4 | 0 | -21.31 |
|               | b8a13 | H + shear | 93.5 | 43.1 | 0.46 | -23.2 |
| Bowland shale, downdip flow | b4  | Hydro only | 31.4 | 0 | -20.8 |
|               | b4  | H + shear | 31.4 | 14.1 | 0.45 | -21.53 |
|               | b9  | Hydro only | 59 | 0 | -20.85 |
|               | b9  | H + shear | 59 | 29 | 0.49 | -22.53 |
|               | b11 | Hydro only | 93.5 | 0 | -20.68 |
|               | b11 | H + shear | 93.5 | 42.1 | 0.45 | -22.71 |
| Pennant sandstone, along strike flow | Pc10a8 | Hydro only | 24.48 | 0 | -16.74 |
|               | Pc10b11 | H + shear | 24.48 | 8.62 | 0.352 | -17.71 |
|               | Pc12b1 | Hydro only | 52.07 | 0 | -17.36 |
|               | Pc12b15 | H + shear | 52.07 | 26.9 | 0.517 | -18.99 |
|               | Pc11a11 | Hydro only | 86.55 | 0 | -17.23 |
|               | Pc11c17 | H + shear | 86.55 | 40 | 0.462 | -19.27 |
| Pennant sandstone, downdip flow | PC4a | Hydro only | 24.48 | 0 | -16.72 |
|               | PCSa7 | H + shear | 24.48 | 10.69 | 0.44 | -17.64 |
|               | PC2f | Hydro only | 53.3 | 0 | -17.13 |
|               | PC2g3 | H + shear | 53.4 | 32.33 | 0.51 | -18.58 |
|               | Pc7a1 | Hydro Only | 86.55 | 0 | -17.15 |
|               | Pc7a12 | H + shear | 86.55 | 37.24 | 0.43 | -19.61 |
| Westerly granite, along strike flow | WG4fa4 | Hydro only | 34.83 | 0 | -17.34 |
|               | WG4fa15 | H + shear | 34.83 | 20 | 0.574 | -17.63 |
|               | wg4c1 | Hydro Only | 52.07 | 0 | -17.78 |
|               | wg4c7 | H + shear | 52.07 | 14.48 | 0.278 | -18.24 |
|               | WG3fb3 | Hydro only | 86.55 | 0 | -18.35 |
|               | WG3fb14 | H + shear | 86.55 | 31.03 | 0.359 | -19.43 |
| Westerly granite, downdip flow | WG16fa2 | Hydro only | 31.38 | 0 | -19.14 |
|               | WG16fa10 | H + shear | 31.38 | 11.72 | 0.37 | -20.12 |
|               | WG9fa7 | Hydro only | 52.07 | 0 | -18.79 |
|               | WG9fa17 | H + shear | 52.07 | 21.72 | 0.42 | -20.33 |
|               | WG12fa3 | Hydro only | 86.55 | 0 | -19.08 |
|               | WG12fa16 | H + shear | 86.55 | 29.31 | 0.34 | -20.27 |

Note: For each test transmissivity under only effective hydrostatic stress is shown, then transmissivity after loading to the shear stress indicated. Complete data set forms part of supporting datafile. Shale samples surface finish 25 microns, others 60 microns. Pore fluid for shale = argon gas; for pennant Sand and westerly granite = oil. Pore pressure = 10 MPa
of transmissivity by approximately 100 times. At the end of each shear test, the shear stress was removed, while normal stress was held constant. This locks in the shear offset and any shear structures or frictional wear materials produced, and in all cases the transmissivity did not recover but stayed at the low level attained when under shear stress (Figures 7 and 8). However, subsequent removal of the normal stress also (as shown for Westerly granite, Figure 6f) did cause complete recovery of the initial transmissivity at low normal stress. It is inferred that this is because while initial loading of the shear stress alone at constant normal stress would not allow the elastically stored shear stresses to relax, the additional removal of the normal stress would allow the surfaces to unstick.

Figure 6. Influence of Terzaghi effective normal stress on transmissivity of cracks in (a) and (b) Bowland shale, (c and d) Pennant sandstone, and (e and f) Westerly granite, for the two flow directions used. Different symbol shapes, with tie lines as required for clarity, show data for a given test assembly. Multiple cycles, for example, triangular symbols for downdip flow in shale (four loading/unloading cycles), show that behavior is elastic and highly reproducible, although each individual assembly can be different from the others. (f) Additionally shows data (triangles) whereby after sliding under shear stress, complete offloading of the normal stress was carried out. This caused complete recovery of the initial transmissivity at low normal stress.
The shale (Figures 8a and 8b and 9a) displayed a small degree of transmissivity reduction with shear stress prior to the onset of sliding. This accelerated as stable sliding began, with transmissivity decreasing uniformly with progressive slip. Recovered specimens showed the formation of a thin veneer, a few microns thick, of striated and smeared fault gouge on the slip plane.

In the sandstone (Figures 8c and 8d and 9b) transmissivity remained constant until the onset of slip, which was marked by a series of small stick-slip events punctuating stable sliding. There was a gradual

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**Figure 7.** Increasing shear stress on the crack surface while effective normal stress is held at each of three constant values causes substantial decrease of crack transmissivity ($m^3$), shown as product of crack “permeability” with thickness, for flow both parallel and normal to the long axis of the elliptical cut surface for all three rock types until frictional sliding begins. (a and b) Bowland shale, (c and d) Pennant sandstone, and (e and f) Westerly granite. Ratio of shear stress to normal stress becomes the friction coefficient during sliding. In all cases there is no recovery of transmissivity after unloading shear stress. Horizontal arrowheads indicate stick-slip events (only in Pennant sandstone and Westerly granite), which are always accompanied by a substantial decrease in transmissivity. The Bowland shale only exhibited stable sliding.
transmissivity decrease during stable sliding, but each stick-slip event was accompanied by a marked decrease of transmissivity. After specimen recovery a small amount of gouge, rather less than for the shale, of ~10 μm grain size was recovered from the slip plane.

Westerly granite (Figures 8e and 8f and 9c) was the only rock that showed some preslip increase in transmissivity, but mainly for tests in which the flow was normal to the slip direction. The amount of preslip transmissivity enhancement was small, less than 2 times, compared with the transmissivity reductions of 10 times to 100 times that accompanied sliding accommodated by violent stick-slip events. A similar amount of fine gouge was collected from the slip plane after a run as for the sandstone, and the slip surface roughness was markedly greater after slip than before (Figure 3).

In all three rock types the formation of frictional wear debris is inferred to have been responsible for blocking permeation pathways, and thus, is a major contributor to reduction of transmissivity as slip begins.

Figure 8. Examples of stress-strain data for each rock type, also showing the evolution of transmissivity for flow parallel to the long axis of the elliptical cut (downdip flow). Axial displacement rate in each case = 0.05 mm/min. Different levels of shear stress supported depend on effective confining pressures (shown). The shale displays time-dependent stress relaxation by creep during the hold periods when transmissivity measurements were made, while the sandstone and particularly the granite display stick-slip behavior (indicated by s), with large transmissivity decreases accompanying slip events.

transmissivity decrease during stable sliding, but each stick-slip event was accompanied by a marked decrease of transmissivity. After specimen recovery a small amount of gouge, rather less than for the shale, of ~10 μm grain size was recovered from the slip plane.

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In all three rock types the formation of frictional wear debris is inferred to have been responsible for blocking permeation pathways, and thus, is a major contributor to reduction of transmissivity as slip begins.

Figure 9. Comparative compilation of the results of all experiments on Pennant sandstone, Westerly granite, and shale, arranged in order of decreasing crack transmissivity. Vertical axis is the same in each case and shows crack transmissivity (permeability × thickness). Matrix permeability is equivalent to the transmissivity of a 1 m thick layer of the rock. In each case the effect of increasing shear stress is shown as contours of constant τ/σn. Increasing shear stress, especially at higher effective normal stresses, substantially further decreases transmissivity.
4. Discussion

4.1. Influence of Hydrostatic Pressure—Comparing the Three Rock Types

These experimental results show that for three radically different rock types, increasing effective normal stress across low roughness crack faces causes the transmissivity of the crack to decrease by between 1 and 2 orders of magnitude over an effective pressure range of 100 MPa. This is comparable to the rate at which the permeability of the rock matrix decreases with effective pressure. This comparison is made graphically in Figure 9, in which the data of Figures 4 and 6 have been generalized as single trend lines. We have not attempted to investigate whether changing effective stress by changing externally applied pressure is different from the effect of the same effective pressure change produced by changing the pore fluid pressure. For matrix permeability measurements, the first cycle of application of hydrostatic pressure tends to decrease permeability more than subsequent ones, but from the first pressure cycle for crack transmissivity, elastic behavior applies.

These effects are well known from previous experimental studies (e.g., Chen et al., 2015; Cuss et al., 2011; Engelder & Scholz, 1981; Guo et al., 2013; Kranz et al., 1990; McKernan et al., 2017; Rutter & Mecklenburgh, 2017; Tanikawa et al., 2010; Zhang et al., 2013, 2015; Zimmerman & Bodvarsson, 1996). In experiments designed to investigate the effect of low amplitude fluid pressure oscillations of seismogenic origin on permeability of Berea sandstone, Elkhoury et al. (2011) and Candela et al. (2015) reported permeability enhancements by up to 50% following fluid pressure oscillations of 20 s period for 3 min. They attributed the effect to the oscillations dynamically unblocking flow paths. However, we were unable to discern any such effects in the much longer period fluid pressure oscillations to which our samples were subjected.

In Figure 9, for ease of comparison, the vertical scale of transmissivity is the same for each rock type and the materials are arranged from left to right in order of decreasing crack transmissivity. Because matrix permeability is numerically equal to the hydraulic transmissivity of a layer 1 m thick, it is possible directly to compare flow through the rock matrix to flow through a single crack. Thus, for the shale, the transmissivity of a single crack is approximately the same as the permeability of the rock matrix. That is, one crack has the same transport capability as 1 m thickness of rock matrix. For the granite, on the other hand, a single crack is almost 300 times more conductive than 1 m thickness of rock matrix, that is, a single crack can conduct as much fluid as 300 m of rock. For the Pennant sandstone, the contrast is less extreme, with a single crack being 30 times more conductive than flow through the rock matrix. Matrix flow in the shale is more rapid than in the granite, but cracks in the shale are almost 50 times less conductive than in the granite.

4.2. Influence of Shear Stress at Constant Interfacial Normal Stress

Increasing shear stress at a constant value of normal stress until the onset of permanent slip in the shale and sandstone caused reduction in the transmissivity of low roughness cracks, very slowly at first, but accelerating as permanent displacement on the crack developed. After even a small permanent shear offset (<1 mm), crack transmissivity remained low when the shear stress was removed while maintaining the normal stress. Only the granite showed some small degree of increase (up to 2 times) of crack transmissivity as shear stress was initially applied, when the deformation was elastic only. While this was most marked for flow normal to the slip direction, it was also seen for flow parallel to the slip direction but only at the lowest normal stress. As soon as permanent slip on the crack surface began, any tendency for increased transmissivity, likely due to dilatation across the slip surface, was overcome by the rapidly decreasing transmissivity. Enhanced decreases in transmissivity in the granite and sandstone were correlated with stick-slip events (Figure 8).

Although decreasing transmissivity with shear stress was seen in all cases, the shear displacements must be accompanied by short-term dilatation, because the positive value of a friction coefficient—an increasing resistance to sliding with increasing normal stress—implies local volume increase. It is inferred therefore that transmissivity reduction as a result of frictional sliding is caused by the development of flow-restricting frictional wear products that blocked the flow paths, coupled with local reductions of crack width through asperity collapse, and that these processes swamp the effects of any dilatation association with slip initiation.

For all three rock types, the overall decrease in transmissivity as a result of slip by 1 to 2 mm could be by 2 orders of magnitude. There was no indication for any of the three rock types studied that decreasing transmissivity would not continue to develop further with increases in the amount of slip. Similar observations...
have been made for clay-bearing materials. Crawford et al. (2008) studied the evolution of both porosity and hydraulic transmissivity in sheared layers of synthetic clay/silt fault gouge with shear displacement at effective normal stresses up to 50 MPa. Shearing of water-wet samples reduced transmissivity for all ratios of clay to silt, but for dry samples that were relatively silt rich there was some recovery of transmissivity after an initial decrease. Broadly comparable results were obtained by Fang et al. (2017), who explored the relationship between frictional sliding and transmissivity of induced fractures in two shales. They found that against a background of steadily decreasing crack transmissivity with slip distance, an upward step of sliding velocity could provoke a transient but small transmissivity increase that was quickly quenched by the downward transmissivity trend.

Other studies on “hard” rocks that reported a marked decrease in crack transmissivity with shearing, and attributed it to the formation of frictional wear products, include Faoro et al. (2009) for diorite and novaculite and Tanikawa et al. (2010) for porous sandstone. Reductions in transmissivity through the formation of cataclastic shear bands in porous sandstones are well known (e.g., Ballas et al., 2015).

The influence of shear stress has been mapped onto the hydrostatic-only loading results in Figure 9, as curves of a constant ratio of shear stress to normal stress. For the Pennant sandstone and Westerly granite, increasing shear stress produces a greater reduction of transmissivity at higher values of applied normal stress, as might be expected. For the smallest value of $\tau/\sigma_n$ (0.1) the transmissivity tends to rise higher than the hydrostatic trend (Figure 9). This implies a small enhancement of transmissivity relative to hydrostatic stress alone, interpreted to mean that a small amount of dilatant elastic strain has occurred. For Pennant sandstone, by the attainment of $\tau/\sigma_n = 0.5$ (onset of permanent slip), the transmissivity of a single crack has been depressed to the level of the matrix permeability.

The shale behaves somewhat differently. For all values of normal stress the transmissivity is reduced by a similar amount for each value of $\tau/\sigma_n$, attributed to the relatively low resistance to abrasion of the shale so that gouge is very easily produced. As a result, the numerical value of crack transmissivity becomes much less than the matrix permeability. Thus, by $\tau/\sigma_n = 0.5$, and permanent slip is occurring, 100 fractures per meter are required to be equivalent to the transmissivity of the rock matrix. Thus, shale is expected to be a good seal, whether by flow through the matrix or via cracks that are subjected to compressive normal stress, especially if some frictional slip has occurred.

In contrast to the above results, and the other examples cited above (Faoro et al., 2009; Tanikawa et al., 2010, etc.), the conventional wisdom is that slip on fault and crack surfaces results in an increase in transmissivity, at least when the crack is sufficiently rough and potentially also at low effective normal stresses so that frictional wear debris is less likely to accumulate (e.g., Carey et al., 2015; Co & Horne, 2014; Gale et al., 1990; Guo et al., 2013; Ishibashi et al., 2012; Lee & Cho, 2002; Yeo et al., 1998). Barton et al. (1995), Barton et al. (1997), and Townend and Zoback (2000) found from televiewer images of borehole walls that higher-temperature fluids preferentially seeped from cracks oriented such that the ratio ($\tau/\sigma_n$) was high with respect to the regional principal stress directions. They inferred that the shear displacements therefore produced dilatancy that caused the transmissivity of those cracks to increase. Together with observations of the state of stress in the upper crust from deep borehole measurements, this led Townend and Zoback (2000) to infer that provided suitably oriented cracks and faults can remain stressed close to failure for long periods of time, the brittle part of the Earth’s crust as a whole behaves as if the bulk permeability is on the order of $10^{-17}$ to $10^{-16}$ m$^2$, high enough to maintain a hydrostatic pore fluid pressure regime to depths on the order of 10 km (total overburden pressure ~270 MPa and effective overburden pressure for a hydrostatic pore fluid pressure regime ~170 MPa). Brace (1980) came to a similar conclusion based on measurements of the permeability of crustal rocks available at that time.

How does this conclusion compare with the results of the present experiments? At an effective hydrostatic confining pressure of 100 MPa, Figure 9 shows that in the absence of transmissivity reduction through shearing, for Westerly granite at 80 MPa effective pressure, an average (fully distributed and connected) array of parallel close-fitting cracks equivalent to those studied here of approximately 3 cm spacing between them would result in a bulk crustal permeability of $3 \times 10^{-17}$ m$^2$, sufficient to satisfy the Townend and Zoback (2000) permeability criterion. At 20 MPa effective hydrostatic pressure, when the transmissivity is higher, the average spacing between cracks need only be about 30 cm. For Pennant sandstone the crack spacing required would be one crack per 20 cm at 80 MPa effective pressure or one per 60 cm at 20 MPa effective
sliding. The ratio of RUTTER AND MECKLENBURGH 1278

Figure 10. Illustration of how a nonhydrostatic stress state produces variations in transmissivity with crack orientation change. (a) Two stress states arbitrarily constrained to lie below a friction limit of $\mu = 0.4$ to prevent sliding. The ratio $\sigma_1/\sigma_2$ is then fixed at $(1 + \sin \phi)/(1 - \sin \phi) = 2.18$, for any value of $\sigma_2$. (b) Angular relations between principal stresses and crack orientation $\theta$. (c) Resultant variation of transmissivity $k_f$ with $\theta$ for three different stress states (values of principal stresses in MPa). The permeability range over 90° variation in crack orientation is greater for higher values of $\sigma_2$.

In a thrust faulting regime, in which the vertical principal stress is smallest, a hydrostatic pore pressure would always be 0.4 of the vertical (minimum) principal stress, leaving a substantial horizontal pressure keeping cracks closed and requiring a much greater crack density to maintain connectivity of the pore pressure through the upper crustal thickness.

5. Conclusions

The frictional properties of smooth, planar “cracks” in (i) a shale (parallel to bedding), (ii) Pennant sandstone, and (iii) Westerly granite were measured, together with the transmissivity of the crack, as a function of effective normal stress and shear stress. The bulk permeability of each rock type was measured as a function of Terzaghi effective pressure. The hydraulic transmissivities of all of the rock-on-rock surfaces are progressively reduced with increasing normal stress, in the same way that bulk rock permeability is reduced by increasing effective confining pressure. However, the transmissivities of cracks in the sandstone and granite are much higher (by 2 and 2.5 orders of magnitude respectively) than the bulk matrix permeabilities. In the shale the crack transmissivity is comparable to the bulk matrix permeability, and the sealing properties of shales are not necessarily degraded by fracturing, especially if there has been some frictional slip along fractures.

With increasing shear stress at constant normal stress, for all rock types crack transmissivity was rapidly reduced further with the onset of frictional sliding. This is inferred to be caused by enhanced overall compaction through asperity collapse and the formation of a thin smear of frictional wear debris that blocks flow pathways. This overwhelms any tendency for transmissivity to be enhanced by dilatation that must occur with the initiation of slip on the crack. This reduction of transmissivity is not recovered when the shear stress is decreased while maintaining the normal stress. Only in the case of the granite and to a lesser extent the sandstone was any preslip, dilatation-induced enhancement of transmissivity observed, but

Are such high crack frequencies reasonable? Perhaps only in damage zones around major faults that might otherwise be sealing, but consideration must also be given to the effects of anisotropy of a nonhydrostatic stress field. For efficient communication by permeation of crack-filling fluid throughout the upper crust, vertical or near vertical cracks are likely to be the most important. They will be subject to the lowest effective normal stress in a normal faulting tectonic regime (vertical maximum compressive stress). Normal stress varies only slowly (as $\cos 2\theta$) with variation of angular orientation $\theta$ of a crack up to $\pm 15^\circ$ about $\sigma_1$; hence, transmissivity will vary only slightly over this angular range (Figure 10), and probably facilitating the development of hydraulic fractures at angles slightly off the optimum if preexisting cracks are available. In contrast, horizontal cracks will experience a normal stress equal to the maximum effective principal stress and will be relatively sealing. At 10 km depth a differential stress of approximately 170 MPa could be maintained by a friction coefficient of 0.6, which would require the minimum horizontal principal stress to be only slightly above a hydrostatic pore fluid pressure. From Figure 9, in this case a bulk crustal permeability of $3 \times 10^{-17} \text{ m}^2$ in the vertical direction could be maintained by only one narrow crack per meter in either Pennant sandstone or Westerly granite, almost irrespective of depth.

In a thrust faulting regime, in which the vertical principal stress is smallest, a hydrostatic pore pressure would always be $0.4$ of the vertical (minimum) principal stress, leaving a substantial horizontal pressure keeping cracks closed and requiring a much greater crack density to maintain connectivity of the pore pressure through the upper crustal thickness.
only at low effective pressures, and it was minor compared to the transmissivity loss when slip began. These observations are contradictory to the common presumption that frictional sliding produces dominantly dilatation and enhancement of crack transmissivity.

A network of narrow cracks can substantially enhance the bulk permeability of granite and tight sandstone, by 2.5 and 2 orders of magnitude respectively per crack, relative to the bulk matrix permeability. In an extensional tectonic regime, narrow cracks in such rocks, at a density of about 1 per meter, may have the capacity to make the upper crust sufficiently permeable to be able to maintain a hydrostatic distribution of pore water pressure with depth, provided that frictional sliding along them is not activated.

Appendix A: Adaptation of Electrical Analogy for Current Flow in a Thin Conductive Sheet to the Problem of Fluid Flow in a Narrow Crack

Potential fields driving electric current flow are analogous to pressure fields driving flow of fluids. Consider flow of electric current in a thin, resistive sheet of thickness $t$ with an elliptical boundary in the $x,y$ plane. Approaches to this and related problems are well known (e.g., Foster & Lodge, 1875; Kennelly, 1909; Bayley, 1959). Here current flows between two cylindrical electrodes, each of radius $r_0$ and centered at $\pm a$ along the $x$ axis (which is also a principal axis of the ellipse) and with their cylindrical axes normal to the sheet. No flow can take place across the elliptical boundary; hence, the current flux is constrained to be parallel to the boundary and isopotential surfaces must intersect it at right angles (Figure A1). $V$ is the measured voltage difference between points close to the electrodes, and $I$ is the measured total current flowing between them. The conductance of the medium between and around the electrodes is therefore $G = I/V$.

From Gauss’s law, the radial electric field intensity $E(r)$ through a cylindrical surface around each electrode at distance $r$ is given by

$$E(r) = \frac{Q}{2\pi \varepsilon_0 r}$$

where $Q$ is the charge per unit length of surface, $\varepsilon_0$ is the permittivity of free space, and $d$ is dielectric constant of the medium (Bayley, 1959; Ida, 2000). The total field at any point is the sum of the fields around each of the two (negatively and positively charged) electrodes. Because of the symmetry of the dipole arrangement (Figure A1), the line $x = 0$ is an isopotential surface and the field lines are parallel to the $x$ axis at all points along it. Along the line $y = 0$ (connecting the two electrodes), the variation of field strength is given by

$$E_{x(y=0)} = \frac{Q}{2\pi \varepsilon_0} \left( \frac{2a}{a^2 - x^2} \right)$$

Figure A1. (a) Coordinate system for electric dipole with image dipole at $y = 2na$ to account for the nonconductive boundary at $y = na$. (b) Nonconductive elliptical boundary to a conductive surface with electrode positions forming a dipole. Current flow lines and orthogonal isopotential lines are shown.
$E_y$ also varies with $y$ along the line $x = 0$ according to

$$E_y(x=0) = \frac{Q}{2\pi d} \log_c \left( \frac{2a}{a^2 - y^2} \right)$$

The voltage between the electrodes is the line integral of the electric field along any path from one electrode to the other. The simplest line is $y = 0$. Thus,

$$V = \int_{-a}^{a} E_y \, dx = \frac{Q}{\pi d} \int_{a}^{a} \log_c \left( \frac{a + x}{a - x} \right) \, dx = \frac{Q}{\pi d} \log_c \left( \frac{2a}{r_0} - 1 \right)$$

The total current flowing through any closed surface in the medium is everywhere the same, and obtained by integrating the electric field over any isopotential surface and multiplying by the specific conductivity of the material of the medium, $\sigma$ (ohmmeter). Once again the simplest one is the symmetry line between the two electrodes, across which the current flux is everywhere parallel to the $x$ axis, and integrating between $y = \pm na$, where $na$ is the ellipse semi-axis length normal to line $y = 0$ and $x = 0$ to $t$.

$$I = \int_{x=0}^{x} \int_{y=-a}^{a} \frac{Q \sigma}{2\pi d} \frac{2a}{a^2 + y^2} \, dz \, dy$$

To account for the presence of the nonconducting boundary at $y = na$ along $x = 0$, an image of the dipole (Figure A1) is added at $y = 2na$ (Nelson, 1955).

$$I = 2 \frac{Q \sigma}{\pi d} \int_{-a}^{a} \left[ \tan^{-1} \left( \frac{2a}{a^2 + y^2} \right) \right]_{0}^{a} = \frac{Q \sigma B}{d}$$

where $B = 2/\pi \tan^{-1} 2n$. $B = 1$ for a cell with infinitely distant boundaries.

The overall cell conductance is then given by

$$\frac{I}{V} = \frac{B \pi \sigma t}{\log_c \left( \frac{2a}{r_0} - 1 \right)}$$

The reciprocal value is the resistance of the cell.

Comparing Ohm's law with Darcy's law, specific electrical conductivity of the medium is analogous to the ratio permeability/fluid viscosity, $k/\mu$. Voltage is analogous to hydraulic pressure gradient $dP/dx$ (Pa m$^{-1}$) and electrical current is analogous to volumetric fluid flux $J$ (m$^3$/m$^2$ s). Darcy's law for steady flow through the cell may be written

$$J = \frac{dP}{dx} \frac{k t}{\mu} \frac{B \pi}{\log_c \left( \frac{2a}{r_0} - 1 \right)}$$

in which it is understood that $J$ is volumetric fluid flux through thickness $t$ of the conductive layer. Thus, in this analogy a crack is visualized as a thin hydraulically conductive layer of thickness $t$ and permeability $k$ embedded in a (relatively) nonconductive matrix. The product $kt$ is the hydraulic transmissivity of the thin layer, and this product is what is measured from the ratio of fluid flow through the crack and the pressure gradient between the fluid injection and withdrawal holes. The value of the effective crack thickness $t$ is generally not known; it depends on the interface geometry. The permeability value $k_m$ of the rock matrix can be visualized as equivalent to the transmissivity of a layer 1 m thick. If the numeric value of the transmissivity of a thin, permeable layer representing a crack is equal to the numeric values of the matrix permeability, it means that a single crack has the same capacity to transport fluid as a 1 m thickness of the rock matrix. If the transmissivity is numerically 10 times the matrix permeability value, then a single crack has the same transport capacity as 100 m of rock matrix.

Steady state flow measurements are usually too time consuming for very low transmissivity materials. In these cases the pressure pulse transient decay method (Brace et al., 1968; Cui et al., 2009) or the oscillating pore pressure method (Bernabé et al., 2006; Faulkner & Rutter, 2000; Fischer, 1992; Kranz et al., 1990; Song & Renner, 2007) must be employed. In the steady state flow method the mass of fluid in the pore spaces
remains constant, but in nonsteady pore pressure methods fluid volume is required to fill and drain pore volumes, hence specimen porosity and upstream and downstream volumes, plus fluid compressibility feature in the governing equations. In this case also, the electrical analog provides an approach to the problem.

A1. The Low-Pass Filter Analogy

Oscillatory fluid flow through a crack coupled with the downstream storage capacity presented by the pipework behaves in an analogous way to an electrical low-pass filter. A low-pass filter consists of a capacitor \( C \) that is charged through a resistor \( R \) (Figure A2) (Paarmann, 2001). The transfer function \( \frac{v_{\text{out}}}{v_{\text{in}}} \) is frequency \( (f) \) dependent because of the time required to charge the capacitor through the resistor. The angular frequency \( \omega \) (rad s\(^{-1}\)) = \( 2\pi f \text{s}^{-1} \). At low frequencies the capacitor is infinitely resistant so a waveform applied as \( v_{\text{in}} \) passes unimpeded (as long as the output does not draw current). Beyond the break frequency \( f_b \) the capacitor can conduct so the \( R \) and \( C \) elements form the arms of a potential divider and the output is progressively attenuated as frequency is increased. This is a low-pass filter, because the unattenuated frequencies are low frequencies. The high-frequency waveform amplitude attenuation rate (gain, \( A \)) is always 20 db per decade (= 6 db per octave), that is, has a slope of \(-1\) (one decade of attenuation per decade of frequency; 20 db = a change of 10 times) on a plot of log \( A \) versus log \( f \) (Figure A3a). The linear prolongation of the high-frequency slope intersects the gain = 1 abscissa at a characteristic break frequency (or corner frequency) \( f_b = 1/(2\pi RC) \). The roll-off of the curve passes through \( f_b \) at \(-3\) db (= \(-0.15 \log_{10} \) divisions below the abscissa) at \( 0.15 \log_{10} f \).

As well as progressively attenuating it, the filter also progressively shifts the phase \( \theta \) of the output waveform over the frequency range between the two linear segments, from \( 0^\circ \) to \( 90^\circ \) (Figure A3b). Recall \( f_b = 1/(\pi RC) \), and any arbitrary frequency can be normalized with respect to the break frequency as \( f/f_b \), or equivalently \( \omega/\omega_b \). Thus, the gain can alternatively be expressed as

\[
\frac{v_{\text{out}}}{v_{\text{in}}} = A = \frac{1}{\sqrt{1 + (\omega/\omega_b)^2}} \quad \text{or} \quad A = \frac{1}{\sqrt{1 + \tan^2\theta}}
\]  

(A2)

The phase shift is given by \( \theta(\omega) = -\tan^{-1}(\omega/\omega_b) \). The minus sign signifies that the output lags the input wave by \( \theta \). The phase shift approaches \( 90^\circ \) as \( A \) approaches 0.

Rearranging equation (A2),

\[
\omega RC = 2\pi fRC \frac{\sqrt{1 - A^2}}{A}
\]

Hence,

\[
\frac{T}{\pi RC} = \frac{2A}{\sqrt{1 - A^2}}
\]  

(A3)

where \( T \) is the period of the waveform.

This may be recast in terms of the analogous problem of an oscillating fluid pressure applied to one end of a permeable material of zero storage capacity (porosity) with the other end terminated in a downstream storage volume \( V_d \). For a compressible fluid the downstream storativity \( \beta_d \) is \( V_d \mu K \), where \( K \) is the compressibility of the fluid (Pa\(^{-1}\)). Thus, \( C \) is replaced by \( \beta_d \) and resistance \( R \) is replaced by \( \mu L/kS \), where \( S \) and \( L \) are respectively the cross-sectional area and length of the permeable element:

\[
\frac{T KS}{\pi \mu L \beta_d} = \frac{2A}{\sqrt{1 - A^2}}
\]  

(A4)

This equation is the same as that derived by Bernabé et al. (2006) for the determination of permeability by the oscillating pore pressure method when there is zero storativity in the permeable element. In the case of flow...
through a crack the storativity of the crack can be negligibly small compared to that of the downstream storage volume.

Equating the measures of resistance in equations (A1) and (A4) gives

\[ R = \frac{T}{\pi \beta d \sqrt{1 - A^2}} = \frac{\log_e \left( \frac{2a}{t_0} - 1 \right)}{B \pi t} \]

Replacing specific conductivity \( \sigma \) by \( k/\mu \) and rearranging gives

\[ k t = \frac{2 \mu \beta D}{T} \frac{2A}{\sqrt{1 - A^2}} \frac{\log_e \left( \frac{2a}{t_0} - 1 \right)}{B} \]

as derived by Rutter and Mecklenburgh (2017).

\( kt \) for flow through a crack can also be determined from pulse transient decay measurements. Brace et al. (1968) introduced this method using a solution based on the low-pass filter analog. To make a measurement, the upstream pore pressure was held constant using the servo-controlled pore volumeter, so that it behaved effectively as a reservoir of infinite volume. A step change of about 0.5 MPa was applied to the downstream pressure, and the recovery of that pressure transient was measured as a function of time. The solution to the transport equation for these conditions is

\[ P(t) \frac{P(0)}{P(0)} = \exp \left( -\frac{f_1 S k t}{\mu L \beta_D} \right) \]

in which \( P(t) \) is the time-dependent decaying amplitude of the pressure step of amplitude \( P(0) \) at \( t = 0 \). \( f_1 \) is a function introduced by (Cui et al., 2009) to account for a nonzero sample porosity and all other parameters are as previously defined. In these experiments, the void volume within the specimen is negligible compared to the volume of the downstream reservoir, hence \( f_1 \) becomes unity. A plot of \( \log_e (P(t)/P(0)) \) versus \( t \) is a straight line of slope \( M \):

\[ M = -\frac{S k}{\mu L \beta_D} \]

Casting in terms of the analogous electric current flow solution:

\[ k t = \frac{\mu \beta_D}{\pi} M \frac{\log_e \left( \frac{2a}{t_0} - 1 \right)}{B} \]
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