Crystallographic Controls on the Frictional Strengths of Layer-Structured Minerals

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ABSTRACT

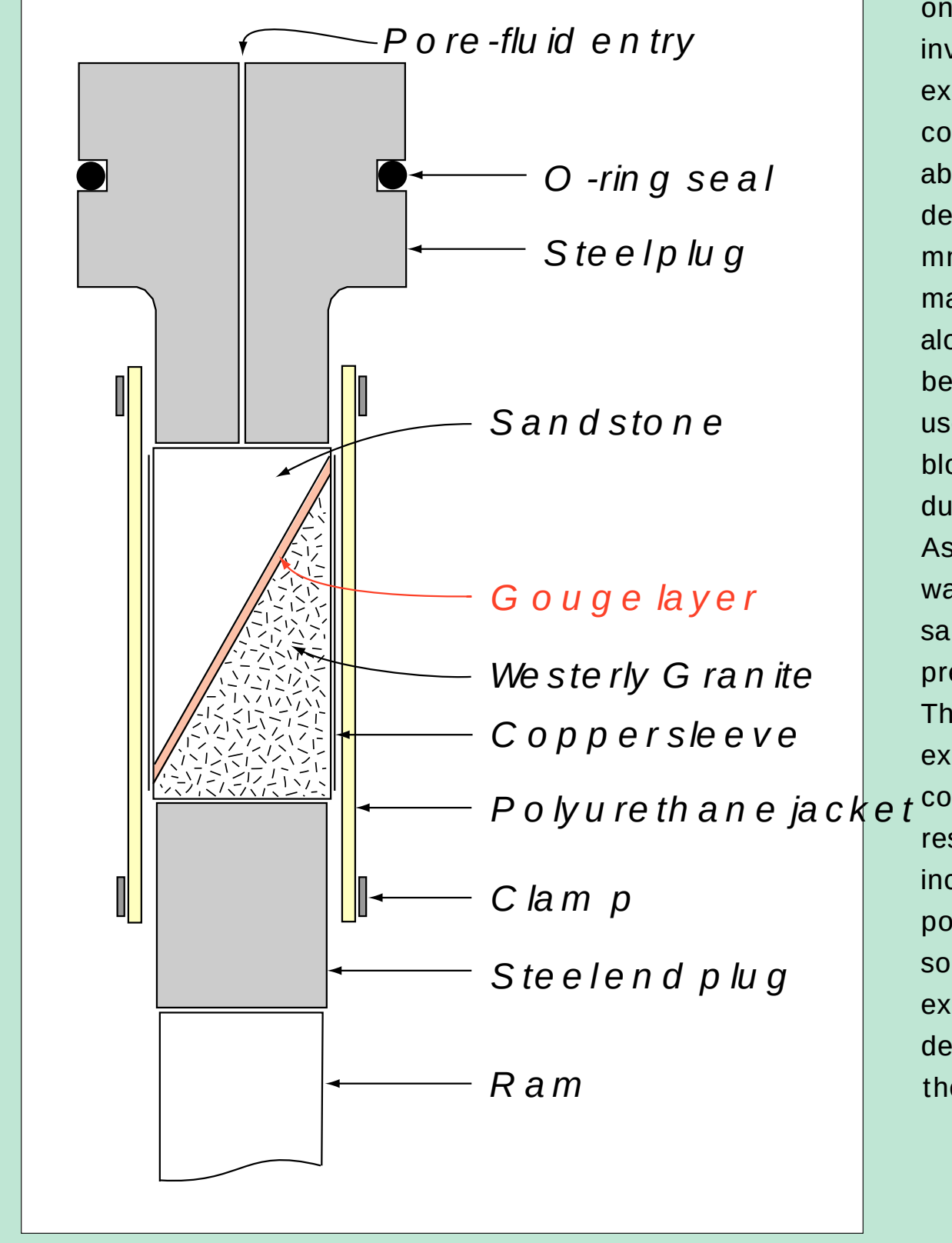
Phyllosilicates are common constituents of fault gouge, and their presence in faults is significant because they are weaker than most other rock-forming minerals whose coefficients of friction (shear stress/effective normal stress), μ ≈ 0.8 (Byerlee's Law). We are investigating the frictional strengths of phyllosilicate and other layer-structured minerals, to identify the factors that limit their strengths and ultimately to use this knowledge to determine fault-zone properties at depth. As part of a preliminary study (Morrow et al., 2000), we tested mineral separates of talc, muscovite, chlorite, lizardite, kaolinite, brucite, and graphite. Here, we report new data for margarite, pyrophyllite, a biotite and two phlogopites, a second muscovite and a paragonite/muscovite mixture. Each mineral separate was hand-ground and passed through a 90-μm sieve, to produce a synthetic gouge. We ran room-temperature frictional sliding experiments on sawcut rock samples containing a 1-mm layer of gouge. In order to compare dry and water-saturated strengths, the samples were vacuum-dried at 120°C overnight and then immediately tested in a triaxial apparatus at 100 MPa normal stress and 0.5 μm/s sliding velocity. The samples were sheared dry to 4 mm displacement, then water was introduced to a pressure of 10 MPa. After an approximately 1-hour equilibration period, sliding was resumed at 100 MPa effective normal stress to 9 mm displacement.

Our initial experiments indicated a correlation between the coefficients of friction of the dry gouges and the strengths of their interlayer bonds. The new results support this correlation. The values of μ (dry) range from 0.18 for graphite to 0.80–0.85 for lizardite, kaolinite, and margarite, the peak strengths being consistent with Byerlee's Law. For the trioctahedral micas biotite and phlogopite μ (dry) ≈ 0.54, and for the dioctahedral micas muscovite and paragonite μ (dry) ≈ 0.59. We propose that shear in those dry gouges with μ < 0.8 occurs by breaking through the interlayer bonds to form new cleavage surfaces, or by breaking adhesive contacts whose strengths may also be proportional to the interlayer bonds. Preliminary SEM examinations suggest that the cleavage mechanism is operative to at least some extent. Where μ (dry) ≥ 0.80, the interlayer bonds are sufficiently strong that other frictional processes dominate. The addition of water caused μ to decrease for every mineral except graphite, which showed no change. The range of μ (wet) for the sheet silicates is 0.20 (talc) to 0.68 (margarite). The controls on the strength of water-saturated gouge appear to be more complex than for dry gouge. However, if hydrogen bonded and non-hydrogen-bonded phyllosilicates are considered separately, μ (wet) increases with increasing interlayer bond strength for both groups. In water-saturated gouge subjected to high normal stresses, the water may exist as very thin, structured films whose attraction to the plate surfaces is in part proportional to their surface energies/interlayer bond strengths. The coefficient of friction of the wet gouge would then reflect the stresses required to shear through the water films.

INTRODUCTION

It is well known that adding clays or other sheet silicates to fault-zone materials will weaken the fault. Many rock-mechanics investigators have studied individual phyllosilicate minerals, to determine the extent of their weakening effect. However, no one has previously conducted a systematic investigation of the layer-structured minerals, in order to identify the general cotrols on their frictional behavior. We are currently attempting such a study, focussing on the extent to which crystal structure and mineral chemistry influence strength.

Sample Assembly

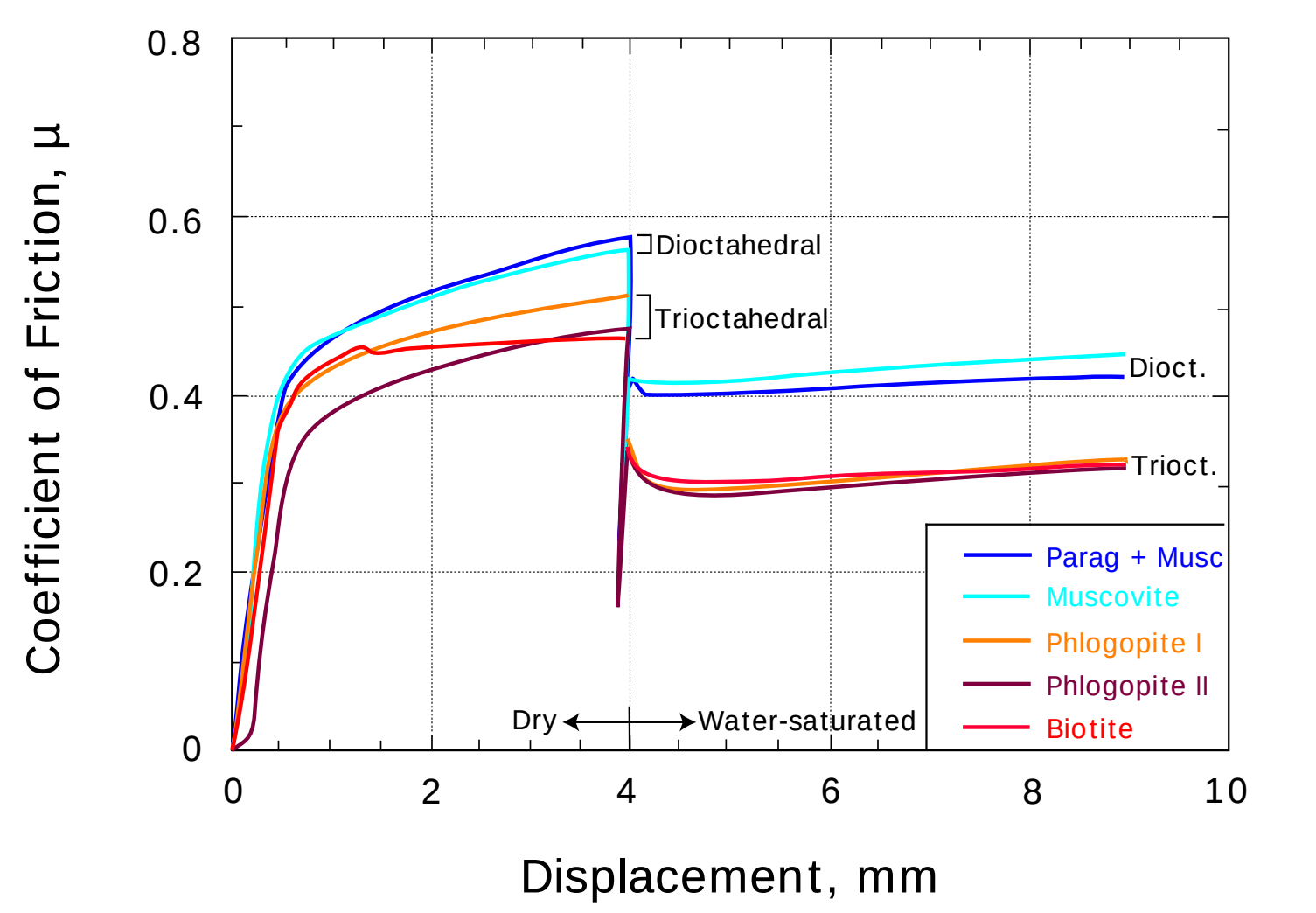


The sample assembly is a standard one for rock-mechanics investigations on gouge. The experimental procedures and conditions are summarized in the abstract above; a few additional details are presented here. A 1-mm thick layer of the gouge material to be tested was placed along a 30° sawcut surface between rock forcing blocks. We used sandstone for the upper block to facilitate fluid entry during the wet portion of the run. As soon as the oven-dried sample was in the pressure vessel, the sample assembly and pore-pressure lines were evacuated. The combined dry/wet experiments were run for direct comparison with our previous results. In some cases, μ was still increasing at the end of the dry portion of the test; consequently, some additional all-dry experiments were run to better determine μ (dry). Only a few of the all-dry runs are shown at right.

EXPERIMENTAL RESULTS

All tests were run at 100 MPa effective normal stress and 0.5 μm/s axial displacement rate. Fluid pressure was 10 MPa during water-saturated portions of experiments. Mineral composition data reported below were obtained with an electron microprobe.

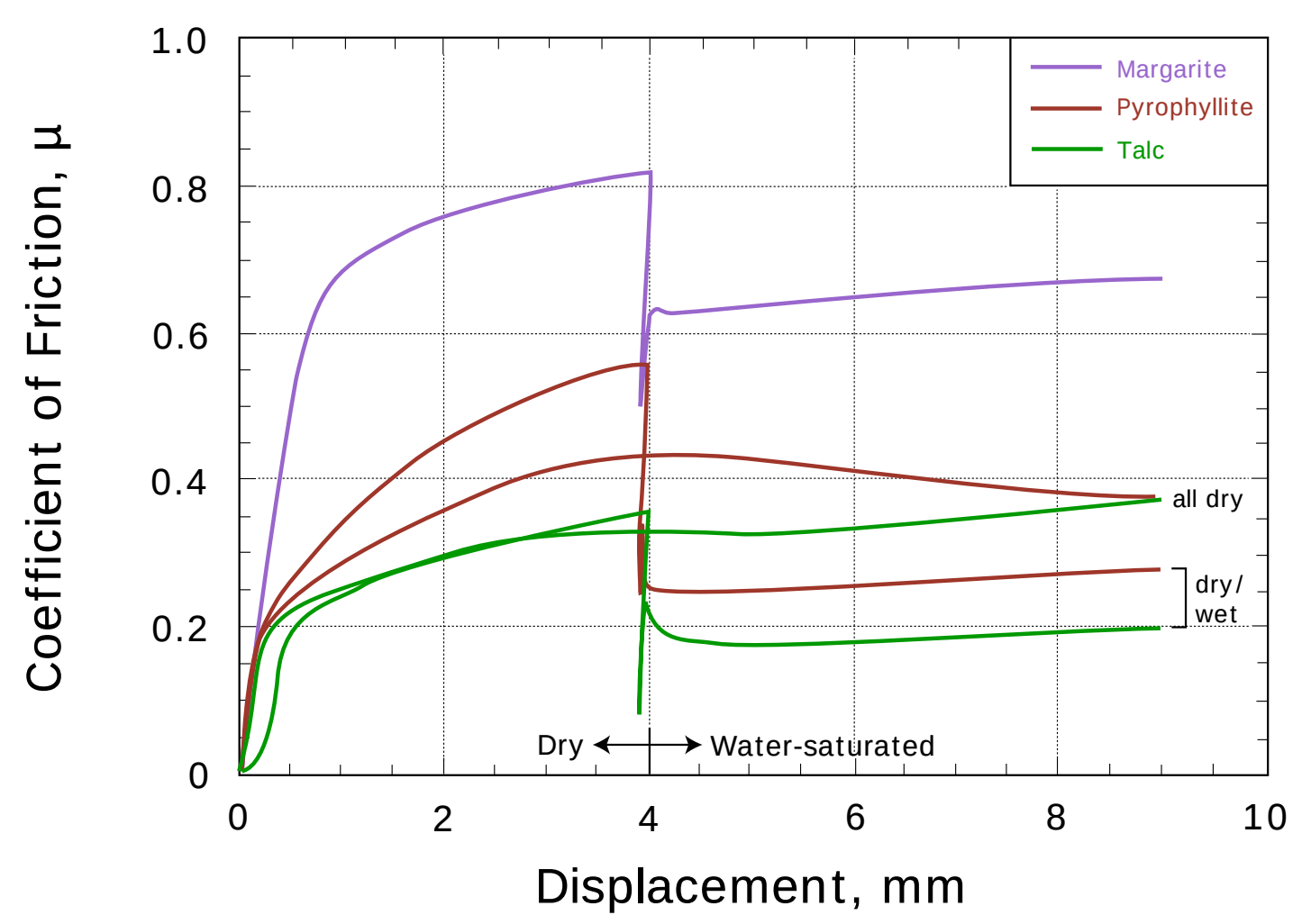
Flexible Micas



Minerals: Paragonite ≤ Muscovite — The two minerals could not be separated from a paragonite schist from Chester, VT. The paragonite contains 1.0 wt % K_2O, 0.8% FeO* (=total Fe), and 0.5% CaO, and the muscovite about 1.6 wt % Na_2O, 2.7% FeO, and 1.2% MgO. Muscovite — Large crystals from Stoneham, ME, containing 0.7 wt % Na_2O, 2.6% FeO*, 0.4% MgO, and 0.8% F. Biotite — Large black crystals from Bancroft, Ontario. The color is consistent with biotite, but Fe/Mg is low enough to qualify it as phlogopite. It has 4.7 wt % F, 11.3% Al_2O_3, 11.0% FeO*, and 18.9% MgO. Phlogopite I — Large, brownish-gray crystals from Quebec, with 4.1 wt % F, 14.4% Al_2O_3, 1.8% FeO*, and 26.3% MgO. Phlogopite II — Light-green crystals from Little Butte, Montana; 0.5 wt % F, 18.7% Al_2O_3, 3.5% FeO*, and 23.5% MgO.

Major Points: The flexible micas can be separated into two groups based on their strengths, the dioctahedral minerals having consistently higher values of μ, both dry and wet, than the trioctahedral minerals. Compositional variations within a group, such as the range of F and Fe contents among the trioctahedral micas and the mix of Na- and K-bearing dioctahedral micas, do not appear to affect strength.

Other 2:1 Sheet Silicates



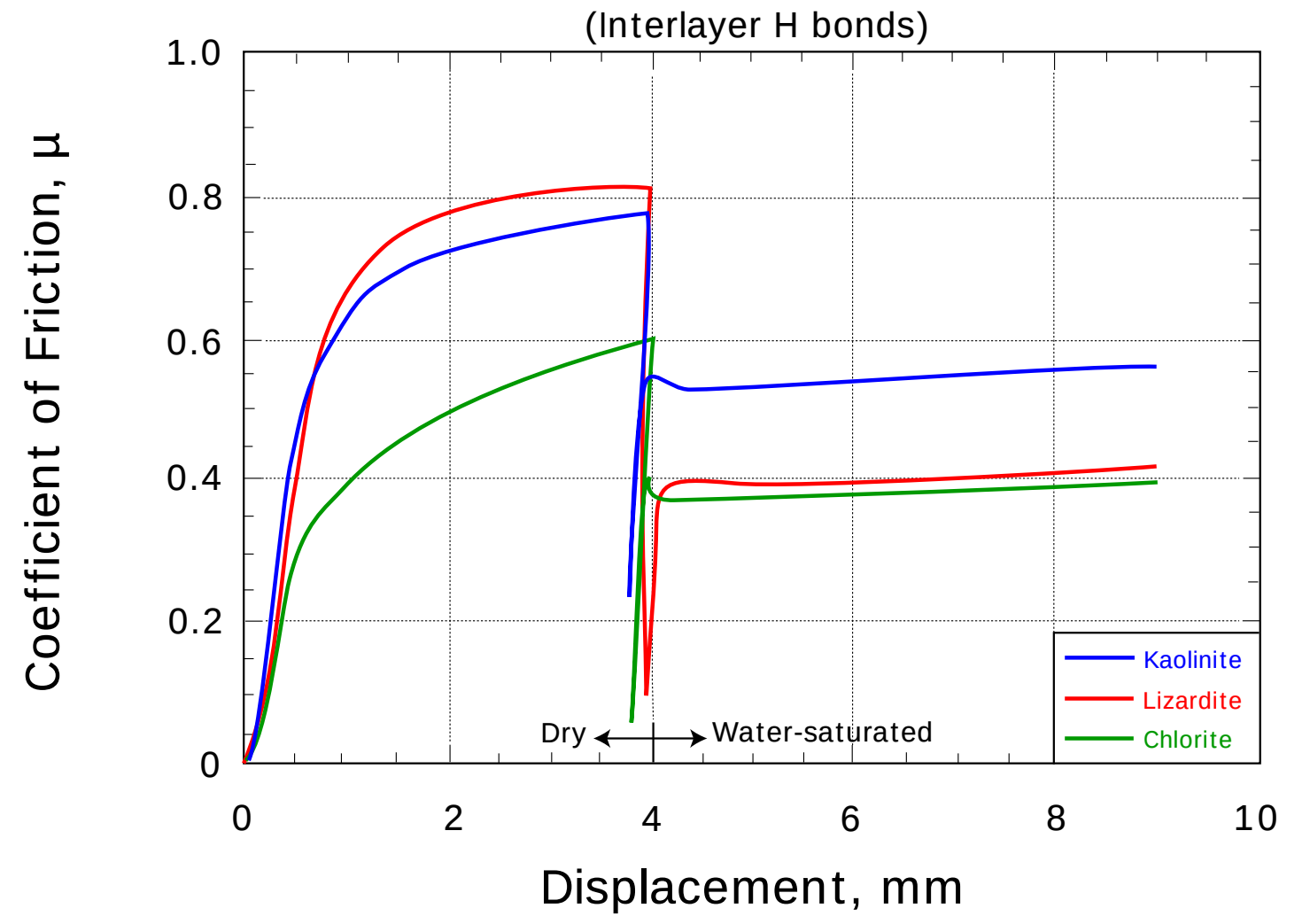
Minerals: Margarite — Pale pink crystals from Chester, MA; 1.7 wt % Na_2O, 0.8% FeO*, and 0.5% MgO. Talc — Purified grade talcum powder from Fisher Scientific. Pyrophyllite — Acicular sprays of white crystals, Hillsboro, NC. Nearly end-member composition; 0.2 wt % FeO* is the main impurity.

Major Points: μ ≥ 0.8 for the brittle mica margarite, comparable to μ of dry kaolinite and lizardite (see below). Under water-saturated conditions, margarite is the strongest of all the layer-structured minerals tested in this study, with μ = 0.68.

Our value of μ (dry) for talc is higher than that reported by Morrow et al. (2000). An all-dry experiment on talc suggests that the higher value for μ (dry) is the correct one. Pyrophyllite and talc form another dioctahedral-trioctahedral pair, and water-saturated pyrophyllite is stronger than talc. Further study is needed to verify μ (dry) of pyrophyllite. Its coefficient of friction increased rapidly during the dry portion of the dry/wet run. In an all-dry pyrophyllite experiment, μ reached a maximum at ≈4 mm displacement, then decreased to the value for talc; but a second all-dry run yielded a significantly higher value of μ. Preliminary textural examinations suggest that the pyrophyllite may have reacted with the sandstone forcing block during the drying process.

1:1 Sheet Silicates and Chlorite

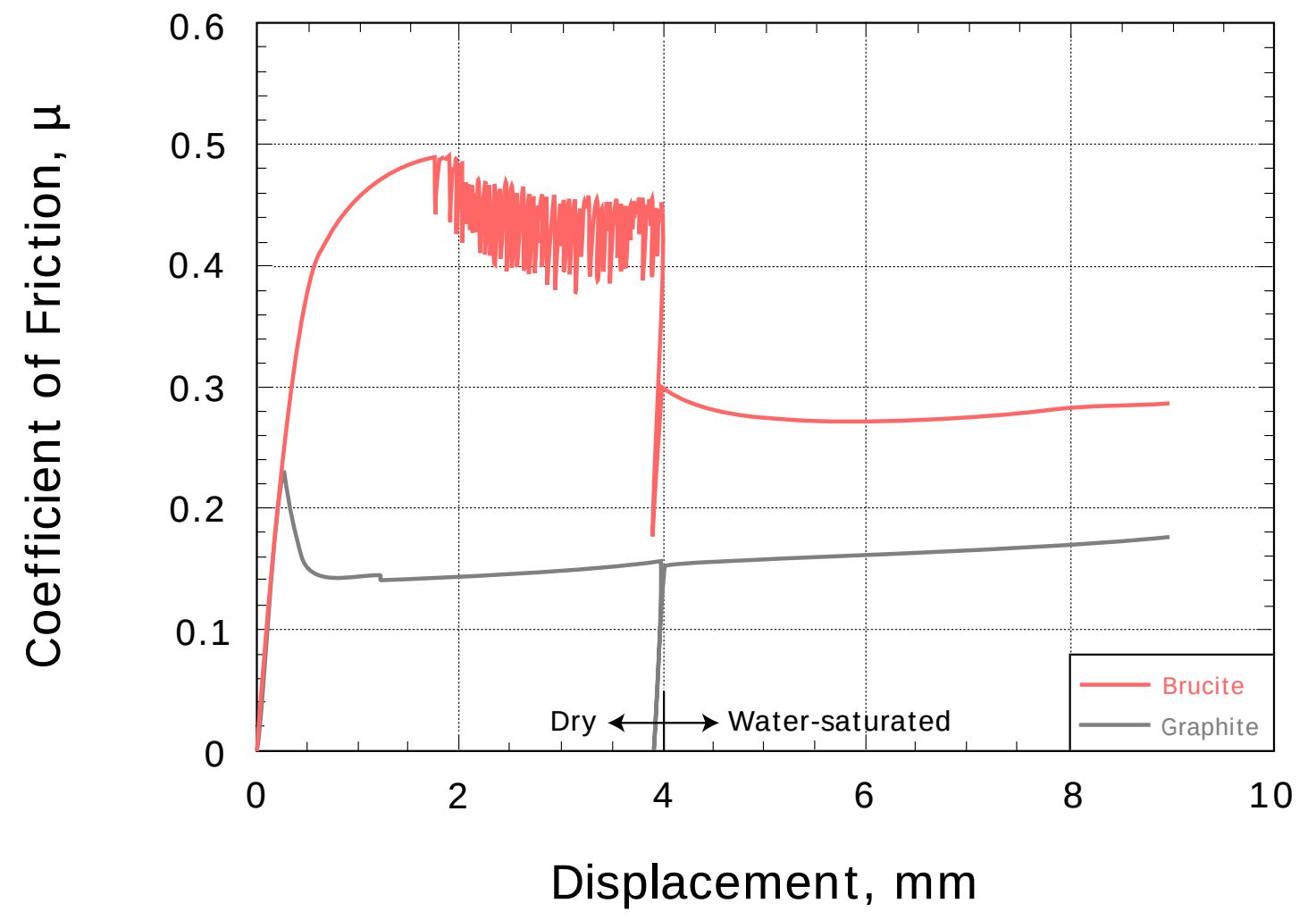
(Interlayer H bonds)



Minerals: Lizardite — Thoroughly serpentinized peridotite from Gold Beach, OR; the XRD pattern of the separate shows only 1T lizardite. Lizardite replacing olivine has 0.6–2.2 wt % Al_2O_3 and that replacing pyroxenes has 3.6–5.0% Al_2O_3. Kaolinite — Hydrothermal deposits, Mammoth Lake, CA. Nearly end-member composition; traces of Fe. Chlorite — Garnet-bearing schist from Flagstaff Hill, CA. Approximate mineral formula: $Fe_{3.75}Mg_{3.65}Al_{2.6}(Si_{5.35}Al_{2.65})O_{20}(OH)_{16}$.

Major Points: Both kaolinite and lizardite have μ (dry) ≥ 0.8. However, wet dioctahedral kaolinite is stronger than its wet trioctahedral equivalent, lizardite. Chlorite is weaker than the other two minerals in this figure, although the wet strengths of chlorite and lizardite are very similar. From Morrow et al. (2000).

Non-Silicates



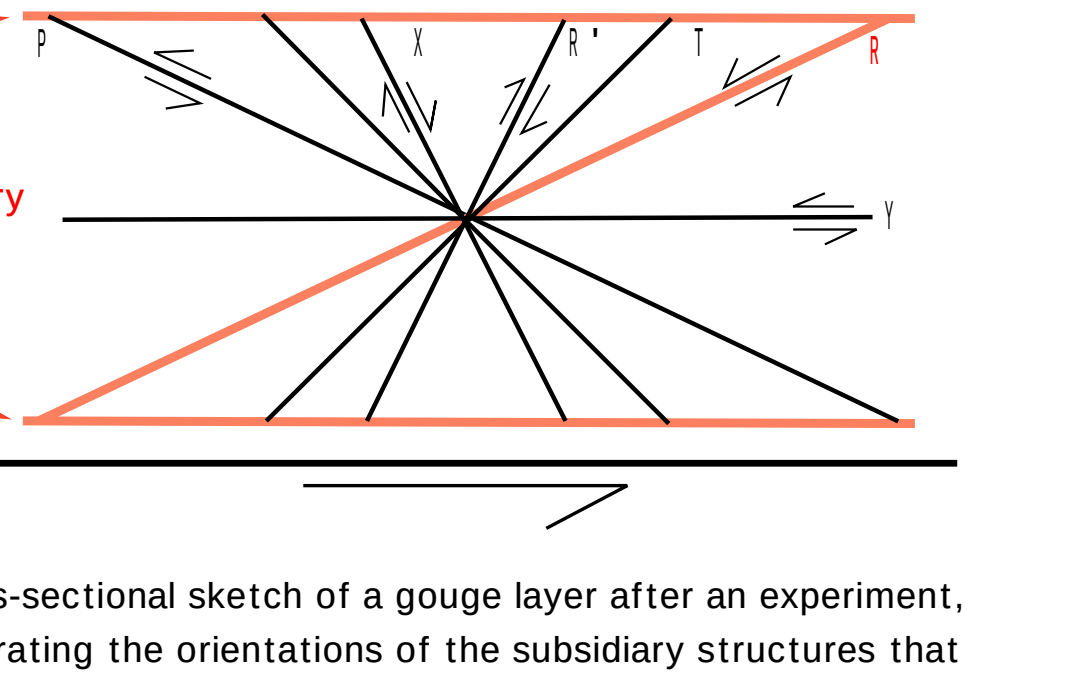
Minerals: Brucite — Clear, colorless lamellae from Lancaster Co., PA. The composition is nearly end-member $Mg(OH)_2$, the only substitutions for Mg being ≈0.25 wt % each FeO* and MnO. Graphite — Commercial graphite powder from Fisher Scientific.

Major Points: These two experiments are repeats of ones reported by Morrow et al. (2000). These new results are nearly identical to the earlier ones, including the stick-slip behavior of dry brucite. Adding water to the graphite sample after 4-mm displacement had no effect on its strength.

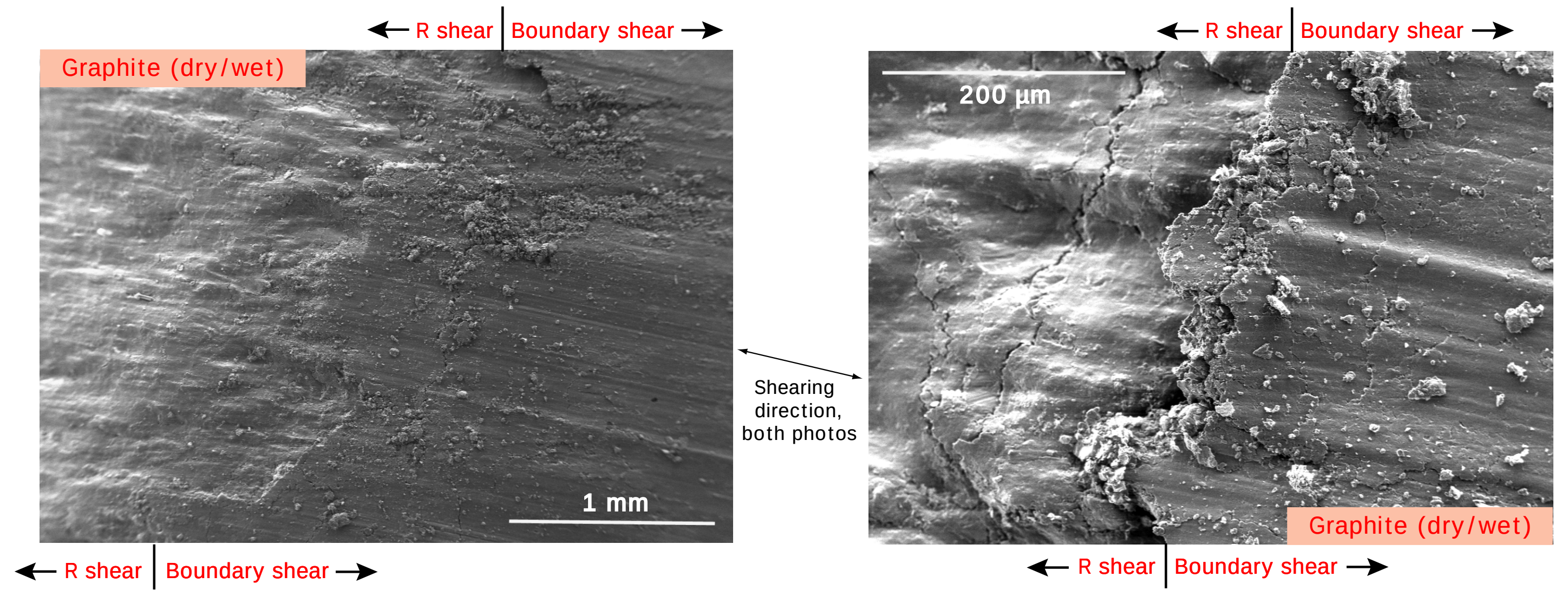
PETROGRAPHY

The samples selected for SEM study were cut out of their polyurethane jackets, and the sandstone and granite forcing blocks were separated to expose the gouge layers. The samples were examined first with a stereomicroscope; then, small fragments of gouge were removed and mounted on circular holders.

(1)

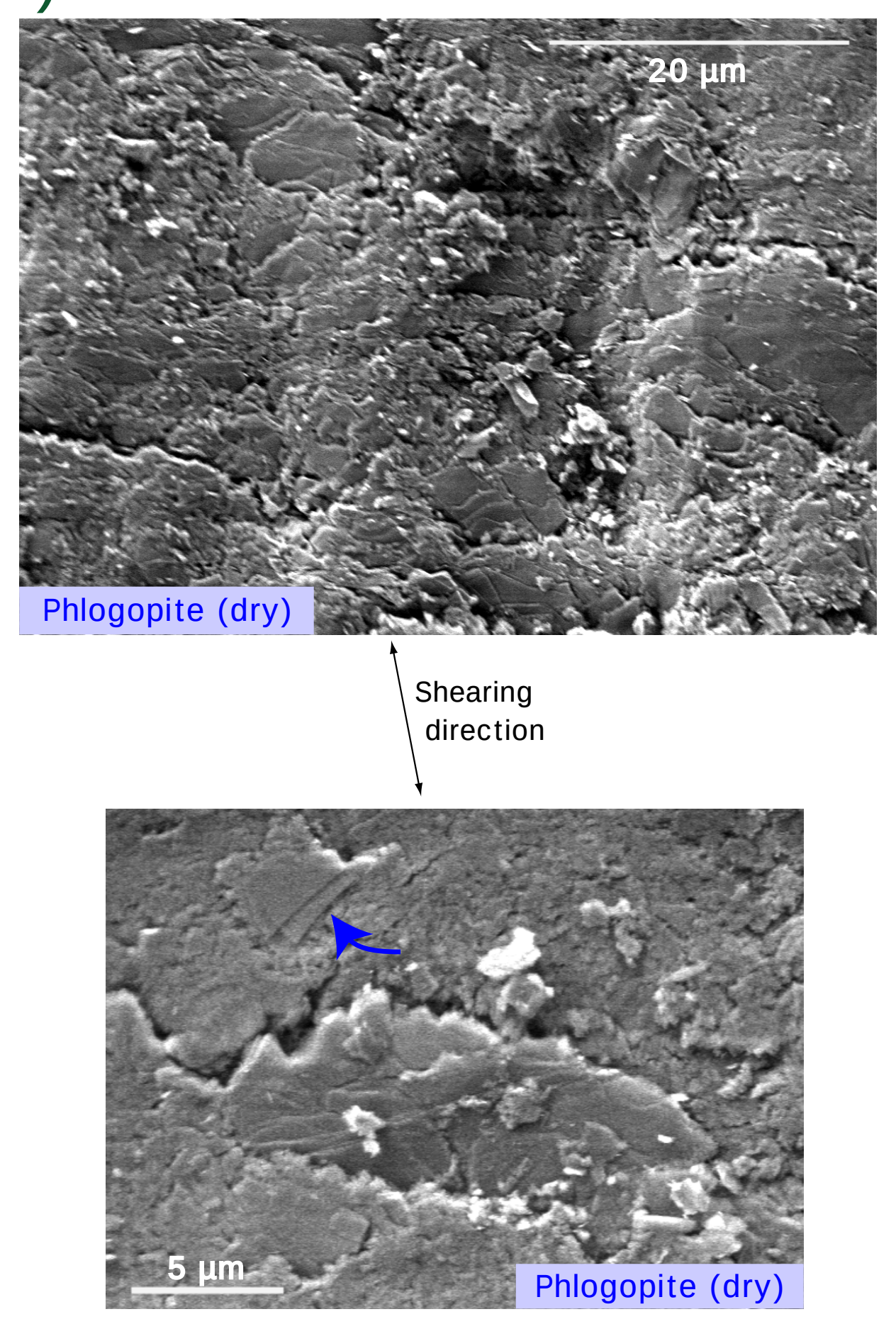


Cross-sectional sketch of a gouge layer after an experiment, illustrating the orientations of the subsidiary structures that have been identified in previous many studies. Boundary shears and R-type Riedel shears predominate in the samples of this study, and this is typical of laboratory sam-ples run for relatively short displacements at high pressures. When the samples are disassembled, the gouge layers tend to separate along the shear planes.



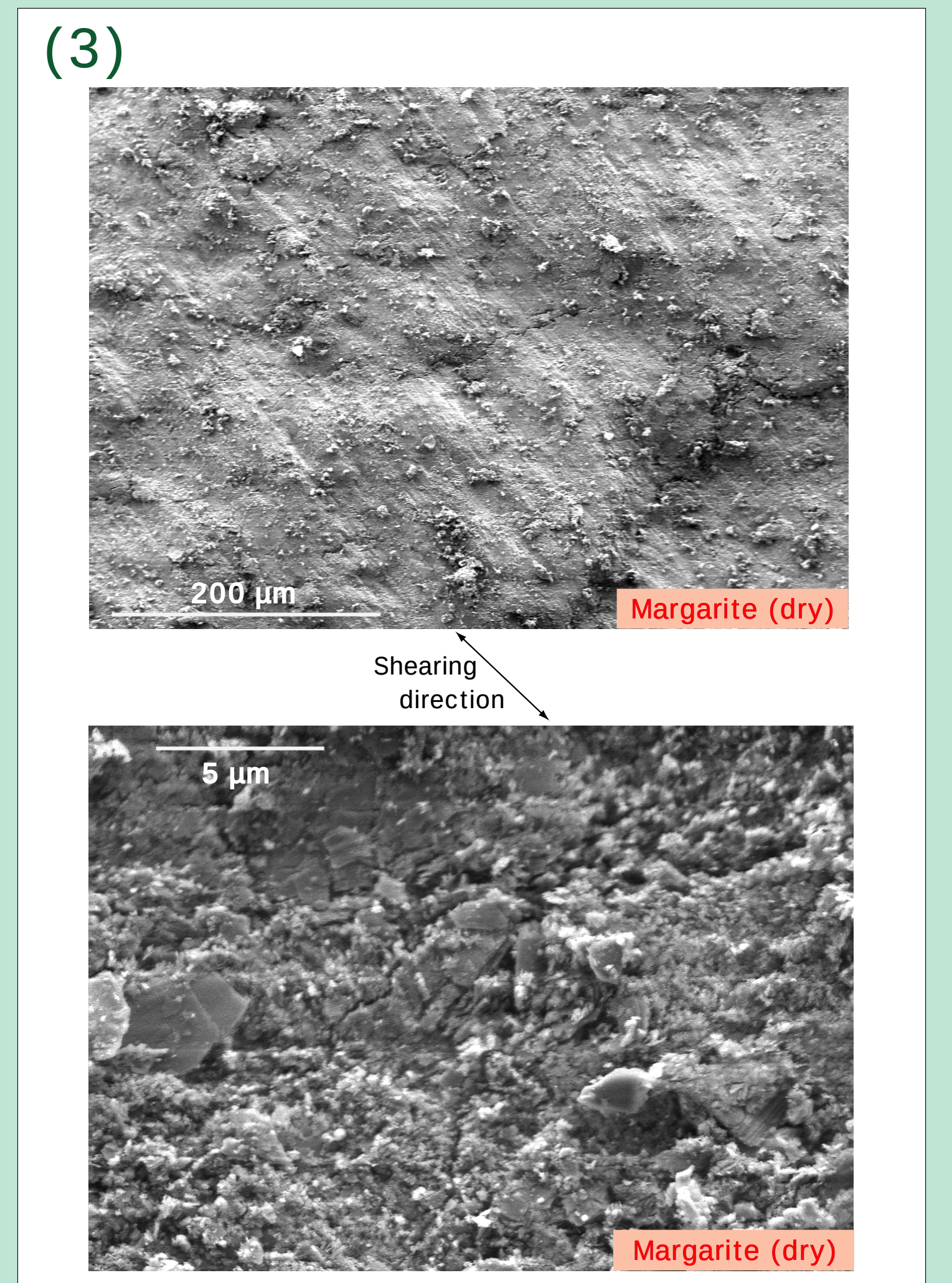
These two secondary-electron SEM images of a graphite sample provide a general view of the R- and boundary-shear surfaces. The weaker gouges have shiny shear surfaces resulting from the alignment of the crystal platelets parallel to the shears, and graphite — the weakest gouge tested — has the most highly reflective surfaces of all those examined. The boundary shears are characterized by elongate corrugations or striae aligned in the direction of shear. The shorter R shears have a more irregular, lumpy appearance, but their surfaces also are shiny and striated.

(2)



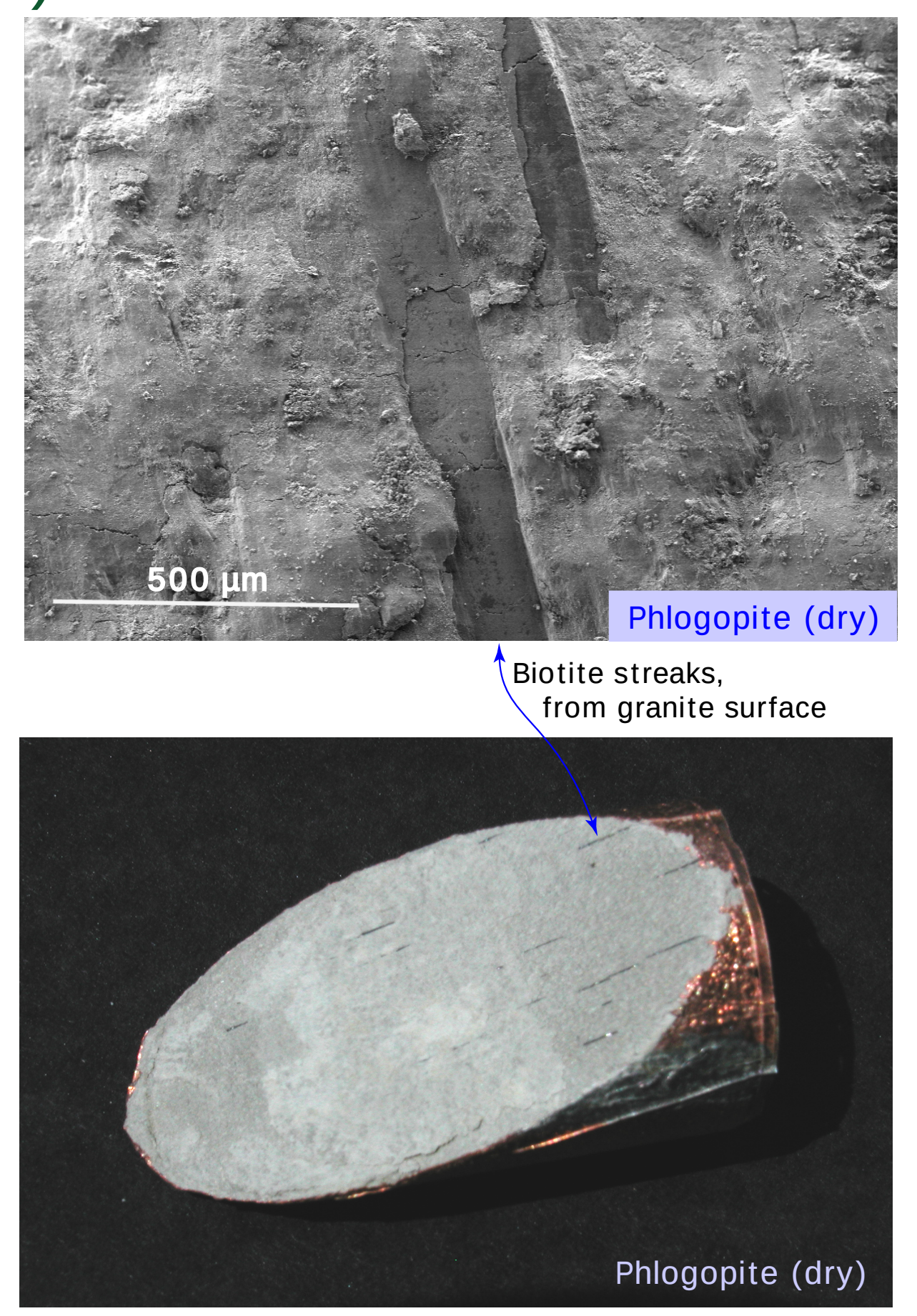
All-dry samples for which μ < 0.8, such as the phlogopite shown here, have shiny shear planes similar to those in graphite (1). The upper view shows the parallel arrangement of plates along the striae of a shear. The platy crystal marked by a blue arrow in the lower image may have been slightly offset along an (001) cleavage plane.

(3)



Dry margarite has μ > 0.8, and the shear planes of this all-dry margarite sample differ in appearance from those of phlogopite (2) and graphite (1). The margarite boundary shear does have faint striae (upper photo) similar to the weaker samples, but the striae are relatively short and the shear surface is rough, grainy, and dull rather than shiny. A few ≈5 μm-long, subparallel plates are visible in the close-up (lower) view, but most of the shear surface consists of extremely fine-grained, equigranular, broken fragments.

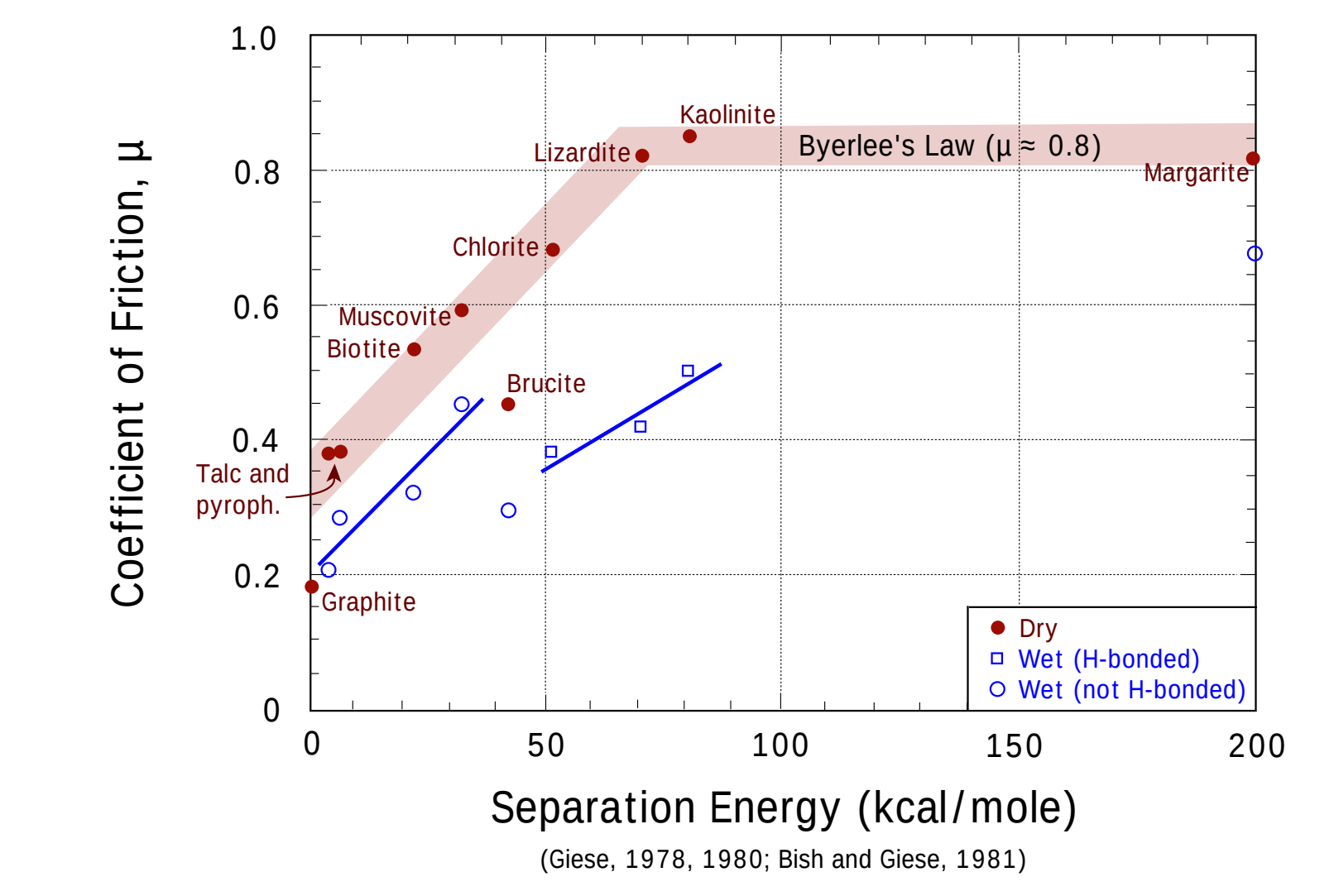
(4)



The granite used in the lower forcing block contains biotite. For those dry or dry/wet tests for which μ (dry) of the gouge ≥ μ (dry) of biotite, biotite flakes were incorporated into the gouge and smeared out in the direction of shear, forming black streaks. Some biotites were so strongly thinned that the streaks are nearly colorless. This phlogopite sample was sheared dry for the entire 9-mm of displacement, and the longest streaks are ≈9 mm. Some biotite streaks cross the gouge layer along R shears (upper photo) and continue on the opposite boundary shear. A dry/wet phlogopite sample contains streaks that are ≤4 mm in length, corresponding to the amount of dry shear. The all-dry margarite sample (3) contains 9–10 mm-long streaks, while those in the dry/wet margarite sample are all ≤3 mm long. Dry talc samples do not contain biotite streaks.

SUMMARY

Giese and co-workers calculated the electrostatic energy required to separate the layers of a wide range of layer-structured minerals. Below, we plot the peak values of μ (dry) and μ (wet) for the monomineralic gouges we studied against their separation energies.



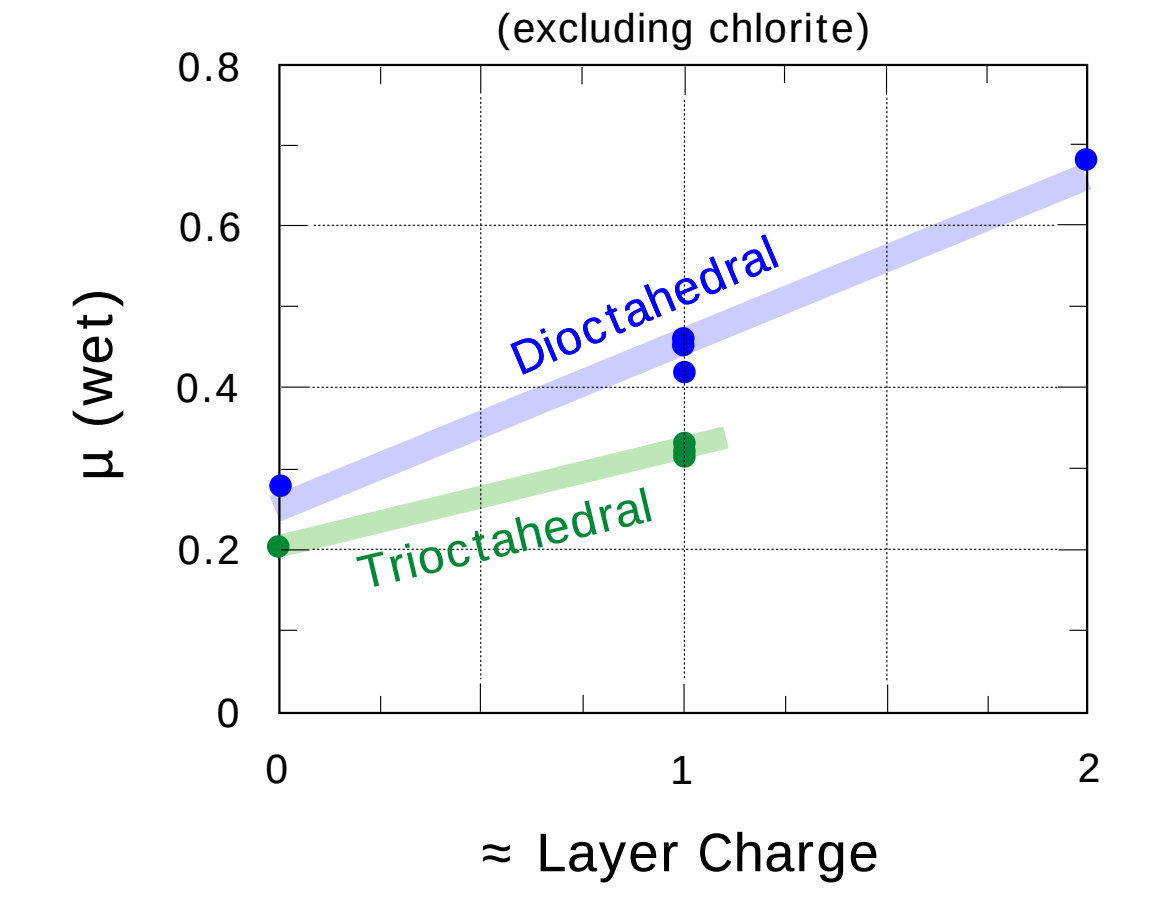
(Giese, 1978, 1980; Bish and Giese, 1981)

Dry Friction: Overall, values of μ (dry) increase with increasing separation energy up to energies of ≈65 kcal/mole, then μ levels off at 0.80–0.85. Byerlee (1978) compiled room-temperature friction data for a wide range of rock types and rock-forming minerals; he found most values of μ to be 0.80–0.85 at confining pressures up to 200 MPa (Byerlee's Law). We propose that the minimum energy required to initiate "standard" frictional processes in fault gouge (fracturing, abrasion...) is ≈65 kcal/mole. For dry layer-structured minerals with weaker interlayer bonds, it is easier to break those bonds (or the adhesive contacts between plates) than to initiate other frictional processes. The biotite streaks are evidence that this process does occur. The interlayer bonds of margarite, kaolinite, and lizardite are strong enough that they do not cleave during shear. Rather, as seen in the margarite SEM photos, the plates break down to small fragments that rotate past each other during shear.

Wet friction: Values of μ (wet) are more scattered, but in very general terms μ (wet) also increases with increasing separation energy. The correlation improves if the silicates are split into two groups: (a) 1:1 minerals and chlorite, which form interlayer H bonds, and (b) the remaining 2:1 sheet silicates. A plot of μ (wet) relative to the approximate layer charges of group (b) minerals, below, shows a better correlation, with separate trends for the dioctahedral and trioctahedral minerals. Adding water to any dry, layer-mineral gouge has a lubricating effect, lowering the frictional strength. However, the positive correlations among μ, separation energy, and layer charge suggest that in these high-pressure experiments the water forms thin films between the platy minerals, and the polar water molecules are bonded to the layer surfaces in proportion at least in part to their surface energies. Higher stresses are needed to shear through the more strongly bonded water films.

2:1 Sheet Silicates

(excluding chlorite)



Future Studies: We are currently preparing mineral separates of gibbsite $[Al(OH)_3]$ and the brittle mica clintonite for testing, to add two more dioctahedral-triocrahedral pairs. We will then work at sorting out the controls on the frictional strength of wet layer-structured minerals.

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