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The effect of mineralogy and effective normal stress on frictional strength of sheet silicates

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ABSTRACT

Phyllosilicates are common constituents of upper crustal faults and subduction forearcs. We studied the effect of mineralogy and controlled effective normal stress (between 5 MPa and 100 MPa) on frictional strength. Although the effect of mineralogy on frictional strength of single-phase phyllosilicate gouges has been previously studied, the influence of effective normal stress has not. We conducted water-saturated and vacuum-dry frictional tests on single-phase phyllosilicate gouges using a triaxial apparatus. Minerals included talc, pyrophyllite, kaolinite, lizardite, illite, montmorillonite, chlorite, muscovite, phlogopite, and biotite (particle size <30 μm). Results show friction coefficients between 0.22 − 0.44 (dry) and 0.12–0.38 (wet). Wet strength is always lower than dry strength for the same phyllosilicate, and those with hydrophilic surfaces are especially weakened by water. Tri-octahedral minerals are weaker than di-octahedral minerals with otherwise similar structures. The dependence of friction on interlayer bond strength is less clear than previously suggested. At effective normal stresses > 20 MPa dry friction coefficients are constant, and wet friction coefficients show a small increase. This is attributed to loss of water and increased contact area. The results indicate that frictional strength of clay-rich faults increases at depths less than ≈1 km under hydrostatic pore fluid pressures.

1. Introduction

Clays and other sheet silicates, or phyllosilicates, are abundant in the upper crust and are a significant component of fine-grained fault rocks. They have been found both in samples from exhumed faults (Chester et al., 1993; Evans and Chester, 1995; Faulkner et al., 2003) and in cores recovered during recent drilling projects into the San Andreas fault (USA), the Chelungpu fault (Taiwan) or the Nojima fault (Japan) (Lockner et al., 1999; Kuo et al., 2009; Solum et al., 2006; Schleicher et al., 2009). Phyllosilicates have also been recovered from Ocean Drilling Program (ODP) sites in the Nankai subduction zone and can make up to 80% of the sediments in the decollement (Underwood and Pickering, 1996; Steurer and Underwood, 2003). The phyllosilicate-rich sediments of the accretionary wedge have been suggested to play an important role in the nucleation and propagation of great subduction zone earthquakes (Byrne et al., 1988; Moore and Saffer, 2001; Saffer and Marone, 2003; Ujiie and Tsutsumi, 2010; Faulkner et al., 2011) and in the generation of anomalously large tsunamis (Tanioka and Seno, 2001; Seno, 2002).

Clays and micas are sheet (phyllo-) silicates, characterized by their common basic structure in which platy crystals, built from of one or two silicate tetrahedral layers and one Al- or Mg- based octahedral layer, are stacked upon each other. Isomorphous substitutions, variety in layer charge and interlayer cations create a wide range of crystal structures. Phyllosilicates commonly exhibit weak strength and low-frictional behavior (e.g. Shimamoto and Logan, 1981; Moore and Lockner, 2004). Friction coefficients (μ) are generally lower than the range of $\mu = 0.6–0.85$ established for a variety of rocks by Byerlee (1978) and are mostly in the range of $\mu = 0.2–0.5$. Some studies find friction coefficients below $\mu = 0.1$, depending on presence and composition of pore fluids, shear rate, temperature and type of mineral or crystal structure (Saffer and Marone, 2003; Ikari et al., 2007; Moore and Lockner, 2007).

In this study, we focus on single-phase minerals to investigate the effect of mineralogy and effective normal stress on frictional properties. Natural gouges tend to concentrate shear strain along well-developed zones of weak phases so that the overall strength of the aggregate is dominated by these weak phases (Collettini et al., 2009a; Lockner et al., 2011). Hence understanding the frictional properties of the 'end-member' phases helps to constrain the overall strength of aggregates as well as establish any direct mineralogical influence on the physics of frictional slip. Much previous work has been done on natural and mixed mineralogy

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gouges, but here we concentrate our study on single-phase gouges of controlled grain size.

Two of the most studied minerals in the literature have been montmorillonite and illite (Logan and Rauenzahn, 1987; Bird, 1984; Morrow et al., 1992; Moore and Lockner, 2007; Saffer et al., 2001; Saffer and Marone, 2003; Ikari et al., 2007, 2009; Tembe et al., 2010; den Hartog et al., 2012). Smectites, such as montmorillonite and saponite (Lockner et al., 2011) are very weak when water-saturated, but their dry strength is significantly higher. Talc has been found to be one of the weakest phyllosilicates even when dry (Morrow et al., 2000; Moore and Lockner, 2004; Escartin et al., 2008). Talc is often found as an alteration product of ultramafic rocks in oceanic faults (Escartin et al., 2008) or of sedimentary rocks such as dolostones (Collettini et al., 2009b), and has also been discovered fault cores recovered from the San Andreas fault (Moore and Rymer, 2007). Consequently, a number of studies have focused on frictional properties of talc (Collettini et al., 2009b; Escartin et al., 2008; Moore and Lockner, 2008; Moore and Rymer, 2007). Other studies have focused on the 1:1 minerals kaolinite (Bos et al., 2000; Bos and Spiers, 2001; Brantut et al., 2008; Crawford et al., 2008), lizardite and chrysotile (Reinen et al., 1994; Moore et al., 1996, 2004). Most of the work on micas has been at higher temperatures (Kronenberg et al., 1990; Mares and Kronenberg, 1993; Mariani et al., 2006), but muscovite and biotite have also been deformed at lower temperatures (Scruggs and Tullis, 1998; Van Diggelen et al., 2010). Only a few studies have tried to compare more than two or three minerals and explain trends in frictional strength (Shimamoto and Logan, 1981; Morrow et al., 2000; Moore and Lockner, 2004).

In their 2004 study, Moore and Lockner compare the frictional properties of 17 minerals and phyllosilicates and link their dry frictional strength to the electrostatic attraction (interlayer bonding energy (ILBE), as calculated by Giese (1978, 1980) and Bish (1981)) between individual layers. They suggest that for phyllosilicate minerals with ILBE of 70 kcal/mol or less, dry shear occurs mainly by breaking through interlayer bonds between basal planes. Friction coefficients increase with a gradient of 0.007 per kcal/mol ILBE. Minerals with an ILBE greater than 70 kcal/mol showed no further increase in frictional strength, from which Moore and Lockner (2004) concluded that above the threshold, frictional processes other than cleavage must dominate gouge deformation. All of Moore and Lockner (2004) experiments were conducted at 100 MPa effective normal stress, corresponding to about 5–6 km depth within the upper crust. One hypothesis we test is that the relationship between mineralogical properties, such as interlayer bonding energy, and frictional strength varies with effective normal stress.

In subduction zones, where low consolidation and high fluid pressure can significantly lower the effective stress, and thrusting continues all the way to the surface, much lower pressures than the 100 MPa used by Moore and Lockner (2004) might be appropriate (Tobin et al., 1994; Seno, 2002). The frictional strength of single-phase phyllosilicates and their dependence on effective normal stress is still relatively poorly understood. Studies by Moore et al. (2004) and Moore and Lockner (2008) on chrysotile and talc, respectively, report an increase in friction coefficient with effective normal stress, while the results of Saffer et al. (2001), Saffer and Marone (2003) and Ikari et al. (2007) on smectite and illite gouges show a decrease with effective normal stress.

In this study, we present data on frictional strength of 10 different phyllosilicates over a range of low to medium effective normal stress (5–100 MPa). Both oven-dried samples (tested under vacuum) and water-saturated gouges (constant pore pressure of 10 MPa) have been tested. Our choice of phyllosilicate spans a range of different interlayer bonding energies (Giese, 1980; Bish, 1981) and includes both di-and tri-octahedral minerals to test the hypothesis introduced by Moore and Lockner (2004) over a range of effective normal stresses. We attempt to minimize the influence of particle size by keeping all samples within a similar size range (<30 μm). Experimental conditions are kept as similar as possible to allow comparison of the properties of a range of different minerals. After presenting the experimental results we compare them to those from other studies. We then discuss the influence of crystal structure and water–mineral interaction on frictional strength of phyllosilicate gouges, as well as the implications of our results for the strength of phyllosilicate-rich faults.

2. Materials and methods

2.1. Phyllosilicate powders

The origin, treatment and characteristics of the clays used in this paper are summarized in Table 1. The samples were ground to powders and either sieved or separated by centrifugation to obtain a small size fraction without destroying the crystal structure. An attempt was made to obtain samples as pure as possible and to minimize the amount of quartz.

Illite, chlorite, biotite and phlogopite were purchased and received as rocks or single crystals. They were broken into smaller pieces and ground by hand to fit through a 63 μm sieve. The biotite and phlogopite samples were then wet-ground in a micronizing mill (McCrone) and freeze-dried. Chlorite was ground further to fit through a 30 μm sieve. Lizardite was received as a <63 μm powder and also sieved to obtain the <30 μm fraction. Talc, pyrophyllite and kaolinite samples were received as powders with a particle size of 30–45 μm. The muscovite sample was received commercially ground with an average particle size of 12.7 μm (Mariani et al., 2006). Crushed illite and Wyoming bentonite powders were dispersed in de-ionized water and the <2 μm fraction separated by centrifugation. The samples were then freeze-dried. Smectites such as montmorillonite naturally have a very small particle size, and sieving the bentonite powder to <30 μm would not have been sufficient to remove quartz and other impurities from the sample. Instead, a separation procedure by centrifugation was performed to obtain the <2 μm size fraction. The illite shale was treated similarly, but it proved too time-consuming to obtain a sufficient amount of <2 μm material.

2.2. Sample preparation for friction tests

The gouge layer was prepared by mixing about 0.8 g of dry clay powder with a few drops of de-ionized water into a stiff paste, which was applied to the sliding block. For dry tests, the sliding blocks with the gouge layer were dried in the oven (110 °C) overnight. They were transferred into the jacket and inserted into the pressure vessel while still warm to avoid re-adsorption of water. Montmorillonite samples, which cannot be treated in this way due to shrinking when drying, were prepared by compacting dry powder directly onto the steel sliding block and drying the sample at 80 °C overnight. For wet tests, the sample was prepared in the same way, but used instantly instead of drying in the oven.

2.3. Experimental set-up and procedures

All shear strength tests were performed on a triaxial deformation apparatus in the Rock Deformation Laboratory in Liverpool. The apparatus is capable of applying confining pressures up to 250 MPa and pore pressures up to 200 MPa with servo-controlled pumps. Resolution of axial force (measured with an internal force gauge) is better than 0.1 kN. Further details of the apparatus are given in Mitchell and Faulkner (2008) and Behnsen and Faulkner (2011). A diagram of the sample assembly is included in Fig. 1.