The effect of mineral bond strength and adsorbed water on fault gouge frictional strength

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Abstract. Recent studies suggest that the tendency of many fault gouge minerals to take on adsorbed or interlayer water may strongly influence their frictional strength. To test this hypothesis, triaxial sliding experiments were conducted on 15 different single-mineral gouges with various water-adsorbing affinities. Vacuum dried samples were sheared at 100 MPa, then saturated with water and sheared farther to compare dry and wet strengths. The coefficients of friction, μ, for the dry sheet-structure minerals (0.2-0.8), were related to mineral bond strength, and dropped 20-60% with the addition of water. For non-adsorbing minerals (μ =0.6-0.8), the strength remained unchanged after saturation. These results confirm that the ability of minerals to adsorb various amounts of water is related to their relative frictional strengths, and may explain the anomalously low strength of certain natural fault gouges.

Introduction

Deformation of the Earth's crust typically localizes onto fault surfaces which, with continued slip, develop layers of fine-grained material known as fault gouge. An important material property of fault gouge is its frictional strength, τ_f, often quantified by the coefficient of friction, μ, defined as the ratio of shear stress, τ, to normal stress, σ_n, acting on the fault surface. A broad class of earth materials are found to have coefficients of friction in the range 0.6 to 0.9, with an approximately linear dependence on normal stress according to a relation referred to as Byerlee's Law *(Byerlee,* 1978).

While Byerlee's Law is representative of "typical" gouge derived from crystalline and quartzo-feldspathic rock, many alteration and hydrated minerals have notably lower shear strength. Montmorillonite, an expandable clay that can take on large amounts of interlayer water, has a coefficient of friction, μ, of only 0.2 at room temperature under moderate pressure conditions. This gouge mineral has been extensively studied because its strength is near the range required to satisfy the low shear stress limit along the San Andreas Fault inferred from heat flow constraints *(Lachenbruch and Sass,* 1980).

Adsorbed water, resulting from the attraction of the water dipole to electrically charged mineral surfaces, can also substantially reduce frictional strength of gouge materials by providing a low-resistance slip interface, much like the interlayer water of montmorillonite. For instance, *Moore et al.* (1997) found that the serpentine variety chrysotile, which readily adsorbs water onto its surface, also had a coefficient of friction of 0.2 and was only half as strong as the varieties lizardite and antigorite at room temperature. *Israelachvili et al.* (1988) demonstrated that for mineral grains that are separated by a thin film of water, the first few layers of water are organized at an atomic level and the shear strength is inversely related to the number of water layers present.

Many fault gouge minerals also contain water that is bound within the crystal structure. This structural water does not act to reduce the coefficient of friction, μ, of the material in the manner of the loosely-bonded water adsorbed on the mineral's surface. Thus, it is where and how the water is bound that determines its effect on strength. Because adsorbed or interlayer water is driven off by the heat and pressure found at depth in the seismogenic zone, some low-strength gouge minerals can potentially become as strong as materials obeying Byerlee's Law, whereas others may remain relatively weak. This variable strength behavior could have important implications for processes in the seismogenic zone, because although the low frictional strength of fault gouge is generally not sufficient to explain the inferred low shear stresses of many faults, weak fault minerals in combination with other factors such as elevated fluid pressure and low fault permeability may ultimately affect fault strength. Consequently, we have examined the mechanical properties of 15 gouge minerals under both dry and wet conditions. Our results demonstrate a correlation between low strength and an affinity for adsorbed (or interlayer) water.

Method

A 1-mm thick layer of monomineralic gouge (sieved to <90 μm) was placed between cylindrical driving blocks containing a 30° sawcut. The upper driving block was composed of Berea sandstone (or Westerly granite, for the stronger samples); the lower block was fused silica. The impermeable silica in the lower half of the sample column is preferable to a porous material, in which pore fluids could become trapped and develop excess fluid pressure due to poro-elastic effects during shearing. This method has proven successful in strength tests on low-permeability clays *(Morrow et al.,* 1992). The rock-gouge-silica assembly was vacuum dried at 180°C for several days to drive off all water in both the upper driving block and the gouge layer. The choice of temperature and length of heating is important, because although differential thermal analysis investigations of many clays indicate a loss of adsorbed water at slightly above 100°C, (or higher for montmorillonite, depending on composition), a temperature of 180°C is necessary to remove adsorbed water in chrysotile *(Mackenzie,* 1957*).* Room-temperature sliding experiments were conducted at 100 MPa constant normal stress with a sliding velocity of 0.5 μm/sec. This sliding rate was chosen as a convenient standard, as there is very little information on the effect of absorptive properties on the velocity dependence of strength *(Reinen et al.,* 1994). However, *Morrow et al.* (1992) found that the velocity-dependence of montmorillonite and illite was not related to the expandable or non-expandable

nature of the minerals. Clearly, this is a topic for further study.

The dry samples were sheared for 4 mm axial displacement with the pore pressure system under vacuum. Shear stress was then reduced and the sample was saturated with deionized water. A constant pore fluid pressure, p_p, of 10 MPa and constant normal stress of 110 MPa were applied to the sample to reestablish an effective normal stress $(\sigma_n\text{-}p_p)$ of 100 MPa, as during the dry sliding. The sample was then re-sheared an additional 5 mm displacement to 9 mm. For some samples with significant strain hardening during the dry run, additional experiments were run entirely dry to 9 mm displacement in order to properly assess the maximum dry frictional strength.

Results

Calcite, and the framework silicates albite and quartz (Figure la) were generally strong, following Byerlee's Law. There was little or no difference between the dry and saturated portions of the albite and quartz frictional strength curves, indicating that the presence of water did not affect their strength. Quartz deformation was unstable but reproducible under the conditions

of these experiments. Calcite, exceptionally strong when dry $(\mu = 0.85)$, was still relatively strong even after the coefficient of friction dropped 15% following water saturation. The final wet strength $(\mu = 0.72)$, was similar to *Shimamoto and Logan's* (1981) nominal dry coefficient of friction of 0.74 for calcite, although they did not vacuum dry their gouge at temperature before testing.

The zeolite gouges laumontite and clinoptilolite (Figure 1b), also framework silicates, showed high coefficients of friction during both the dry and wet segments of the experiment, consistent with Byerlee's Law. The coefficient of friction of laumontite $(\mu = 0.8)$ was identical to the results of similar studies on laumontite conducted under a variety of effective pressures *(Morrow and Byerlee,* 1991). Note that the clinoptilolite regained strength slowly after saturation compared to the laumontite, which recovered full strength after about 1 mm slip. The reason for the relatively slow strength recovery of the clinoptilolite is not clear, however, based on the trend of the curve, the coefficient of friction, μ, would have reached the initial dry value of 0.75 if the sample had slid an additional I mm.

In contrast, the sheet-silicate serpentinite gouges (Figure
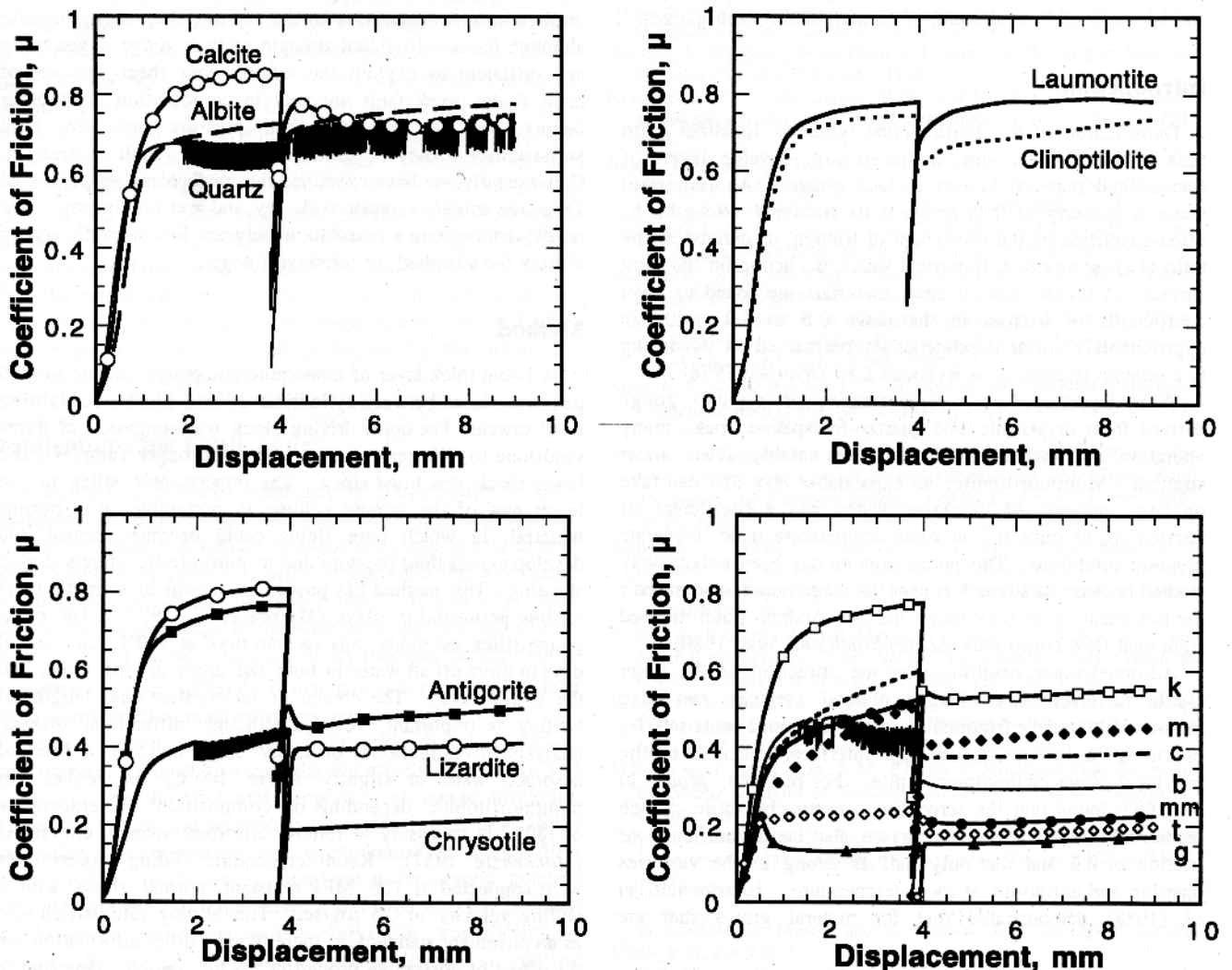
Figure 1. Coefficient of friction, μ, versus axial sliding displacement for fault gouge minerals. The samples were saturated at 4 mm displacement. (a) Calcite, albite, and quartz; (b) Zeolites: laumontite and clinoptilolite; (c) Serpentinites: antigorite, lizardite, and chrysotile; (d) Sheet-structure minerals: k, kaolinite; m, muscovite; c, chlorite; b, brucite; mm, montmorillonite; t, talc; g, graphite.

1c) showed dramatic differences in the coefficient of friction after saturation, with strength reductions of 39, 51, and 64% for the antigorite, lizardite and chrysotile gouges, respectively. These data demonstrate the important effect of adsorbed water on strength, especially for the mineral chrysotile ($\mu = 0.2$), as observed in previous studies *(Reinen et al.,* 1994; *Moore et al.,* 1997). In repeated tests using both sandstone and granite upper driving blocks, chrysotile was the weakest serpentine mineral even when dry ($\mu = 0.4$-0.5), and also displayed consistently unstable deformation. *Iwata et al.* (1996) and *Moore et al.* (1997) reported dry chrysotile coefficients of friction of $\mu = 0.65$-0.7 for similar room-temperature experiments at 100 MPa normal stress using serpentinite driving blocks on both sides of the gouge layer. The reason for the dry strength disparity is not clear.

The remaining sheet-structure minerals, kaolinite, muscovite, chlorite, brucite, montmorillonite, talc, and graphite (Figure 1d), are plotted together to illustrate the wide variety in frictional strength behavior, from anomalously weak gouges (graphite, talc) to those consistent with Byerlee's Law (kaolinite). With saturation, most of these frictional strengths were reduced by 20 to 40%, and the relative wet strengths were not ordered the same as the dry strengths. Note that the weakest mineral, graphite ($\mu = 0.15$), was not affected by saturation. In addition, muscovite, montmorillonite, chlorite and kaolinite showed significant strain hardening when dry, making it difficult to assess the maximum coefficient of friction. These gouges were retested to 9 mm without the addition of water, and in all cases the rate of strain hardening gradually decreased with displacement until the dry and wet friction curves were parallel.

Discussion

Dry Strength

It is important to remember when comparing results of different studies that 'dry' strength may be a relative term depending on the length and temperature of drying, if any. *Dieterich and Conrad* (1984) found that carefully dried slip surfaces had stronger frictional resistance than those exposed to room humidity. This may explain why *Shimamoto and Logan's* (1984) room-dry calcite data were similar to our wet
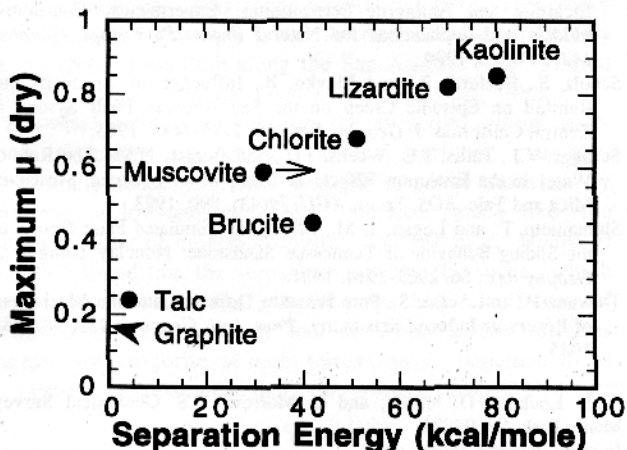
Figure 2. Maximum dry coefficients of friction, , (this study) versus separation energy of sheeted-structure minerals, from *Giese* (1978, 1980) and *Bish and Giese* (1981). Minimum separation energy shown for muscovite.
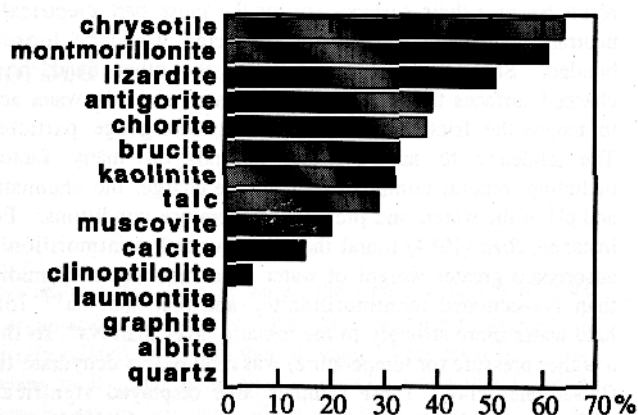
Figure 3. Percentage decrease in frictional strength of gouge minerals after saturation.

values, and why *Morrow et al.* (1992) reported coefficients of friction of montmorillonite dried at 100°C that were lower than in this study. We tested montmorillonite dried at 120°C, and found it had identical strength to a sample dried at 190°C, suggesting that drying at 100°C did not remove all the adsorbed water that was removed at 120°C. However, drying temperatures should not be chosen so high as to alter the crystal structure of the minerals, and x-ray analysis of our run products confirmed that the mineral structures were unaffected by heating.

Even with the careful drying of these samples, a wide variety of frictional behavior is observed in Figure 1d. This can be explained by comparing the type of bonds and associated interlayer bond strength in minerals with sheeted crystal structures. Figure 2 shows the dry coefficient of friction, μ, of several sheet-structure minerals (this study) versus the separation energy in kcal/mole required to separate individual layers of the sheet structure (from *Giese,* 1978, 1980 and *Bish and Giese,* 1981). Separation energy is determined by calculating the energy change of electrostatic bonds accompanying increasing increments of separation of the interlayers. A clear trend is evident progressing from weak bonds with low coefficients of friction (talc), to dipole-dipole-type bonds with intermediate coefficients of friction (brucite), to stronger hydrogen bonds with higher coefficients of friction (lizardite and kaolinite). We have included graphite at $\mu = 0.15$ along the y-axis in this plot, because although the weak van der Waals forces acting between layers of this mineral were not considered by Giese, the friction data are consistent with the intercept of the energy trend.

Figure 2 demonstrates a correlation between interlayer bond strength and frictional resistance in sheeted-structure minerals. However, hydrogen bond strengths are low compared to bond strengths in most other minerals, and yet the strengths of dry lizardite and kaolinite are consistent with Byerlee's Law. This figure would suggest that for low separation energies, the dry coefficient of friction is controlled by bond strength, but at higher energies, other mechanisms, such as microcrack growth, limit the coefficient of friction to the typical range of $\mu = 0.6$-0.85 above about 70 kcal/mole. This hypothesis will be tested further.

Effect of Water

The framework silicates and calcite (Figures la, b) showed no significant effect of water on frictional strength. This may

result because their surfaces are for the most part electrically neutral and so any water layers attracted would be loosely bonded. Sheet-structure minerals, on the other hand, have charged surfaces that readily adsorb water, and this water acts to reduce the frictional resistance between gouge particles. The tendency to adsorb water depends on many factors including mineral composition, surface charge, the chemistry and pH of the water, and pressure-temperature conditions. For instance, *Bird* (1984) found that Ca-saturated montmorillonite adsorbed a greater weight of water as a function of humidity than Na-saturated montmorillonite, and that the Ca^{+2} ions held water more strongly to the mineral layer than Na^+ so that a higher pressure (or temperature) was required to dehydrate the Ca-saturated clay. These samples also displayed significant differences in frictional strength. *Scruggs et al.* (1993) found that surface charge in muscovite and talc (hydrophyllic versus hydrophobic surfaces, respectively) explained differences in the friction evolution effect.

A thorough analysis of the factors influencing water adsorption on gouge minerals is beyond the scope of this short paper. Therefore, we take a qualitative approach and show a ranking of the gouge minerals according to the percentage decrease in frictional strength after water saturation (Figure 3*)*, which is equivalent to a relative ordering of the mineral's tendency to adsorb or take on interlayer water. With the exception of the covalently-bonded graphite, which has no significant surface charge, this ranking effectively separates the sheet-structure minerals from the others. An important observation is that the serpentinite gouges as a group are the most affected by the presence of water. Montmorillonite, which swells with interlayer water in addition to adsorbing water on grain surfaces, was also greatly weakened upon saturation. We conclude that two factors cause many common sheet-structure fault gouge minerals to be anomalously weak. First, the maximum (i.e., dry) coefficient of friction is related to the strength and type of the interlayer bonds. Second, this dry strength is reduced to various degrees by the mineral's tendency to adsorb water.

Implications for Fault Zones

A decrease in frictional resistance of gouge materials with saturation can be observed in the field. For example, *Schulz et al.* (1983*),* found that certain near-surface creep events across active faults were correlated with rainfall and the associated "swelling and softening of fault gouge". Conversely, they observed that a downdraw of the water table due to a lack of rain dewatered the slip zone and led to an increase in the failure strength of gouge materials, causing a delay in near-surface creep events until a threshold stress was reached.

Because major faults extend beyond the near-surface environment, we must also consider the effects of pressure and temperature on the frictional properties of gouge minerals. Again focusing on the weakest gouges, *Morrow et al.,* (1992) found that montmorillonite was strengthened by around 50% when interlayer water was squeezed out under several hundred MPa pressure at room temperature. *Moore et al.* (1997*)* found that when the serpentine variety chrysotile was sheared at increasingly higher temperatures and pressures simulating depths of up to 9 km, adsorbed water was removed and the anomalously low frictional strength increased to levels more comparable to the antigorite and lizardite serpentine varieties.

Due to the strengthening effects of temperature and pressure, the average shear resistance of the weakest gouge minerals within the seismogenic zone is greater than the 10-20 MPa shear stress limit inferred from heat flow measurements on the San Andreas Fault. Thus, gouge strength alone cannot account for the low apparent strength of this fault. However, it is important to understand why certain gouge minerals are inherently weak, as we have explored in this paper, because low strength in combination with other factors such as above-hydrostatic fluid pressures, low fault permeability or strain-rate dependence may be key to fault behavior in many environments.

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