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Reduction of friction on geological faults by weak-phase smearing

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Most common crustal rock types display friction coefficients of 0.6 or higher, but some faults must be frictionally weak as they slip when the stress state is unfavourably-oriented (i.e. the resolved shear stress is low for a given normal stress across the fault surface). A role for low-friction minerals and high pore fluid pressures, either separately or in combination, is frequently invoked to explain such slip, but volume fractions of dispersed weak phases often seem to be present in fault gouge in amounts too small to produce significant mechanical weakening. By means of mechanical tests on synthetic fault gouge and microstructural study of run products, we show that the effective area of an embedded weak phase (graphite) on a slip plane can be substantially increased by mechanical smearing, and that the enlarged area of the weak phase on the slip plane follows a linear mixing law. This allows a relatively small volume fraction of the initially dispersed weak phase to have a disproportionately large effect, provided the smearing is concentrated into a narrow planar slip zone or into an interconnected network of them.

1. Introduction

Byerlee (1978) found that the friction coefficient, μ, for rock-on-rock sliding was 0.6–0.8 for a wide range of siliceous and carbonate rocks, and this generalization was subsequently extensively applied to modelling the mechanical behaviour of the upper continental crust. Subsequent studies (e.g. Rutter and Glover, 2012, and references therein) have supported the Byerlee generalization. However, there are several geological situations in which tectonic faults are or have been active despite lying in an unfavourable orientation with respect to the regional stress field, such that a low resolved shear stress along the fault plane is combined with a high effective stress acting normal to it. Examples include the San Andreas fault (Zoback et al., 1987; Hickman and Zoback, 2004; Carpenter et al., 2009; van Diggelen et al., 2009; Schleicher et al., 2010), and oceanic and continental detachment faults (Axen, 2004; Collettini et al., 2009b). Attempts to resolve the apparent paradox have focused upon appealing to the role of frictionally weak materials in the fault zone (Moore and Rymer, 2007; Collettini et al., 2009a, b), perhaps coupled with abnormally high pore fluid pressures to reduce the effective normal stress across the fault zone (Faulkner and Rutter, 2001).

Some experimental studies (e.g. Moore and Lockner, 2011; Tembe et al., 2010) have shown that the presence of initially dispersed grains of frictionally weak minerals in fault gouge can have a disproportionately large effect on bulk friction relative to the volume fraction present. Mechanically weak phases in fault rocks can include talc, clay minerals (particularly swelling clays), serpentine minerals such as chrysotile, graphite and organic carbon (macerals). Although no detailed explanation for this effect has been proposed, in the case of talc Viti and Collettini (2009) and Moore and Lockner (2011) note that easy cleavage and basal slip of talc will help to spread it over slip planes. The quantity of weak mineral phases and their spatial disposition in fault zones can also be influenced by mineral growth reactions (e.g. Viti and Collettini, 2009; Ellis et al., 2010) and/or by selective removal or redistribution of frictionally strong phases such as quartz and feldspars through mineral reactions or pressure solution (e.g. Bos and Spiers, 2002; Holdsworth et al., 2011).

The above studies show that a wide range of processes can contribute to friction on faults becoming lower than would be expected from the Byerlee generalization. Here we show by means of mechanical tests on synthetic fault gouge coupled with microstructural study of the fault surface, how the effective shear stress-supporting area of an embedded weak phase can be substantially increased by mechanical smearing on the slip plane. This can produce a dramatic reduction in frictional strength, provided the smearing is concentrated into a narrow planar fault or into an interconnected network of them.

2. Experiments performed

Synthetic fault gouges were prepared by mixing kaolinite of mean particle size 5 μm and quartz powder of mean particle size

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50 μm in the ratio by weight 1:2. This mixture can be considered comparable to some common clay-bearing fault gouges (e.g. Rutter et al., 1986) but also to some siliceous 'shales' or mudstones (Crawford et al., 2008). Kaolinite is a 'non-swelling' clay mineral and its use avoids friction-lowering effects that would arise with swelling clays in the presence of water. The mixing ratio was chosen so that the quartz grains would initially form a contiguous load-bearing framework with the clay-phase filling the pore spaces between the quartz grains, depending on how much of the initial pore space has been removed by compaction. Graphite powder of mean particle size 74 μm was then added to the dry mixture in the proportions 2 wt%, 5 wt%, 10 wt%, 20 wt% and 50 wt%. Taking into account the relative densities of the mineral components, and assuming an average porosity after initial compaction and shearing of 27% (see below), the above wt% values correspond respectively to 1.79, 4.50, 9.05, 18.29 and 47.20 vol% of graphite. Graphite is a low-friction additive, but it has the advantage that it has a marked optical contrast with the minerals that make up the rest of the mix, so that its distribution can easily be seen, especially on fault surfaces. Mixing of each batch was achieved by slow tumbling in a bottle for several hours followed by mixing with distilled water to form a stiff paste prior to compaction. Additionally, shearing experiments were carried out on the kaolinite/quartz mixture without added graphite and also on 100% graphite samples.

Most samples were sheared as thin (1 mm before pre-shearing compaction by approximately 30%) layers sandwiched between rigid forcing blocks fabricated either from a granite or a low-porosity sandstone. The uniaxially-symmetric compaction behaviour of the initial quartz/clay mixture was determined under distilled water-saturated conditions of no lateral expansion by progressive loading up to 10 MPa axial load (Fig. 1). Rapid compaction to ~30% porosity (after removal of pressure) occurred, beyond which the specimen became very stiff and resistant to further compaction. We infer that at ~30% porosity the quartz grains form a load-bearing framework.

Shear tests at low normal stress (up to 3 MPa) were carried out using an ELE type 26-2111 direct shear machine on gouge samples 60 mm long and 30 mm wide. Shear displacements up to 7 mm were applied under constant normal loads up to 505 kg at a sliding rate of 17 μm s^{-1}. This results in a reduction of shear area as the overlap area between the forcing blocks decreases, so that both normal and shear stresses increase with displacement, in the ratio of the friction coefficient. Each sample was sheared at five different normal loads in order to obtain the friction coefficient, after initial overconsolidation at the maximum normal load. The shear test at maximum normal load was repeated to verify reproducibility.

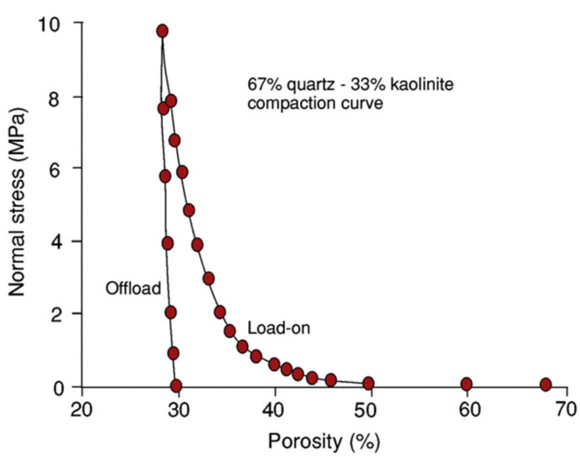

Fig. 1. Uniaxial compaction behaviour of 2:1 quartz:kaolinite mixture. High pressures are required to reduce mechanically the porosity below about 29%.

Higher normal stress tests, between 20 and 300 MPa, were run in a standard triaxial machine with the gouge material in sawcuts oriented at 45° to the cylinder axis of 20 mm diameter forcing blocks of Pennant sandstone (from South Wales coalfield, 4% porosity). 1 mm thick layers of the wet paste were applied to the sawcut surface. This sequence of samples was compacted and tested after oven drying at 60 °C, to minimise risk of development of elevated pore pressures at high normal stresses, although the graphite-free quartz/kaolinite gouge was also tested wet. Tests on each sample were run at constant confining pressures of 50, 100 and 150 MPa at room temperature using both compressional ($\sigma_1 > \sigma_2 = \sigma_3$, where σ_1, σ_2 and σ_3 are respectively the greatest (most compressive), intermediate and least principal stresses) and extensional ($\sigma_1 = \sigma_2 > \sigma_3$) loading geometries. Extensional testing is accomplished in a triaxial machine by using a bayonet connector between the lower loading piston and internal force gauge so that by withdrawing the upper loading piston the axial load can be reduced below the confining pressure (e.g. Rutter, 1998). Specimens were repeatedly shortened and extended by up to 2 mm shear displacement at each initial confining pressure, and the values of normal and shear stress required to determine the friction coefficient were taken as the forcing blocks passed through the zero displacement position, so that no corrections for changes in contact area with displacement were required. Samples were jacketed in heat-shrink plastic tubing which required no correction for jacket strength. These tests were run at a constant shear displacement rate of 2.3 μm s^{-1}.

Additionally, in the direct shear machine, cakes of wet, compacted gouge material of areal dimensions 60 × 60 mm and thickness 20 mm were pre-compacted to a porosity of 30 ± 1% and then sheared at a displacement rate of 17 μm s^{-1}. In this configuration, the width of the shear zone that develops is unconstrained and can broaden and become a composite of Riedel shears with linking fracture systems extending over about 2 mm thickness, so that the resultant fault zone was initially relatively topographically rough. By comparison with the behaviour of the thin gouge layers, this allowed the role of the smoothness and connectivity of the sliding surface to be evaluated.

Amorphous carbon and kerogen can also form a weak component of organic shales, from which unconventional gas is increasingly being recovered. This can impact on the frictional properties of such rocks, and might be an important influence on borehole stability. We therefore also measured the friction coefficient for 45° sawcut planar surfaces (wet, ground to 16 μm SiC) in samples of Barnett Shale (Texas) recovered from a borehole at a depth of approximately 2.5 km. Tests were carried out in extension and compression at constant normal stresses up to 140 MPa and at a constant shear displacement rate of 2.3 μm s^{-1}. The modal composition (vol%) is approximately 53% quartz, 12% carbonate, 16% illitic clays, 1% pyrite, 4% Fe-oxides, 5.5% organics and 8% porosity.

3. Experimental results

3.1. Mechanical tests

A total of 30 experiments were run, all at room temperature (20 °C), both wet and dry. Experimental conditions and results are listed in Table 1. In all cases sliding was stable (no stick-slip) and in most cases occurred at nearly constant stress, so that well-constrained values of the coefficient of friction could be obtained.

Fig. 2 shows some of the range of results at low normal stresses (up to 3 MPa) obtained for wet frictional sliding of (a) thick cakes of quartz:kaolinite mixture 20 mm thick (so that the shear zone finds