Hydraulic conductivity of bedding-parallel cracks in shale as a function of shear and normal stress

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Abstract: Conductivity of fluids along fractures in all rocks is reduced by increasing normal stress. For sandstones and other hard rocks the onset of shear failure along planar cracks is thought to enhance fluid flow owing to a small amount of dilatancy, yet such effects are poorly quantified. Here we determine experimentally how independently increasing normal and shear stress affects fluid flow along fractures in shale. Gas flow along bedding-parallel planar interfaces was measured for flow parallel and normal to the shear direction. Increasing shear stress causes accelerating reduction of conductivity, even before the onset of macroscopic slip. Such reduction in fluid flow rate is non-recoverable, and the combined effects of normal and shear stress can reduce fracture conductivity by more than 3 orders of magnitude over the range of shale reservoir conditions. Bedding plane-parallel slip is common in shales; it can result in a large enhancement of permeability anisotropy, because flow across bedding planes becomes inhibited. This can impact upon the geometry of developing hydraulic fractures, encouraging complexity and favouring lateral relative to vertical growth. The results will facilitate modelling of fluid flow through fracture networks.

Supplementary material: A CSV file containing all experimental conditions and tabulations of results is available at https://doi.org/10.6084/m9.figshare.c.3721831.

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Fluids flow through rocks is via some combination of flow through the rock matrix according to its permeability, and through cracks and fissures according to their conductivity, density and degree of interconnection. In low-permeability rocks flow through fractures may dominate the transport properties, despite what might be a low fraction of the cross-sectional area presented to the flow by the fractures. Flow through fractures, whether natural or induced hydraulically, is important for the production of oil, natural gas and water, reservoir compartmentalization, geothermal energy production, disposal of waste fluids by deep injection, underground storage of CO₂ and natural gas, and in the containment of radioactive wastes (Green et al. 1988; Davies et al. 2013; Wilson et al. 2015). Understanding and modelling flow through fractures is important for minimizing the hazards of induced earthquakes (Healy et al. 1968; Cappa & Rutqvist 2011; Guglielmi et al. 2015; McGarr et al. 2015; Rubinstein & Mahani 2015).

The usual starting point for the description of flow of fluid along a planar thin crack of width t is the idealization of Poiseuille flow between stationary parallel plates (Brown 1989; Zimmerman & Bodvarsson 1996; Paluszny & Matthai 2010; Chen et al. 2015). The analytical solution to the Navier–Stokes equations is the well-known ‘cubic’ law. If the fracture is of length w and slow flow of fluid of low Reynold’s number and viscosity μ takes place in the x direction under pressure gradient dP/dx, the volume flow rate Q is

\[ Q = \frac{w^3}{12\mu} \frac{dP}{dx} \]

The fluid velocity varies parabolically across the crack width owing to viscous drag against the crack faces.

A real crack in a rock matrix will usually have roughness however, with some points of contact bearing the normal and shear stress components across the crack so that a tortuosity of flow paths will result. Initial roughness may be further complicated by irregular or incomplete cement growth and multiphase fluids (Tokan-Lawal et al. 2014). In previous experimental and theoretical studies of such flows in rough fractures much effort has been expended to take into account these latter factors (e.g. Neuzil & Tracy 1981; Heffer & Koutsabeloulis 1995; review by Zimmerman & Bodvarsson 1996;
Chivers 2002; Rogers 2003; Cappa & Rutqvist 2011; Guo et al. 2013), including the use of rubber and epoxy impressions for the characterization of fracture surfaces. In this paper, to avoid these issues we will instead treat a crack as a thin layer containing a more conductive medium than the matrix, rather than a rough, fluid-filled void space.

Experimental studies of fluid flow along fractures have been made in laboratory experiments and on natural fractures in situ in hard, brittle rocks such as granitoids (Kranz et al. 1979; Jung 1989; Gale et al. 1990; Hakami & Barton 1990; Tokunaga & Wan 1997; Talbot & Sirat 2001; Ishibashi et al. 2012; Co & Horne 2014; Carey et al. 2015), including the effects of displacements between fracture walls, arising from application of combinations of normal (σn) and shear (τ) stresses (Yeo et al. 1998). Such studies have usually been at quite low pressure conditions. Lee & Cho (2002) showed that at normal stresses up to 3 MPa fracture conductivity increased by 2 orders of magnitude between shear displacements of 1 and 15 mm, although there was little change during the approach to sliding or in the first 1 mm of slip. This was in accord with an analytical model of Barton et al. (1985). Using borehole wall televiewer imagery, Barton et al. (1995), with further developments (Barton et al. 1997; Townend & Zoback 2000), found that higher-temperature fluids seeped from cracks oriented with respect to the regional stress field such that the ratio (τ/σn) was high, and hence inferred that the onset of shear displacements produced dilatancy that enhanced hydraulic conductivity of the crack. This inference was supported by the experimental observations of Yeo et al. (1998) who also found that fluid flow normal to the direction of incipient shear displacements was enhanced more than fluid flow parallel to resolved maximum shear stress. Observations such as these have established a ruling consensus regarding the role of normal and shear stress on the hydraulic conductivity of cracks in rocks.

In shales, the greatest interest has focused on the geometry and hydraulic conductivity of hydraulic (opening mode) fractures, and particularly on the efficacy of proppant sand grains to enhance hydraulic conductivity (e.g. Zhang et al. 2013, 2015; Guo et al. 2013). The American Petroleum Institute industry-standard API RP 61 and RP 60 (1989, 1995) conductivity cell provides a method for measuring fracture conductivity as a function of normal stress over the range of reservoir pressures and temperatures. In this way Zhang et al. (2013, 2015) found that increasing normal stress decreased conductivity, as expected, and demonstrated how this was substantially mitigated for propped fractures. They also demonstrated some time dependence in fracture closure.

The effect of shear stress on the conductivity of fractures in shale has been assumed to follow the same pattern as seen in other silicic rock types (Johri & Zoback 2013), but few experimental studies have been carried out. These have been at low normal and shear stresses but to substantial shear displacements. Gutierrez et al. (2000) reported conductivity data for water flow in a rough fracture normal to bedding in Kimmeridge Clay, demonstrating dilatancy that enhanced conductivity during shear. Cuss et al. (2011) found that crack conductivity to water first increased and then decreased with progressive shear displacements. In this paper we report the results of experiments on a shale in which the shear stress was increased at constant values of resolved normal stress across the fracture up to the onset of permanent slip offset, whilst the hydraulic conductivity to gas was measured.

Test materials and experiments performed

Experiments were carried out on samples cut from a 20 cm-long core sample of a well-layered, very fissile Carboniferous shale recovered from a deep (2 km) borehole in northern England. From thin section observation and X-ray diffraction the rock is dominated by quartz particles and quartz-dominated lamellae with a matrix of detrital muscovite and diagenetic clay (kaolinite) and an absence of carbonate. There is an estimated 1–2 vol% diagenetic pyrite and about 2.5 vol% organic matter, plus traces of calcite and ankerite.

Samples were oven-dried at 60°C to constant weight before testing, and the porosity from helium injection was 1.9 ± 0.4%. Total organic carbon content was estimated from thermogravimetry to be 1.8 ± 0.2 wt % (4.0 vol%). Initial water saturation was 36 ± 8 vol% of the pore space.

Experiments were performed to:

1. determine the matrix permeability of the starting material;
2. measure the frictional resistance to sliding parallel to bedding surfaces;
3. measure the hydraulic conductivity parallel to bedding surfaces using argon gas, at different values of normal and shear stress up to failure.

Apparatus used and specimen preparation

All experiments in the present study were carried out in a standard triaxial testing machine in axisymmetric shortening, except for one friction test carried out in axisymmetric extension. 25.4 mm diameter cylinders of aluminium were cut at an angle of 45° to the cylinder axis. Elliptical slabs of shale were cut, 3 mm thick, parallel to bedding and glued to the inclined aluminium surfaces using
high-strength epoxy cement. The contacting surfaces of shale were ground to smooth surfaces using a 25 μm particle size abrasive. Holes of 1.0 mm diameter were drilled between the centres of the aluminium blocks and positions near the periphery of the ground surfaces of the shale for fluid injection and withdrawal (Fig. 1). These holes were partially blocked using copper wire inserts to reduce the upstream and downstream gas volumes. The specimen assembly was jacketed with a 1 mm wall-thickness inner tube of neoprene rubber to prevent gas flow around the outer periphery of the sawcut and sealed to the loading pistons of the triaxial testing machine using an outer sleeve of heat-shrunk rubber tubing. The jackets were established not to contribute any significant load bearing capacity to the sample assembly (0.1 MPa or less).

Specimen assemblies were made for flow normal to shearing direction (i.e. along-strike) and parallel to shearing direction (i.e. downdip) of the shale surfaces. Thus in addition to the capacity for different confining pressures so that normal and shear stresses could be applied to the shale surfaces, pore fluid could be passed into either end of the specimen assembly via the hollow piston assemblies, then flow along the shale–shale interface and be withdrawn at the other end. Note that the use of this experimental method to measure interface conductivity relies on the interface conductivity being much larger than the conductivity of the 3 mm-thick layer of shale lying on either side of the interface, which represents a possible contributory path to fluid flow. The results obtained confirm that this is true.

Prepared samples were stored in an oven at 60°C until used. All samples were shortened parallel to the cylinder axis at 20°C. The conventional loading path in this type of apparatus is to hold constant the confining pressure then to increase the differential stress until failure occurs. Here we used a loading path wherein resolved normal stress across the cut surface was held constant (Fig. 2). This was done by means of servo-control of the confining pressure, such that (for a 45° sawcut) the confining pressure decreases by an amount equal to the resolved shear stress (Fig. 2). In a loading path in which the sawcut angle $\theta$ is greater than $\pi/4 - \phi/2$, where $\phi$ is the friction angle, part of the Mohr circle bulges above the failure envelope for frictional sliding when the sliding condition on the weak plane is attained. It is important that this amount is less than the cohesive strength of the rock, to avoid the formation of fresh shear failure surfaces (Hackston & Rutter 2016). This constraint applies for this shale bearing a 45° sawcut.

The confining pressure fluid was a synthetic ester, dioctyl sebacate (Reolube DOS®), and the maximum normal stress used was nominally 100 MPa. Argon gas was used as pore fluid. Liquids (water or oil) were avoided as a pore fluid to eliminate possible water weakening effects relative to tests on the dry rock, such as have been previously reported for some sandstones (e.g. Colback & Wiid 1965; Hadizadeh & Law 1991; Baud et al. 2000), carbonates (Rutter 1972; Rhett & Lord 2001) and shales (van Eeckhout 1976; Erguler & Ulusay 2009; Hu et al. 2014), and to avoid clay expansion and capillary pressure effects. Upstream gas pressure was controlled using a servo-controlled pore volumeter. Pressure transducers with a sensitivity of ±0.02 MPa were used. The mean gas pressure used in all experiments was 10.0 MPa. This is
sufficient to keep gas-adsorbing particles in the rock saturated and to avoid Klinkenberg-type effects.

The sensitivity of pore pressure measurements to small changes in pore volume is enhanced by minimizing the volumes of all parts of the pore pressure system. Thus the downstream volume (excluding the test specimen) was only 319 mm$^3$ for the matrix permeability measurements, 445 mm$^3$ for the along-strike flow measurements and 440 mm$^3$ for downdip measurements. The effective void volume of the specimen itself was much smaller, estimated to be 102 mm$^3$, most of which was the rock pore volume. For samples undergoing shear the effective storage volume of the crack was only about 2 mm$^3$. This means that the dominant storage in the system was provided by the pipework downstream of the sample and the downstream pressure transducer, thus the form of the solution to the transport equation for the oscillating gas flow becomes greatly simplified.

Axial load was measured using an internal load cell that permitted stress measurements to an accuracy of better than 0.5 MPa. Axial loading and confining pressure regulation was achieved by computer-controlled electromechanical servo-systems. Confining pressure was measured to an accuracy of better than 0.3 MPa. Axial displacement was measured outside the pressure vessel, and specimen displacements were determined by subtracting the calculated elastic machine displacement from the total measured displacement using the calibrated apparatus stiffness of 82 kN mm$^{-1}$.

**Fluid flow in the crack**

The details of the flow depend upon how fluid is introduced into the crack and withdrawn from it. In these experiments the flow lines are not parallel; we employ a geometry in which fluid is introduced via a small injection hole (source) of radius $r_o$ and is withdrawn through a similar hole (sink) distance $2a$ from it, such that $a \gg r_o$.

The flow of viscous fluids through permeable media is analogous to the flow of electric charge, therefore we can use the solution to the problem of electric current flow through a conductive cell with two parallel electrodes of length $t$. Charge is injected at one circular electrode, and flows through the intervening resistive material to be withdrawn.

**Fig. 2.** Mohr diagram illustrating the constant normal stress loading path for a 45° sawcut sample. Effective confining pressure is initially applied and this becomes the value of constant normal stress. The stress path on the sawcut rises vertically as the Mohr circle expands about a fixed centre, until the weak plane intersects the frictional sliding criterion. Part of the Mohr circle extends above the sliding criterion line when slip occurs on the weak plane.

**Fig. 3.** Flow pattern in an infinite plane of fluid or of electricity, introduced at source positive and withdrawn at sink negative, separated by distance $2a$. Source and sink diameters are $2r_o$. Flow lines are normal to the isopotential curves, and the flow is symmetrical about the dashed median line.
at another electrode (Blythe 1984; Tsai & Bresee 2001). The isopotential line pattern and the orthogonal pattern of current flow lines in an infinite cell are well known and are illustrated in Figure 3. The pattern is always symmetrical about the median line, $x = 0$, along which the flow paths are parallel to each other and normal to $x = 0$. The measured resistance $R_r$ is the voltage difference $V$ between the electrodes divided by the current flow $I_s$, and will change as the electrode spacing and electrode length are changed. For this flow pattern the specific resistivity $\rho_s$ (resistance of unit volume) of the conductive layer is related to the measured resistance and the electrode configuration by

$$R_s = \frac{V}{I_s} = \frac{\rho_s}{\pi} \log_e\left(\frac{2a}{r_o} - 1\right)$$

The ‘cell constant, $K$’ is given by $\rho_s/R_s$, and is proportional to cell thickness, hence

$$\frac{K}{\pi} = \frac{\pi}{\log_e((2a/r_o) - 1)}$$

The term on the right-hand side describes only the influence of the electrode radius and the separation between them for an infinite cell, and is close to unity (0.83 and 0.90) for the slip-parallel and slip-normal flow geometries used in the present experiments. The additional effect of a finite outer arcuate boundary of zero conductivity at radial distance $R$ from the cell centre is to force the outermost flow lines into parallelism with the boundary as it is approached (Koplik et al. 1994). The effect can be incorporated as a multiplier $B$ on the right-hand side of equation (1). $B$ was measured using an analogous electrolytic conductivity cell with the same ratio of $r_o : a : R (r_o < a < R)$ and found to be 1.09. Thus the overall cell constants $\pi B/\log_e((2a/r_o) - 1)$ were 0.91 and 0.98 for the slip-parallel and slip-normal flow directions respectively. Approximatively 90% of the flux was contained between the semicircular flow lines between the source and sink.

We used the oscillating pore fluid pressure method to measure the hydraulic conductivity of a parallel-sided ‘crack’ in shale. Bernabé et al. (2006) obtained the solution to the problem of sinusoidally varying flow of fluid through a permeable medium in terms of two dimensionless parameters $\eta$ and $\xi$:

$$\eta = \frac{STk}{\pi L \mu \beta D} \quad \text{and} \quad \xi = \frac{SL\beta}{\beta D}$$

in which $S$ is the cross sectional area and $L$ is the length of a cylindrical sample of permeability $k$ and storativity $\beta$. $T$ is the wave period and $\beta D$ is the downstream storage ($\text{m}^3 \text{Pa}^{-1}$). $\mu$ is the pore fluid viscosity (Pa s). $SL\beta \ll \beta D$, $\xi \sim 0$. $\beta D$ is proportional to the isothermal gas compressibility ($c_g$). For a real gas this is:

$$c_g = \frac{1}{P} - \frac{1}{Z} \left(\frac{dZ}{dT}\right)_T$$

where $P$ is gas pressure and $Z$ is the gas deviation factor, which describes deviation from ideality. For argon, $Z = 0.94$ at 10 MPa pressure and 300 K, i.e. close to ideal (Bridgman 1935; Gosman et al. 1969). This raises the compressibility by 2.9% relative to an ideal gas.

The physical measurements that are made are of the amplitude reduction factor $A$ (the ratio of the downstream to upstream wave amplitudes) and the phase shift $\phi$ of the downstream wave relative to

Fig. 4. (a) A first-order electrical low-pass filter. High-frequency waves of amplitude $V_{in}$ are attenuated ($V_{out}$) at a rate of $\times 10$ per decade increase in frequency but low frequencies are transmitted unchanged. The electrical filter is analogous to fluid flow from a constant pressure source, through a resistant rock $R$ of zero storage capacity, and capacitor $C$ is analogous to the downstream storage reservoir. (b) Illustration of the distinction between a crack modelled as a more permeable ($k_c$) slab of thickness $t$ inserted into a medium of lower permeability $k_m$, (fluid flux $J$ is proportional to $t$), and a crack modelled as a fluid-filled channel of the same thickness (fluid flux $J$ is proportional to $t^3$). The forms of the fluid velocity profiles are illustrated.
the upstream forcing wave. Treating the system as analogous to an electrical low-pass filter (Fig. 4a), consisting of a resistor (the permeable crack) feeding a single capacitor (the downstream volume), the maximum phase shift at a large attenuation (small gain, small A) is limited to 90°. The amplitude attenuation is related to the dimensionless permeability factor $\eta$ by

$$\eta = \frac{2A}{\sqrt{1 - A^2}} \quad (3)$$

The analogy between viscous flow in a crack and electrical conduction is imperfect insofar as there is no viscous drag against the crack walls in the electrical case. The viscous flow profile in an open crack impacts on the hydraulic flow case until the crack width $t$ becomes large (Brown 1989). For electric current flow in a thin film, conductivity is proportional to $t$ rather than $t^2$. Use of this analogy implies that the conductive crack is modelled as a slab of higher permeability and of given width $t$ inserted into the less permeable matrix, rather than as a parallel-sided, fluid-filled open channel of the same width (Fig. 4b). This is an important distinction.

The analogy between electrical resistance $R$ and fluid flow is

$$R = \frac{L\mu}{sk} \quad \text{hence} \quad R = \frac{T}{\pi\eta\beta_D}$$

Equating (2) and (3),

$$\frac{wtk}{L\mu} \frac{T}{\pi\beta_D} = \frac{2A}{\sqrt{1 - A^2}}$$

The first term on the left is $1/R$, hence

$$R = \frac{T}{\pi\beta_D} \frac{1}{\sqrt{1 - A^2} A}$$

in which the cross-sectional area of the flow path is replaced by $wt$, where $w$ is the effective width of the flow path in the plane of the crack.

Using equation (1), the specific hydraulic resistivity, $\rho_s = RK$ is

$$\rho_s = \frac{Tt}{\pi\beta_D} \frac{\sqrt{1 - A^2}}{2A} \frac{\pi B}{\log_e((2a/r_o) - 1)} \quad (4)$$

Also $\rho_s = (\mu/k)T$, hence the product of permeability $k$ with thickness $t$ of the conductive layer is

$$kt = \frac{\mu\beta_D}{T} 2A \frac{\log_e((2a/r_o) - 1)}{B} \quad (5)$$

where $kt$ is a measure of the hydraulic resistance of the crack. The value of the effective crack thickness $t$ is not known; it depends on the interface geometry. However, making a reasonable estimate of $t$ allows an effective permeability of the crack filling to be obtained, which can be compared with rock matrix permeability.

**Experimental procedures**

The bulk permeability of the starting material, oriented for flow parallel to bedding, was measured at constant pore pressure of 10.0 MPa and at total confining pressures up to 100 MPa. The confining pressure was cycled up and down until the permeability variation was reproducible (elastic) (McKernan et al. 2014).

The frictional characteristics of dry rock-on-rock sliding were determined by application of differential stress until sliding began, at different values of initial confining pressure. The friction of samples with two different surface finishes was compared, at 60 $\mu$m and at 25 $\mu$m grit sizes. However, all crack conductivity measurements were made using 25 $\mu$m finished surfaces.

Hydraulic conductivities were measured at three different applied confining pressures (34, 68 and 103 MPa), plus some at other pressures, but at a constant argon pore pressure of 10 MPa, before application of shear stress. Downdip and along-strike flow paths were used. For each principal confining pressure the shear stress was increased in steps at constant resolved effective normal stress and at a constant pore pressure of 10 MPa until the onset of frictional sliding was achieved. At each step, hydraulic conductivity was measured.

**Table 1. Bulk permeability measurements parallel to layering at different Terzaghi effective pressures (confining pressure – pore pressure)**

| Sample | Permeability log$_{10}$ $(k$ m$^2$) | $P_{eff}$ (MPa) |
|--------|---------------------------------|----------------|
| G7a0   | $-17.13$                        | 10.7           |
| G7a1   | $-17.54$                        | 24.5           |
| G7a2   | $-18.16$                        | 45.2           |
| G7a3   | $-18.70$                        | 59.0           |
| G7a4   | $-19.24$                        | 79.7           |
| G7a5   | $-19.22$                        | 59.0           |
| G7a6   | $-19.07$                        | 45.2           |
| G7a7   | $-18.69$                        | 24.5           |
| G7a8   | $-17.85$                        | 10.7           |
| G7a21  | $-18.04$                        | 10.7           |
| G7a22  | $-18.82$                        | 31.4           |
| G7a23  | $-19.52$                        | 59.0           |
| G7a24  | $-20.22$                        | 79.7           |

Mean pore pressure = 10.0 MPa.
Host-rock matrix permeability was measured at total confining pressures ranging up to 90 MPa with a constant mean pore pressure of argon gas at 10 MPa, using the oscillating pore pressure method. The flow path was bedding-parallel. Viscosity \( \mu \) data for argon of Michels et al. (1954) were used, linearly approximated by

\[
\mu \ (\text{Pa s}) = 2.2 \times 10^{-5} + 5.5 \times 10^{-7} P \ (\text{MPa})
\]

where \( P \) is gas pressure. Test conditions and results are summarized in Table 1 and Figure 5. The first cycle of confining pressure application produced a permanent decrease in permeability, and for subsequent pressure cycles the rock behaved elastically. Permeability varied by 2 orders of magnitude over an effective pressure variation of 80 MPa, according to

\[
\log_{10} k = -17.74 - 0.028 P_e
\]

where permeability \( k \) is in \( \text{m}^2 \) and \( P_e \) is Terzaghi effective confining pressure in MPa.

**Sliding friction**

Sliding friction coefficient for this shale is about 0.6 for rock fracture surfaces and for planar ground surfaces, but as grinding powder sizes used for surface preparation are decreased below about 30 \( \mu \)m, visible smearing of organic and clay mineral material over the surface causes a decrease in the initial friction. The friction coefficient for organic carbon lies between 0.1 and 0.2 (Rutter et al. 2013). A series of dry rock-on-rock frictional sliding experiments at zero pore pressure was carried out over a range of normal stresses ranging up to nominally 100 MPa, on prepared bedding-parallel surfaces oriented 45° to the axial loading direction, at a constant axial loading rate of 0.05 mm min

\[
\text{Fig. 5. Bulk bedding-parallel permeability of the shale to argon gas with increasing effective confining pressure at constant pore pressure. After the first up-pressure cycle the response to subsequent cycles is elastic. Error bars at one standard deviation (s.d.) indicated.}
\]

\[
\text{Fig. 6. Bedding-parallel dry frictional sliding behaviour of shale-on-shale for two surface finishes, zero pore pressure.}
\]
Table 2. Sliding friction measurements (with zero pore pressure) parallel to bedding surfaces ground to 60 and 25 \( \mu \)m surface finishes

| Test no. | \( \sigma_n \) (MPa) | \( \tau \) (MPa) | Friction coefficient \( \mu \) |
|----------|----------------------|------------------|-------------------------------|
| **60 \( \mu \)m** | | | |
| B1b      | 68.8                 | 40.0             | 0.58                          |
| B1a      | 33.3                 | 19.4             | 0.58                          |
| GF5a1    | 40.4                 | 23.8             | 0.59                          |
| GF1c     | 40.4                 | 23.8             | 0.59                          |
| GF5a2    | 69.6                 | 40.7             | 0.59                          |
| **25 \( \mu \)m** | | | |
| B8b1     | 95.7                 | 39.3             | 0.41                          |
| B8b2     | 36.8                 | 18.6             | 0.50                          |
| B9a1     | 22.2                 | 9.1              | 0.41                          |
| B9a2     | 42.3                 | 18.9             | 0.45                          |
| B9a3     | 56.3                 | 25.9             | 0.46                          |
| B9a4(ext) | 54.8                | 24.3             | 0.44                          |
| B9a6     | 71.1                 | 34.2             | 0.48                          |

Test # B9a6
Rising Pore Pressure (reduced data quantity presented)

| \( P_p \) MPa | \( \sigma_n \) (MPa) | \( \tau \) (MPa) | Friction coefficient \( \mu \) |
|---------------|----------------------|------------------|-------------------------------|
| 0.1           | 71.3                 | 31.8             | 0.45                          |
| 1.6           | 69.5                 | 31.6             | 0.45                          |
| 3.9           | 67.1                 | 31.2             | 0.47                          |
| 6.5           | 64.5                 | 30.9             | 0.48                          |
| 9.0           | 62.3                 | 30.5             | 0.49                          |
| 11.8          | 59.4                 | 30.2             | 0.51                          |
| 13.2          | 57.0                 | 29.2             | 0.51                          |
| 14.4          | 56.6                 | 27.6             | 0.49                          |
| 16.1          | 55.0                 | 27.3             | 0.50                          |
| 17.8          | 53.3                 | 26.0             | 0.49                          |
| 21.6          | 49.4                 | 24.7             | 0.50                          |
| 23.9          | 47.1                 | 23.7             | 0.50                          |
| 25.6          | 45.5                 | 23.0             | 0.51                          |
| 28.1          | 42.8                 | 21.8             | 0.51                          |
| 30.6          | 40.3                 | 20.8             | 0.51                          |
| 32.5          | 38.5                 | 20.1             | 0.52                          |
| 34.0          | 37.2                 | 19.1             | 0.51                          |
| 35.7          | 35.2                 | 18.4             | 0.52                          |
| 37.1          | 33.8                 | 17.8             | 0.53                          |
| 39.0          | 32.0                 | 17.1             | 0.53                          |
| 39.9          | 30.6                 | 16.6             | 0.54                          |
| 40.7          | 30.5                 | 16.4             | 0.54                          |
| 44.7          | 25.7                 | 14.6             | 0.57                          |
| 47.1          | 23.8                 | 13.5             | 0.57                          |
| 49.5          | 21.2                 | 12.3             | 0.58                          |
| 51.0          | 19.6                 | 11.6             | 0.59                          |
| 53.7          | 16.6                 | 10.4             | 0.62                          |
| 58.4          | 12.5                 | 8.3              | 0.66                          |
| 60.8          | 10.3                 | 6.9              | 0.67                          |
| 64.8          | 6.1                  | 4.7              | 0.77                          |
| 66.9          | 4.0                  | 3.3              | 0.82                          |
| 67.7          | 2.9                  | 3.1              | 1.06                          |
| 67.8          | 3.1                  | 2.7              | 0.86                          |
| 67.3          | 3.6                  | 2.7              | 0.74                          |
| 67.0          | 2.7                  | 1.4              | 0.52                          |

Friction coefficient is shear stress/normal stress. Test B9a6 shows decreasing shear stress as pore pressure is slowly raised from zero to 67 MPa whilst maintaining applied total normal stress constant at 71.5 MPa. All tests in axisymmetric shortening mode except B9a4; (ext) = axial extension test.
contact area with displacement), generation of fault
gouge and stresses arising from bending of the axial
column as a result of the lateral offset of the speci-
men halves. Sliding surfaces after each experiment
showed the formation a small amount (a few microns
thick) of brown, powdery fault gouge with mechan-
ic wear striations.

The friction coefficient with 25 \( \mu \text{m} \) surface fin-
ish (the size of the grinding powder) was 0.449 ±
0.007, but was 0.592 ± 0.005 (1 standard error)
for a surface finished with 60 \( \mu \text{m} \) grinding pow-
der (Fig. 6). 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
one (test B9a4, Table 2), which was tested in
axisymmetric extension (\( \sigma_1 = \sigma_2 \geq \sigma_3 \)). Friction
coefficient was not affected by the difference in
loading conditions, unlike that which was observed
in the case of two sandstones (Hackston & Rutter
2016), for which the friction coefficient in extension
was lower than in compression.

Because the hydraulic conductivity tests were
to be carried out using a non-zero pore pressure,
the applicability of the effective stress principle
on friction measurements was evaluated. A sample
(B9a6, Table 2) was prepared with a single
1 mm-diameter hole drilled through the centre of
the upper forcing block to the centre of the shear
surface to provide unrestricted access of argon
do fluid to the slip surface. The sample was
brought to the onset of slip by raising the shear
stress at constant normal stress (68 MPa). The
sample displayed a small amount of transient
creep deformation that lowered the shear stress by
about 5%, until it became constant. Pore pressure
was increased at a steady rate of c. 1 MPa min\(^{-1}\).
This induced frictional sliding that caused the
shear stress to decrease in sympathy, thus the diam-
eter of the Mohr circle decreased progressively to
zero. The total normal stress remained constant,
but the effective normal stress in the fault plane
decreased by the amount of the pore pressure at
that instant. Thus the locus of points whose coordi-
nates are the shear stress and the effective normal
stress progressively tracked the friction sliding
line as the pore pressure was increased. The result
is shown in Figure 7, and demonstrates that the
effective stress law applies. The same technique
was used by Rutter & Hackston (2017) to investi-
gate the mechanical effects of fluid injection into
sliding interfaces in sandstones. The data on Fig-
ure 7 show a small deviation of the effective stress
tate to the left of the friction line. This implies that
during sliding the pore pressure was not wholly
effective over the entire slip surface. Some excess
pore pressure may have been required to inject
gas into the interface, or impermeable gouge con-
tact areas may have reduced the effective surface
area of the interface accessible to gas, requiring
some pressure excess elsewhere to overcome the
frictional resistance. However, we take this data
to justify the assumption that the effective stress
law applies to the calculation of effective normal
stress in the hydraulic conductivity experiments.

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**Fig. 7.** Influence of increasing interfacial argon gas pressure on frictional sliding resistance, surfaces ground to
25 \( \mu \text{m} \). Sample brought to the onset of frictional sliding and the axial displacement is stopped. Increasing gas
pressure is applied to the weak plane via a central hole. The specimen progressively offloads itself so that the
effective stress condition on the weak plane moves down the frictional sliding line, in accordance with the law of
effective stress. There is a small deviation of shear stress above the frictional sliding line, owing to lack of total
effectiveness of the gas pressure over the slip surface, or because a small excess pressure is required to force the gas
into the slip surface.
Hydraulic conductivity

The results of hydraulic conductivity measurements are listed in Table 3 and shown in Figures 8 and 9. Conductivity was measured parallel and normal to the shearing direction (respectively dip and strike directions). For each sample an initial confining pressure (=normal stress across the interface) of 100 MPa was applied, so that all specimens had been exposed to the same maximum normal stress. Conductivities were measured as a function of normal stress at zero shear stress. Results are shown in Figure 8. As expected, conductivity decreased with increasing normal stress, by about ×100 over the 100 MPa pressure range used, and there was no significant difference between results obtained.

Table 3. Summary of results of hydraulic conductivity measurements parallel to bedding (surface finish 25 μm) parallel to strike and downdip

| Sample   | Test type    | $P$ at shear loading (MPa) | Sliding stress (MPa) | Friction coefficient $\mu$ | log$_{10}$ (Hydraulic conductivity m$^2$ m) |
|----------|--------------|----------------------------|----------------------|-----------------------------|------------------------------------------|
| **Along-strike flow** |              |                            |                      |                             |                                          |
| b5       | Hydro only   | 31.4                       | 0                    |                             | −19.76                                   |
| b5       | H + shear    | 31.4                       | 14.5                 | 0.46                        | −21.10                                   |
| b3       | Hydro only   | 59                         | 0                    |                             | −19.92                                   |
| b3       | H + shear    | 59                         | 25.2                 | 0.43                        | −20.94                                   |
| B8a1     | Hydro only   | 24.5                       | 0                    |                             | −18.74                                   |
| B8a2     | Hydro only   | 24.5                       | 0                    |                             | −18.80                                   |
| B8a3     | Hydro only   | 59.0                       | 0                    |                             | −19.39                                   |
| B8a4     | Hydro only   | 76.2                       | 0                    |                             | −19.60                                   |
| B8a5     | Hydro only   | 93.4                       | 0                    |                             | −19.80                                   |
| b8a13    | H + shear    | 93.5                       | 43.1                 | 0.46                        | −21.68                                   |
| **Downdip flow** |              |                            |                      |                             |                                          |
| b4       | Hydro only   | 31.4                       | 0                    |                             | −19.65                                   |
| b4       | H + shear    | 31.4                       | 14.1                 | 0.45                        | −20.42                                   |
| b10      | Hydro only   | 59                         | 0                    |                             | −19.51                                   |
| b10      | H + shear    | 59                         | 29                   | 0.49                        | −21.19                                   |
| b11      | Hydro only   | 93.5                       | 0                    |                             | −19.17                                   |
| b11      | H + shear    | 93.5                       | 42.1                 | 0.45                        | −21.25                                   |
| **Time Sequence** |              |                            |                      |                             |                                          |
| B12a0    | Hydro only   | 10.7                       | 0                    |                             | −18.68                                   |
| B12a1    | Hydro only   | 24.5                       | 0                    |                             | −18.75                                   |
| B12a2    | Hydro only   | 41.7                       | 0                    |                             | −18.92                                   |
| B12a3    | Hydro only   | 59.0                       | 0                    |                             | −19.04                                   |
| B12a4    | Hydro only   | 76.2                       | 0                    |                             | −19.19                                   |
| B12a5    | Hydro only   | 93.4                       | 0                    |                             | −19.38                                   |
| B12a6    | Hydro only   | 103.8                      | 0                    |                             | −19.44                                   |
| B12a7    | Hydro only   | 93.4                       | 0                    |                             | −19.37                                   |
| B12a8    | Hydro only   | 76.2                       | 0                    |                             | −19.30                                   |
| B12a9    | Hydro only   | 59.0                       | 0                    |                             | −19.23                                   |
| B12a10   | Hydro only   | 41.7                       | 0                    |                             | −19.07                                   |
| B12a11   | Hydro only   | 10.7                       | 0                    |                             | −18.59                                   |
| B12a12   | Hydro only   | 24.5                       | 0                    |                             | −18.81                                   |
| B12a13   | Hydro only   | 59.0                       | 0                    |                             | −19.16                                   |
| B12a14   | Hydro only   | 93.4                       | 0                    |                             | −19.39                                   |
| B12a15   | Hydro only   | 59.0                       | 0                    |                             | −19.22                                   |
| B12a16   | Hydro only   | 24.5                       | 0                    |                             | −18.89                                   |
| B12a17   | Hydro only   | 10.7                       | 0                    |                             | −18.59                                   |
| B12a18   | Hydro only   | 41.7                       | 0                    |                             | −19.07                                   |
| B12a19   | Hydro only   | 76.2                       | 0                    |                             | −19.27                                   |
| B12a20   | Hydro only   | 103.8                      | 0                    |                             | −19.44                                   |
| B12a21   | Hydro only   | 24.5                       | 0                    |                             | −18.93                                   |

Data are shown under effective hydrostatic pressure $P$ (hydro only) prior to shear loading and also at the onset of frictional sliding (H + shear) for a given effective hydrostatic pressure (=normal stress maintained constant). For the downdip flow path four up–down effective hydrostatic pressure cycles were applied to demonstrate the reproducible elastic behaviour of a given sample assembly (time sequence, sample B12a).
for flow paths normal and parallel to shear directions (no shear displacements had been applied at this time). Pressure cycling over the full range of confining pressure produced repeatable conductivity on each single specimen, and implied elastic behaviour of the interface from the start, but the slightly different surface characteristics of the differently numbered specimens resulted in variations in conductivity between them by up to one order of magnitude (Fig. 8).

Conductivities were measured with increasing shear stress at three constant Terzaghi effective normal stresses (defined as applied stress minus pore pressure) of 93.4, 59.0 and 31.4 MPa (Fig. 9). In all cases mean pore pressure was 10 MPa and pore pressure upstream oscillation amplitudes were either 1, 0.5 or 0.3 MPa. Oscillation periods were varied between 60 and 3000 s. These oscillation amplitudes and periods will result in gas pressure gradients that are not expected to produce departures from Darcian flow (Zimmerman & Bodvarsson 1996).

At all normal stresses, increasing shear stress caused further decrease in conductivity, initially slowly, but more rapidly as the frictional sliding stress was attained. In Figure 9 results are compared by plotting log conductivity v. (shear stress/effective normal stress), i.e. v. friction coefficient. Each curve is therefore limited to the right by the friction coefficient determined from the frictional sliding tests. Conductivity decreases by c. ×20 to ×30 between onset of shear stress application and

![Diagram](image)

**Fig. 8.** Effect of increasing effective normal stress (applied stress–gas pressure) on log hydraulic conductivity ($kt$) of the interface (a) parallel to dip direction and (b) parallel to strike direction. Tie lines show successive data at different pressures for a given test. Test B12 (four loading/unloading cycles) shows that behaviour is elastic. Tests on different samples (B#) show similar trends with effective pressure, individual tests are reproducible with pressure cycling, but there is variability of log($kt$) between samples. Thus each interface is geometrically unique.

![Diagram](image)

**Fig. 9.** Effect of increasing shear stress at the different constant effective normal stresses indicated on log hydraulic conductivity ($kt$) (a) parallel to strike (normal to shear direction) of weak plane and (b) downdip (parallel to shear direction). Shear stress is represented as the ratio of shear stress to normal stress (friction coefficient). Steady sliding begins at value 0.45. After offloading shear stress there is no recovery of conductivity.
the early stages of shear displacement. Even the elastic deformation that takes place before the onset of sliding causes significant loss of conductivity, especially for flow normal to the shear direction. For flow parallel to the shear direction the main loss in conductivity commences closer to the initiation of sliding. If there is some degree of dilatation of the shear surface at the onset of sliding, it is swamped by the inhibiting effect of the formation of gouge and the formation of striated and smeared clumps, which can be seen on the slip surface after specimen recovery (Fig. 1b). Overall decrease in conductivity over the shear loading range is similar (about $\times 30$) for flows both parallel and normal to the shear direction, but for the former case the conductivity decreases more sharply close to the onset of sliding. The similarity of the curves is apparent. Upon removal of the shear stress (at constant normal stress) the conductivity does not recover; it remains at the lower level attained at the onset of frictional sliding, presumably as a result of the inhibiting effect of gouge production and permanent modification of the interface geometry by sliding.

At the end of every experiment, the pore pressure pipework and the shear surfaces were checked for liquid contamination, which potentially can lower conductivity by reducing the density of conductive pathways for the gas and by introducing capillary pressure effects. In all of the above tests the post-test sample was dry. However, in two tests evidence of oil contamination, probably confining fluid, was seen on the shear surface after specimen recovery. In these cases the apparent hydraulic conductivity was markedly lower, by about $\times 10$ for a given confining pressure. A single droplet of oil can cause such effects.

**Phase shift during oscillating pore pressure permeametry**

The electrical analogue of a first-order RC low-pass filter corresponding to a rock/downstream volume combination in which the sample has zero storativity produces a phase shift $\phi$ that varies with the gain $A (V_{out}/V_{in})$. This is given by

$$A = \frac{1}{\sqrt{1 + \tan^2 \phi}}$$

(6)

$\phi$ is asymptotic to $90^\circ$ as $A$ decreases towards zero. Experimental observations of $A$ v. $\phi$ are plotted in Figure 10 and also the function in equation (6) for comparison. The experimental observations are bounded by equation (6). Data lying to the right of the bounding curve implies a small degree of storativity in the sample.

**Discussion**

**Interpretation of the experimental results**

The experimental results show that, possibly unlike very brittle rocks such as sandstones and igneous rocks, increasing shear stress at a constant value of normal stress causes progressive and accelerating reduction in the hydraulic conductivity of smooth, bedding-parallel cracks in shale. Even after a small, permanent shear offset (c. 1 mm) conductivity remains low. It is not known whether a larger shear offset or the accumulation of a thickness of coarser granular wear products on the slip surface might reverse this trend. Cuss *et al.* (2011) found that crack conductivity in *Opalinus* shale first increased and then decreased with progressive shear displacements at lower normal stresses and larger shear displacements than in the experiments described here. Also, the experiments of Cuss *et al.* (2011) used water as the permeating fluid and the rock contained water-sensitive clays, hence there were potential chemical interactions that are not present in our experiments. It is also not yet known how cracks that cross-cut the bedding will behave. These are likely to be initially much rougher but also to develop gouge smears with sufficient displacement.

Slip offsets parallel to bedding planes are well known in shales and can result in the formation of
highly polished and striated surfaces that may be enhanced by pressure solution accompanying slow slip (Aydin & Engelder 2014). Dusseault et al. (2001) attributed instances of well casing damage to such bedding-parallel shear produced as a result of bed flexure owing to compaction during production. Grinding of shales containing a few per cent of organic particles parallel to bedding surfaces typically produces a grey, non-reflective surface down to about 400 grit size (40 μm), and the frictional sliding coefficient is typically c. 0.6. Reducing grit size to finer than 1000 (15 μm) produces a smooth, black reflective surface, as organic and clay particles are smeared over the surface. This reduces the friction coefficient further (Rutter et al. 2013). In contrast, in a quartzofeldspathic rock the surfaces must be ground to the order of the wavelength of light (c. 1 μm) to produce mirror-like reflectivity.

We attribute the progressive reduction of crack conductivity with increasing shear stress to microslippage accompanied by clay/organic smearing over the surface, beginning even before conditions for unrestrained frictional sliding are met. The formation of elongate smear patches will increase the total contact area across the surface, and increase the tortuosity of flow pathways.

Whilst bearing in mind that this study has only been carried out on bedding-parallel shear surfaces, we can speculate that cracks in different orientations in a homogeneously stressed rock mass may behave in a similar way, provided they are thin and smooth. Cracks with their normals oriented parallel to σ3 are in opening mode and will be most conductive, Those parallel to σ3 may be 100 times less conductive at 50 MPa effective normal stress, and those oriented in a potential shear faulting orientation, at 35° to σ1, may be 30 times less conductive again.

The graphical shape of the experimental data suggests that it might be approximately described by an equation of the form

$$\log_{10} k_t = \log_{10} A - B\sigma_n - C\left(\frac{\tau}{\mu\sigma_n}\right)^m$$

This concept is illustrated graphically in Figure 11 as contoured plots of the change in $\log_{10}(k_t)$ with stress for each of the shear-parallel and shear-normal flow paths, and provides a clear visualization of how normal and shear stress affect conductivity. The overall conductivity of a crack depends on the combined effects of both effective normal and shear stress, and over the range of likely shale reservoir stress conditions the normal stress component is likely to have the greater effect.

Comparing bulk matrix permeability $k_m$ with permeability $k_c$ of the material in the crack is not straightforward, because an effective crack thickness is required to do so. Assuming the crack to be about 10 μm thick, under only hydrostatic pressure the ‘permeability’ of the material in the crack would be about $10^3$ to $10^4$ times larger than matrix permeability at the same pressure. The difference is greater if a smaller effective crack width is assumed, and vice-versa, and becomes smaller as shear stress is progressively applied.

Considering the relative ability of fluid to flow flow through cracks compared with flow through the rock matrix, it must be borne in mind that each crack presents a very small cross-sectional area for fluid transmission compared with that of the whole rock, despite the greater conductivity of the crack. Physically, a given matrix permeability is equal to the hydraulic conductivity of a thickness of 1 m of rock. Thus a particular $k_m$ that is numerically equal to a crack conductivity $k_c$ means that a 1 m thickness of matrix has the same transport capability as a single crack occurring in a 1 m thickness of rock, irrespective of the crack thickness. As $k_c$ becomes numerically less than $k_m$, more cracks per metre are required to produce the same hydraulic transport capability. Figures 5, 8 and 9 show that, for the shale studied, the numerical value of conductivity of a single crack is always slightly less than the matrix permeability, so that a connected crack frequency of 2 or 3 per metre, or more, will dominate the fluid transport capability of the rock mass. These results justify the initial presumption for these experiments that the conductivity of the interface is much greater than that of the 3 mm of shale lying on either side. To apply this method to a rock of much higher matrix conductivity would require a correction to be applied to account for that proportion of the total flow carried in the rock matrix, but that is not necessary in this case.

The formation of shale smears, produced where faults cut shales in shale/sand multilayers, has long been used as a basis for estimating the sealing capacity of fault planes against fluid flow both across and parallel to the fault (e.g. Yielding et al. 1997; Sperrevik et al. 2000). This can be important in compartmentalization of reservoirs, and is based on knowledge of the ratio of shale to sandstone thicknesses and fault offset. Vrolijk et al. (2016) comprehensively reviewed the geometrical aspects of clay smear formation but were particularly concerned with the effects of large, inelastic shear offsets. Our observations of conductivity reduction are analogous to the formation of shale smears but only up to the onset of significant slip across fault and crack surfaces.

Johri & Zoback (2013) modelled the behaviour of an interconnected network of propped hydraulic fractures and active shear fractures to evaluate flow rate from a fractured shale reservoir. They inferred that the behaviour observed for other silicic rock types (e.g. Barton et al. 1997; Yeo et al. 1998;
Townend & Zoback 2000), in which displacements on rough fractures and generation of conductive granular gouge enhance the permeability of cracks able to undergo shear, will also apply to shales. Our results show that this behaviour may not always map directly to the behaviour of shales for close fitting fractures with small displacements, and inferences from observations of the formation of clay smears in larger offset faults may also imply that a different approach is required to model shale behaviour.

**Application to hydraulic fracturing in shales**

It is commonly assumed that hydraulic fractures in shales will be planar when there is no interaction with pre-existing crack networks (Lee et al. 2015), and that they form normal to the regional least principal stress. However, this may not simply be the case. Figure 12a shows the appearance of a hydraulic fracture in an experimental sample, cored normal to the bedding. The fracture was caused by pressurizing fluid in a smaller central hole. The hydraulic fracture lies roughly normal to the sedimentary layering, as revealed by the opening-mode segments. However, each of the opening segments does not extend far before being offset by a linking shear-mode fracture that forms parallel to the bedding, and can have alternating senses of shear on the same slip plane orientation. The shear offset is small, on the order of 1 mm, approximately equal to the amount of crack opening produced. Figure 12b shows the appearance of one of these hydraulic fracture surfaces. The initial hydrofracture has bifurcated many times, resulting in the formation of geometrically necessary shear mode linking cracks. The orientations of these cracks, as potential microseismic sources, may not be simply related to the regional stress field, but to the mechanical anisotropy of the rock (Rutledge et al. 2013, 2015). Based on our experimental results, the shear mode crack segments are likely to become hydraulically

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**Fig. 11.** Graphical illustration of the relationship between crack conductivity, effective normal stress and shear stress, expressed as the reduction in log conductivity (shown on each curve) relative to zero normal and shear stress at the origin. Results are shown for (a) along-strike flow and (b) downdip flow.
non-conductive, so that flow along the hydrocracks will be along the open, slot-like voids, and little flow will take place across or along the shear-mode segments. These observations help to explain why hydraulic fractures underground propagate a great distance parallel to bedding but are inhibited from propagating very far normal to bedding. Small amounts of bedding-parallel shear (Dusseault et al. 2001) will enhance already existing permeability anisotropy and make it difficult for gas to escape upwards from a shale layer. These geometric characteristics may have implications for approaches to the modelling of the geometry and behaviour of hydraulic fractures.

Figure 13 shows an interpretive diagram of these features of a developing hydraulic fracture. The formation bedding-parallel slip surfaces linking opening-mode segments are also likely to enhance the performance of proppant, because it will inhibit the vertical settling of proppant particles.

The propagation of hydraulic fractures can be mapped from microseismic emissions, probably coming from shear mode segments along the general trend of the hydrofracture. The interpretation of the form of such shear mode sources has proved very controversial (Busetti et al. 2014), but in situ microseismic emissions have been interpreted in terms of shear mode sliding on sub-horizontal (bedding parallel) surfaces of the type we illustrate here (e.g. Rutledge et al. 2013, 2015; Staněk & Eisner 2014).

**Conclusions**

The frictional properties of smooth, planar surfaces parallel to bedding in a shale were measured, plus the hydraulic conductivity of the surface, as a function of normal and shear stress, and the bulk bedding-parallel permeability of the shale as a function of effective pressure. The hydraulic conductivity of the shear surface is progressively reduced with increasing shear stress, reaching a minimum at the onset of frictional sliding, typically by a factor of about $\times 30$ relative to the conductivity at zero shear stress. This is inferred to be due to enhanced compaction and to the formation of a thin smear of gouge particles containing clay and organic matter, swamping any tendency for dilatation-enhanced conduction occurring with the onset of slip. The loss of conductivity is not recovered when the shear stress is removed.

These results show quantitatively that crack conductivity in shales is modified differently with shear...
stress than may be the case in clay mineral and maceral-poor rocks such as sandstones, in which shear-enhanced dilatation may enhance conductivity at the onset of shearing. The results carry implications for the approaches that might be taken when modelling fluid flow through fractured shales, in which variously oriented thin, smooth cracks may respond differently to fluid pressure gradients than rougher fractures.

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References

API RP 61 1989. Recommended Practice for Evaluating Short-Term Proppant-Pack Conductivity. 1st edn. American Petroleum Institute, Washington, DC.

API RP 60 1995. Recommended Practices for Testing High-Strength Proppants Used in Hydraulic Fracturing Operations. 2nd edn. American Petroleum Institute, Washington, DC.

Aydin, M.G. & Engelnder, T. 2014. Revisiting the Hubbert–Rubey pore pressure model for overthrust faulting: inferences from bedding-parallel detachment surfaces within Middle Devonian gas shale, the Appalachian Basin, USA. *Journal of Structural Geology*, 69, 519–537.

Barton, C.A., Zoback, M.D. & Moos, D. 1995. Fluid flow along potentially active faults in crystalline rock. *Geology*, 23, 683–686.

Barton, C.A., Moos, D. & Zoback, M.D. 1997. In situ stress measurements can help define local variations in fracture hydraulic conductivity at shallow depth. *The Leading Edge*, 16, 1653–1656.

Barton, N., Bandis, S. & Bakhtar, K. 1985. Strength, deformation and conductivity coupling of rock joints. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 22, 121–140.

Baud, P., Zhu, W. & Wong, T.-F. 2000. Failure mode and weakening effect of water on sandstone. *Journal of Geophysical Research*, 105, 16371–16389.

Bernabe, Y., Mok, U. & Evans, B. 2006. A note on the oscillating flow method for measuring rock permeability. *International Journal of Rock Mechanics and Mining Sciences*, 43, 311–316.

Blythe, A.R. 1984. Electrical resistivity measurements of polymer materials. *Polymer Testing*, 4, 195–209.

Bridgman, P.W. 1935. The melting curves and compressibilities of nitrogen and argon. *Proceedings of the American Academy of Arts and Sciences*, 70, 1–32.

Brown, S.R. 1989. Transport of fluid and electric current through a single fracture. *Journal of Geophysical Research*, 94, 9429–9438.

Busetti, S., Jiao, W. & Reches, Z. 2014. Geomechanics of hydraulic fracturing microseismicity: part 1. Shear, hybrid, and tensile events. *AAPG Bulletin*, 98, 2439–2457.

Cappa, F. & Rutoivist, J. 2011. Modeling of coupled deformation and permeability evolution during fault reactivation induced by deep underground injection of CO2. *International Journal of Greenhouse Gas Control*, 5, 336–346.

Carey, J.W., Zhou, L., Rougier, E., Mori, H. & Hari Viswanathan, H. 2015. Fracture-permeability behavior of shale. *Journal of Unconventional Oil and Gas Resources*, 11, 27–43.

Chen, D., Zhejun Pan, Z. & Ye, Z. 2015. Dependence of gas shale fracture permeability on effective stress and reservoir pressure: model match and insights. *Fuel*, 139, 383–392.

Chivers, T.C. 2002. The influence of surface roughness on fluid flow through cracks. *Fatigue Fracture Engineering Materials and Structures*, 25, 1095–1102.

Co, C.K. & Horne, R. 2014. Stress-permeability relationships in low permeability systems: application to shear fractures. In: *Proceedings of the Thirty-Ninth Workshop on Geothermal Reservoir Engineering*, February 2014, Stanford University, Stanford, CA. SGP-TR-202, 1–10.

Colback, P.S.B. & Wid, B.L. 1965. The influence of moisture content on the compressive strength of rock. In: *Proceedings of the Third Canadian Symposium on Rock Mechanics*, January 1965, Ottawa Department Mines and Technical surveys, Toronto, 65–83.

Cuss, R.J., Milodowski, A. & Harrington, J.F. 2011. Fracture transmissivity as a function of normal and shear stress: first results in *Opalinus Clay. Physics and Chemistry of the Earth. Parts A/B/C*, 36, 1960–1971, https://doi.org/10.1016/j.pce.2011.07.080

Davies, R., Foulger, G., Bindeley, A. & Styles, P. 2013. Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons. *Marine and Petroleum Geology*, 45, 171–185.

Dusseauilt, M.B., Bruno, M.S. & Barrera, J. 2001. Casing shear: causes, cases, cures. In: *SPE 48864, 1998 SPE International Oil and Gas Conference*, 1998, Beijing, China, 98–107.

Erguler, Z.A. & Ulusay, R. 2009. Water-induced variations in mechanical properties of clay-bearing rocks. *International Journal of Rock Mechanics and Mining Sciences*, 46, 355–370.

Gale, J., Macleod, R. & Le Messurier, P. 1990. Site Characterization and Validation – Measurement of Flowrate, Solute Velocities and Aperture Variation in Natural Fractures as a Function of Normal and Shear Stress, Stage 3. Striha Project Report 90-11, Swedish Nuclear Fuel and Waste Management Company, Stockholm.

Gosman, A.L., Mccarty, R.D. & Hust, J.G. 1969. Thermodynamic Properties of Argon from the Triple Point to 300 k at Pressures to 1000 Atmospheres. National Standard Reference Data Series, National Bureau of Standards, 27, US Department of Commerce, Washington, DC.

Green, A.S.P., Baria, R., Madge, A. & Jones, R. 1988. Fault-plane analysis of microseismicity induced by fluid injections into granite. In: *Bell, F.G., Culsaw, M.G., Cripps, J.C. & Lovell, M.A. (eds) Engineering Geology of Underground Movements*. Engineering Geology Special Publication, 5, Geological Society, London, 415–422.
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Guggiemi, Y., Cappa, F., Avouac, J-P., Henry, P. & Elsworth, D. 2015. Seismicity triggered by fluid injection–induced aseismic slip. Science, 348, 1224–1226.

Guo, T., Zhang, S., Gao, J., Zhang, J. & Yu, H. 2013. Experimental study of fracture permeability for stimulated reservoir volume (SRV) in shale formation. Transport in Porous Media, 98, 525–542, https://doi.org/10.1007/s11242-013-0157-7

Gutierrez, M., Öino, L.E. & Nygård, R. 2000. Stress-dependent permeability of a demineralised fracture in shale. Marine and Petroleum Geology, 17, 895–907.

Hackston, A. & Rutter, E. 2016. The Mohr–Coulomb criterion for intact rock strength and friction – a re-evaluation and consideration of failure under polyaxial stresses. Solid Earth, 7, 493–508, https://doi.org/10.5194/se-7-493-2016

Haddad, J. & Law, R.D. 1991. Water-weakening of sandstone and quartzite deformed at various stress and strain rates. International Journal of Rock Mechanics and Mining Science, Geomechanics Abstracts, 28, 431–439.

Hakami, E. & Barton, N. 1990. Aperture measurements and flow experiments using transparent replicas of rock joints. In: Barton, N. & Stephansson, O. (eds) Rock Joints: Proceedings of the International Symposium on Rock Joints. Balkema, Rotterdam, 383–390.

Healy, J.H., Rubey, W.W., Griggs, D.T. & Raleigh, C.B. 1968. The Denver Earthquakes. Science, 161, 1301–1310.

Heffer, K.J. & Koutsabeloulis, N.C. 1995. Stress effects on reservoir flow: numerical modelling used to reproduce field data. In: Linville, W. (ed.) Reservoir Characterization III. Pennwell Books, Tulsa, OK, 79–822.

Hu, D., Zhang, F. & Shao, J. 2014. Experimental study of poromechanical behavior of saturated claystone under triaxial compression. Acta Geotechnica, 9, 207–214.

Ishibashi, T., Watanabe, N., Hirano, N., Okamoto, A. & Tsuchiya, N. 2012. Upgrading of aperture model based on surface geometry of natural fracture for evaluating channeling flow. Geothermal Resources Council, Transactions, 36, 481–486.

Johnsrud, T. & Zoback, M.D. 2013. The evolution of stimulated reservoir volume during hydraulic stimulation of shale gas formations. In: URTeC 1575434, Unconventional Resources Technology Conference, Denver, CO, 1–11, https://doi.org/10.1190/urte2013-170

Jung, R. 1989. Hydraulic in situ investigations of an artificial fracture in the Falkenberg granite. International Journal of Rock Mechanics and Mining Sciences, 26, 301–308.

Koplik, J., Redner, S. & Hinch, E.J. 1994. Tracer dispersion in planar multipole flows. Physical Review E, 50, 4650–4671.

Kranz, R.L., Frankel, A.D., Engelder, T. & Scholz, C.H. 1979. The permeability of whole and jointed Barre granite. International Journal of Rock Mechanics and Mining Science, Geomechanics Abstracts, 16, 225–234.

Lee, H. & Cho, T. 2002. Hydraulic characteristics of rough fractures in linear flow under normal and shear load. Rock Mechanics and Rock Engineering, 35, 299–318.

Lee, H.P., Olson, J.E., Holder, J., Gale, J.F.W. & Myers, R.D. 2015. The interaction of propagating opening mode fractures with preexisting discontinuities in shale. Journal of Geophysical Research: Solid Earth, 120, 169–181, https://doi.org/10.1002/2014JB011358

McGarr, A., Bekins, B., et al. 2015. Coping with earthquakes induced by fluid injection. Science, 347, 830–810, https://doi.org/10.1126/science.aaa0494

McKernan, R.E., Rutter, E.H., Taylor, K.G. & Covey-Crump, S.J. 2014. Influence of effective pressure on mudstone matrix permeability: implications for shale gas production. In: SPE/EAGE European Unconventional Conference and Exhibition held Vienna, Austria, February 2014, SPE 14UNCV-167762-MS, 1–13.

Michels, S., Botzen, A. & Schuurman, W. 1954. The viscosity of argon at pressures up to 2000 atmospheres. Physica, 20, 1141–1148.

Neuzil, C.E. & Tracy, J.V. 1981. Flow through fractures. Water Resources Research, 17, 191–199.

Paluszny, A. & Matthai, S.K. 2010. Impact of fracture development on the effective permeability of porous rocks as determined by 2-D discrete fracture growth modelling. Journal of Geophysical Research, 115, B02203, https://doi.org/10.1029/2008JB006236

Rhett, D.W. & Lord, C.J. 2001. Water weakening in sedimentary rocks. In: Elsworth, D., Tinnucci, J.P. & Heasley, P.E. (eds) Rock Mechanics in the National Interest. 38th U.S. Symposium on Rock Mechanics, Swets & Zeitlinger Lisse, Washington, DC, 121–128.

Rogers, S.F. 2003. Critical stress-related permeability in fractured rocks. In: Ameen, M. (ed.) Fracture and In-situ Stress Characterization of Hydrocarbon Reservoirs. Geological Society, London, Special Publications, 209, 7–16. https://doi.org/10.1144/GSL.SP.2003.209.01.02

Rubinstein, J.L. & Mahani, A.B. 2015. Myths and Facts on Wastewater Injection, Hydraulic Fracturing, Enhanced Oil Recovery, and Induced Seismicity. Seismological Research Letters, 86, 1060–1067. https://doi.org/10.1785/020150067

Rutledge, J.T., Downie, R.C., Maxwell, S.C. & Drew, J.E. 2013. Geomechanics of hydraulic fracturing inferred from composite radiation patterns of microseismicity. In: SPE Annual Technical Conference and Exhibition, 2013, New Orleans, LA, SPE 166370, 1–9.

Rutledge, J., Yu, X. & Leaney, S. 2015. The signature of shearing driven by hydraulic opening. In: AAPG Datasets/Search and Discovery Article #120181, AAPG/SEG/SPWLA Hedberg Conference, Fundamental parameters associated with successful hydraulic fracturing – means and methods for a better understanding, 2014, Austin, TX, 1–5.

Rutter, E.H. 1972. The influence of interstitial water on the rheological behaviour of calcite rocks. Tectonophysics, 14, 13–33.

Rutter, E.H. & Hackston, A. 2017. On the effective stress law for rock-on-rock frictional sliding, and fault slip triggered by means of fluid injection.
Rutter, E.H., Hackston, A.J., Yeatman, E., Brodie, K.H., Mecklenburgh, J. & May, S.E. 2013. Reduction of friction on geological faults by weak-phase smearing. *Journal of Structural Geology*, 51, 52–60. https://doi.org/10.1016/j.jsg.2013.03.008

Sperrevik, S., Roald, B., Færseth, R.B. & Gabrielsen, R.H. 2000. Experiments on clay smear formation along faults. *Petroleum Geoscience*, 6, 113–123.

Staněk, F. & Eisner, L. 2014. New model explaining inverted source mechanisms of microseismic events induced by hydraulic fracturing. In: *SEG Annual Meeting*, 2013, Houston, TX, https://doi.org/10.1190/segam2013-0554.1

Talbot, C.J. & Sirat, M. 2001. Stress control of hydraulic conductivity in fracture-saturated Swedish bedrock. *Engineering Geology*, 61, 145–153.

Tokun-Lawal, A., Prodanović, M., Landry, C.J. & Eichhubl, P. 2014. Understanding tortuosity and permeability variations in naturally fractured reservoirs: Niobrara Formation. In: *URTeC: 1922870, Unconventional Resources Technology Conference*, August 2014, Denver, CO, https://doi.org/10.15530/urtec-2014-1922870

Van Eeckhout, E.M. 1976. The mechanisms of strength reduction due to moisture in coal mine shales. *International Journal of Rock Mechanics and Mining Sciences, Geomechanics Abstracts*, 13, 61–67.

Vrolijk, P.J., Urai, J.L. & Kettermann, M. 2016. Clay smear: review of mechanisms and applications. *Journal of Structural Geology*, 86, 95–152.

Wilson, M.P., Davies, R.J., Foulger, G.R., Julian, B.R., Styles, P., Gluyas, J.G. & Almond, S. 2015. Anthropogenic earthquakes in the UK: A national baseline prior to shale exploitation. *Marine and Petroleum Geology*, 68, 1–17.

Yeo, I.W., De Freitas, M.H. & Zimmerman, R.W. 1998. Effect of shear displacement on the aperture and permeability of a rock fracture. *International Journal of Rock Mechanics and Mining Sciences, Geomechanics Abstracts*, 35, 1051–1070.

Yielding, G., Freeman, B. & Needham, D.T. 1997. Quantitative fault seal prediction. The *American Association of Petroleum Geologists Bulletin*, 81, 897–917.

Zhang, J., Kamenov, A., Zhu, D. & Hill, A.D. 2013. Laboratory measurement of hydraulic fracture conductivities in the Barnett Shale. In: *SPE 163839, Hydraulic Fracturing Technology Conference*, Woodlands, Richardson, TX, Society of Petroleum Engineers, 1–22, https://doi.org/10.2118/163839-MS

Zhang, J., Kamenov, A., Zhu, D. & Hill, A.D. 2015. Measurement of realistic fracture conductivity in the Barnett shale. *Journal of Unconventional Oil and Gas Resources*, 11, 44–52.

Zimmerman, R.W. & Bodvarsson, G.S. 1996. Hydraulic conductivity of rock fractures. *Transport in Porous Media*, 23, 1–30.