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Solution-Transfer Processes and the Frictional Strength of Heated Brucite

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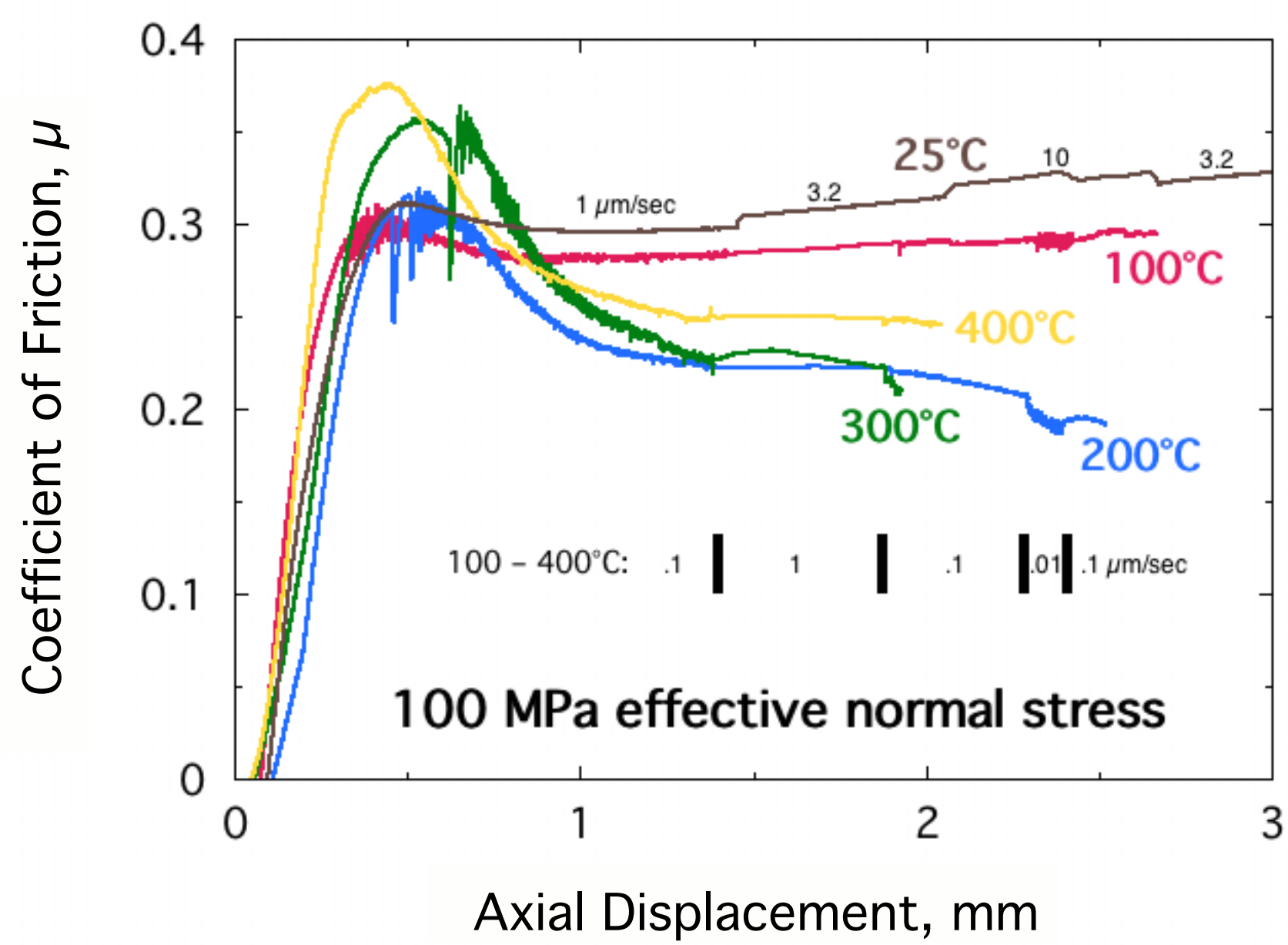


Abstract

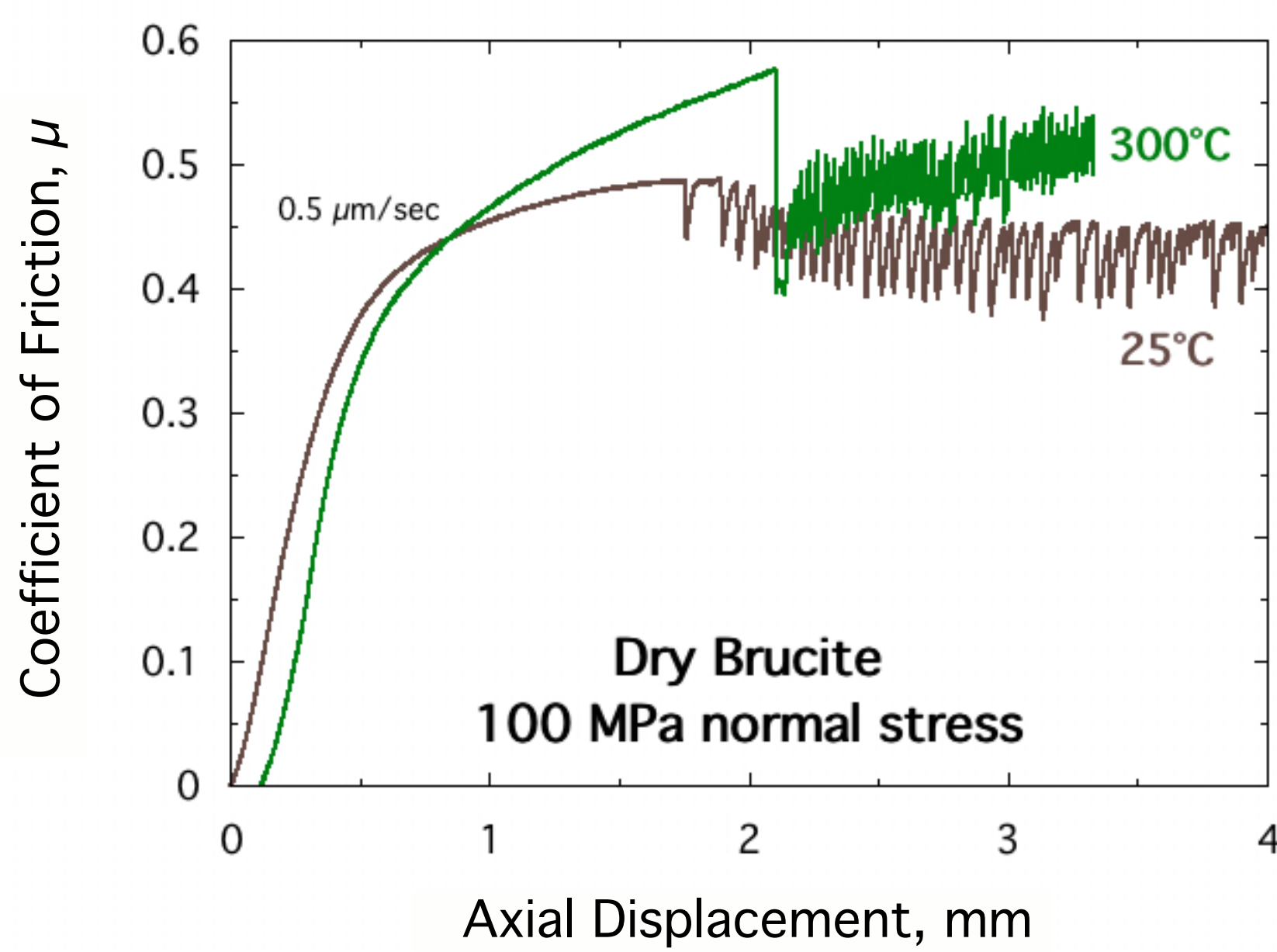
The mineral brucite, $\text{Mg}(\text{OH})_2$, has a layered crystal structure and a platy morphology, and in some respects its frictional behavior is consistent with that of the sheet silicate minerals. These characteristics include relatively low frictional strength that makes brucite an exception to Byerlee’s Law, and the localization of shear in brucite gouge onto slickensided boundary and Riedel shear planes. However, the frictional strength of brucite also differs in some ways from that of sheet silicates such as the serpentine minerals with which brucite is commonly associated in nature. Under water-saturated conditions the serpentine minerals are characterized by increases in coefficient of friction, μ with increasing temperature and effective normal stress. In contrast, the coefficient of friction of water-saturated brucite decreases overall with increasing effective stress and increasing temperature to 300°C. At 100 MPa effective normal stress, $\mu \approx 0.3$ at 25°C and $\mu \approx 0.25$ at 300°C for water-saturated brucite, whereas dry brucite has an essentially constant coefficient of friction of about 0.5 between 25° and 300°C.

We have initiated scanning electron microscope examinations of laboratory samples of sheared brucite gouge, to investigate the source of this discrepancy in frictional behavior between dry and water-saturated conditions. Preliminary observations suggest that solution transfer facilitates the shear of heated, water-saturated brucite. Brucite grains on boundary and Riedel shear surfaces are completely recrystallized to platelets with hexagonal outlines that are typically less than 0.5 μm in diameter. Adjoining small crystals coalesce to form wider, but still very thin, platy aggregates. Score marks on the shear surfaces that are aligned in the direction of shear may form as a result of dissolution in front of asperities that may themselves dissolve over time. Such a predominance of recrystallization textures has not previously been found in comparable laboratory samples of sheet-silicate gouges. The distinctive frictional behavior of brucite is consistent with geochemical data that show that it has high solubility and dissolution/precipitation rates that are several orders of magnitude greater than those of silicate minerals.

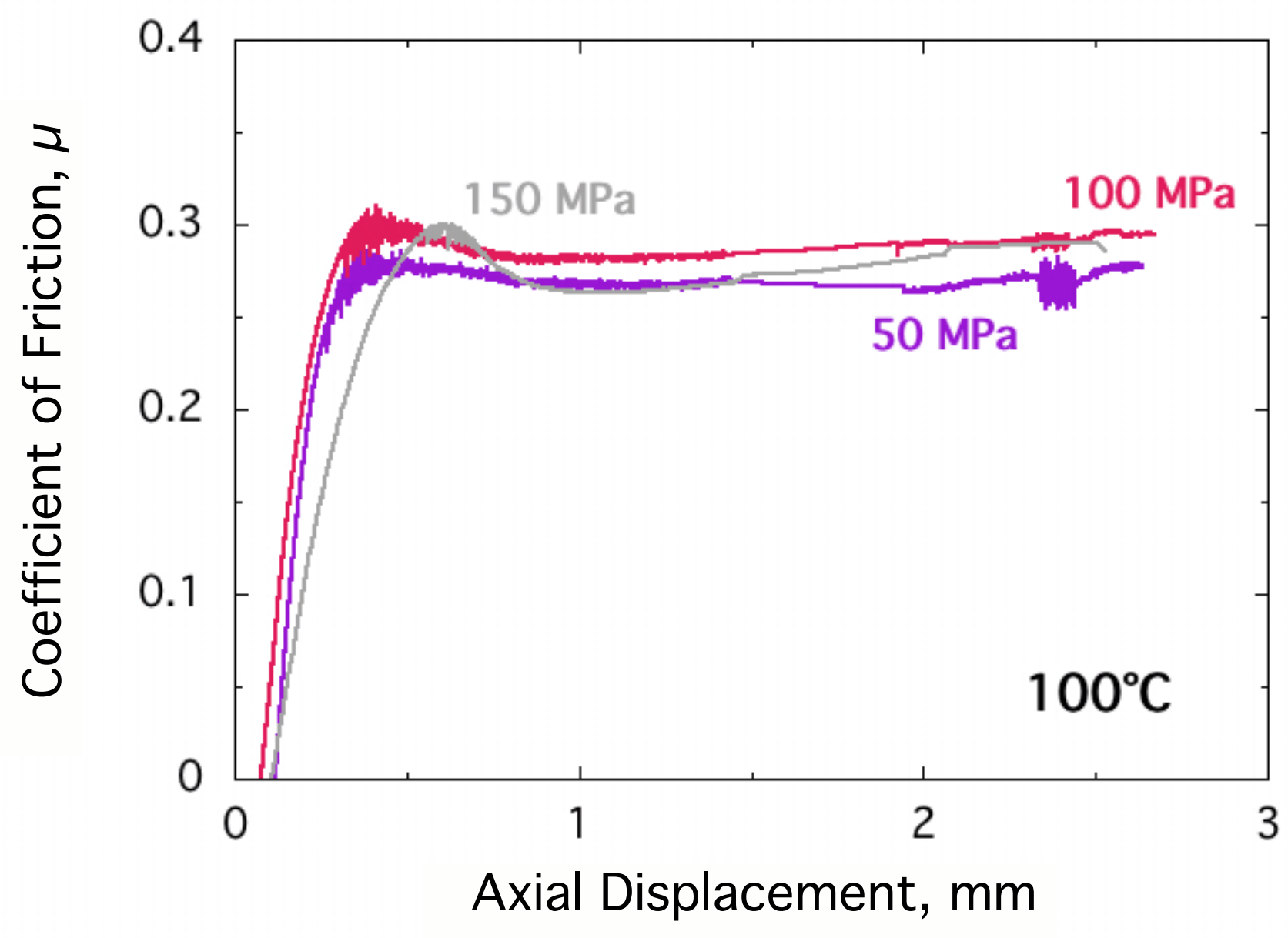
Strength Measurements



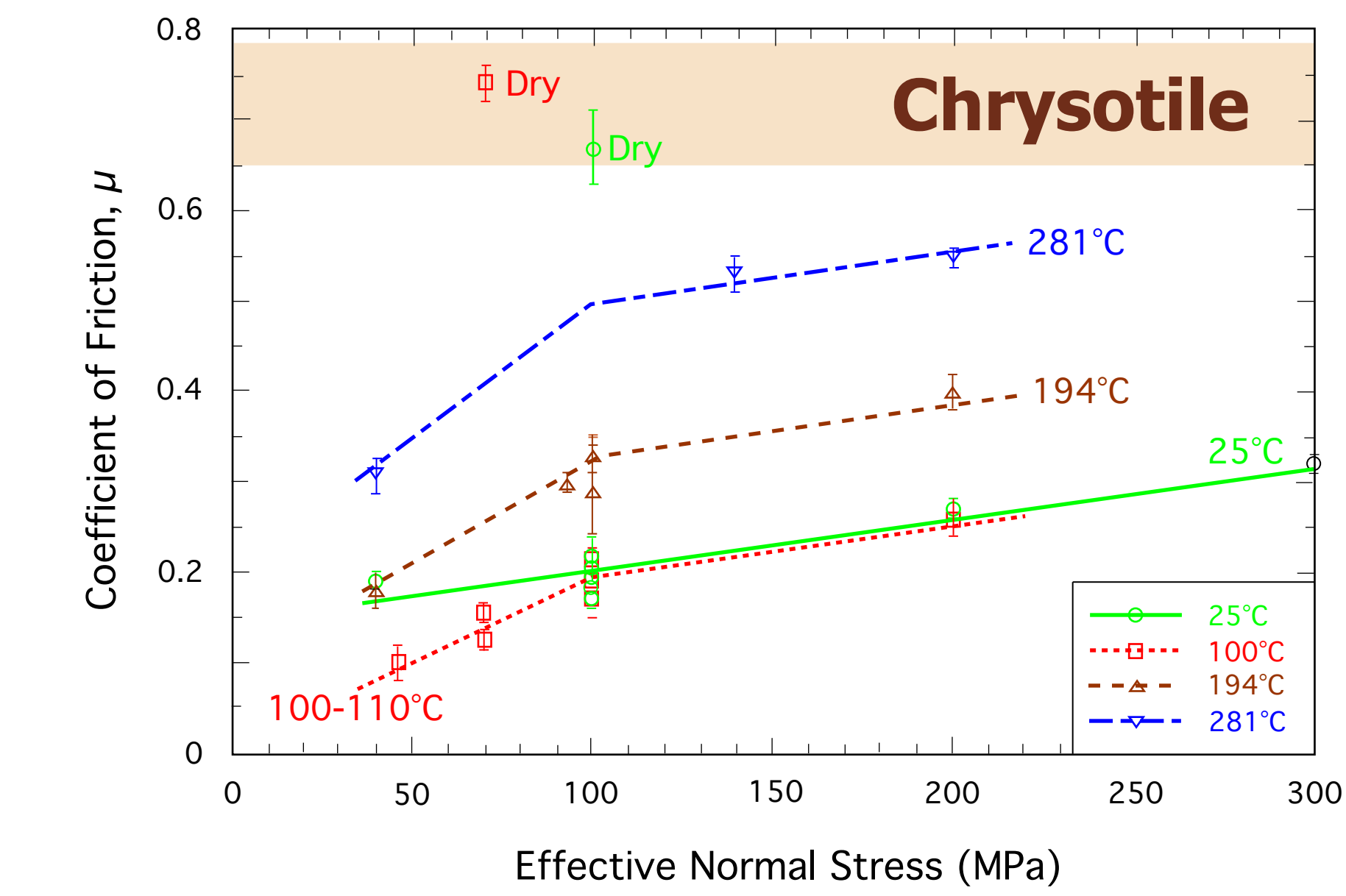
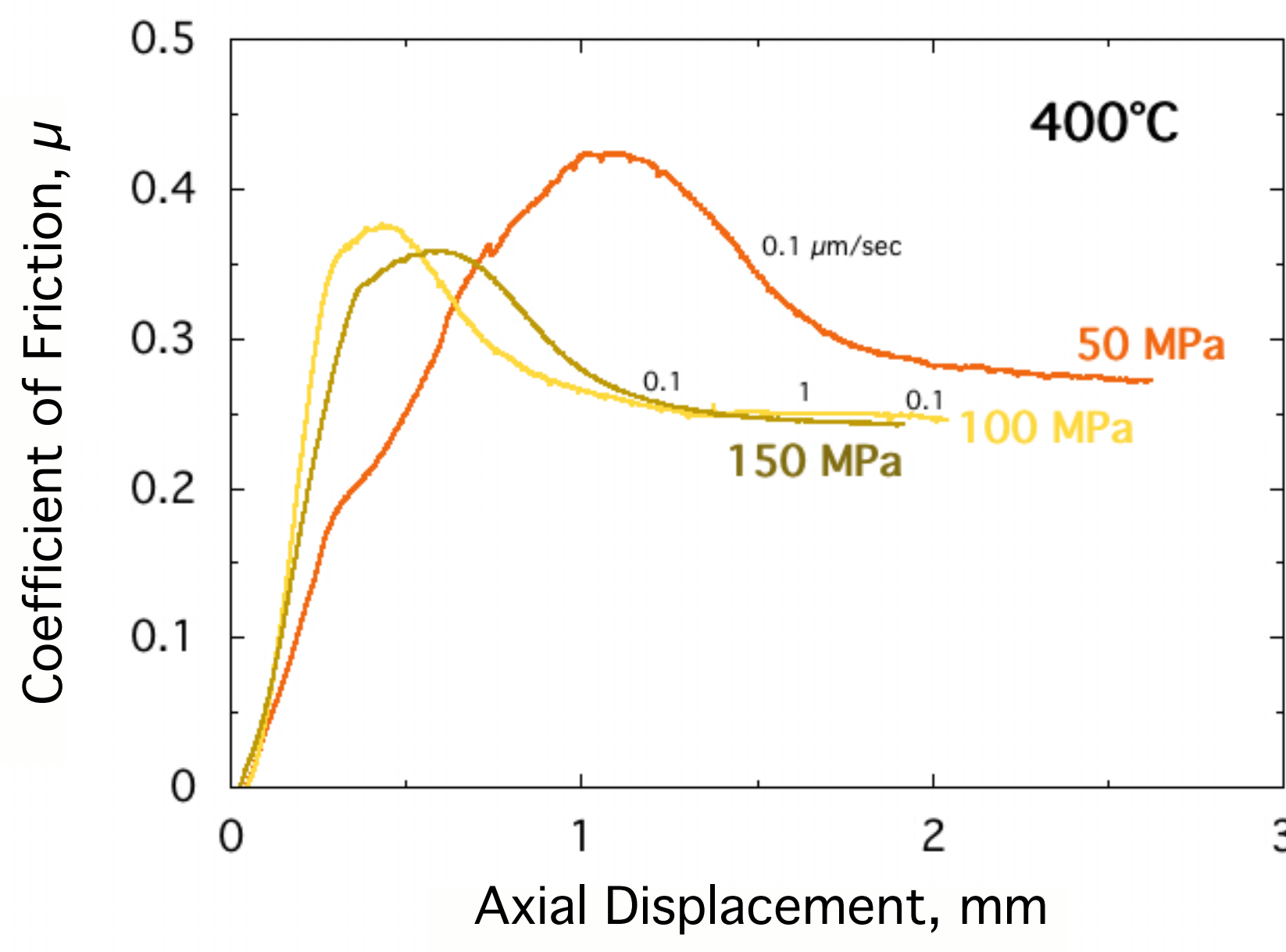
Water-saturated brucite shows decreases in μ with increasing T to 200°–300°C, then μ increases somewhat at higher T. Results at 150 MPa effective normal stress are nearly identical to those at 100 MPa shown above. Velocity steps suggest that heated brucite has zero to slightly positive velocity dependence, yet during initial loading, many of the samples had audible stress drops.



The coefficient of friction of dry brucite is correlated with the strength of its interlayer, or (001), bonds. Those bonds are weak enough that shear through the interlayer bonds is favored over other frictional processes. Heating dry brucite does not lower its frictional strength; if anything, μ_{dry} is somewhat higher at 300°C than at 25°C.

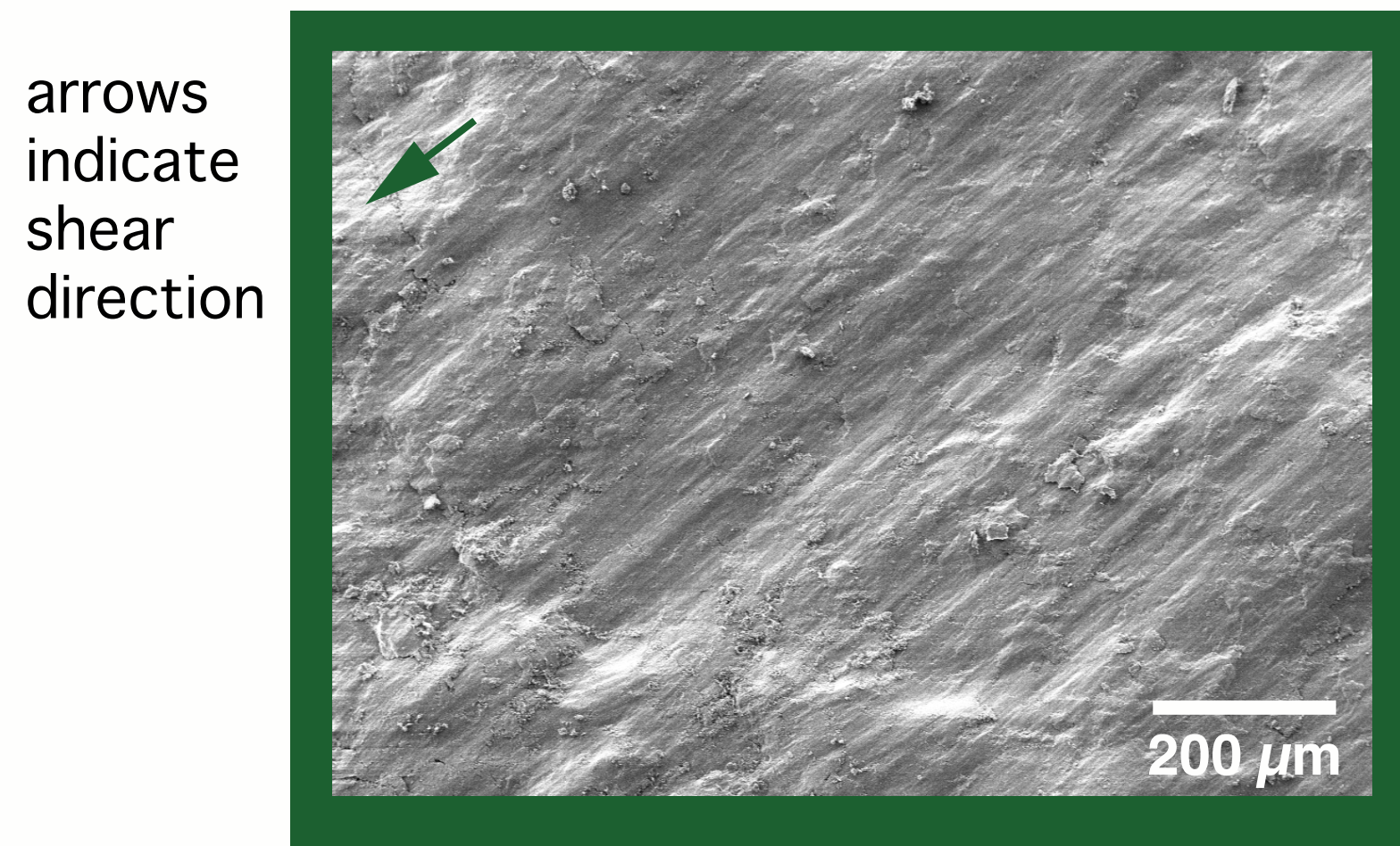


Stress dependence of μ varies between 100° and 400°C, at least for the limited displacement possible in our samples. At 100°C μ increases between 50 and 100 MPa, whereas μ decreases over the same range at 400°C. Differences in μ are minor between 100 and 150 MPa. Note that the early stick-slip events are suppressed at 400°C and at 150 MPa at lower temperatures.



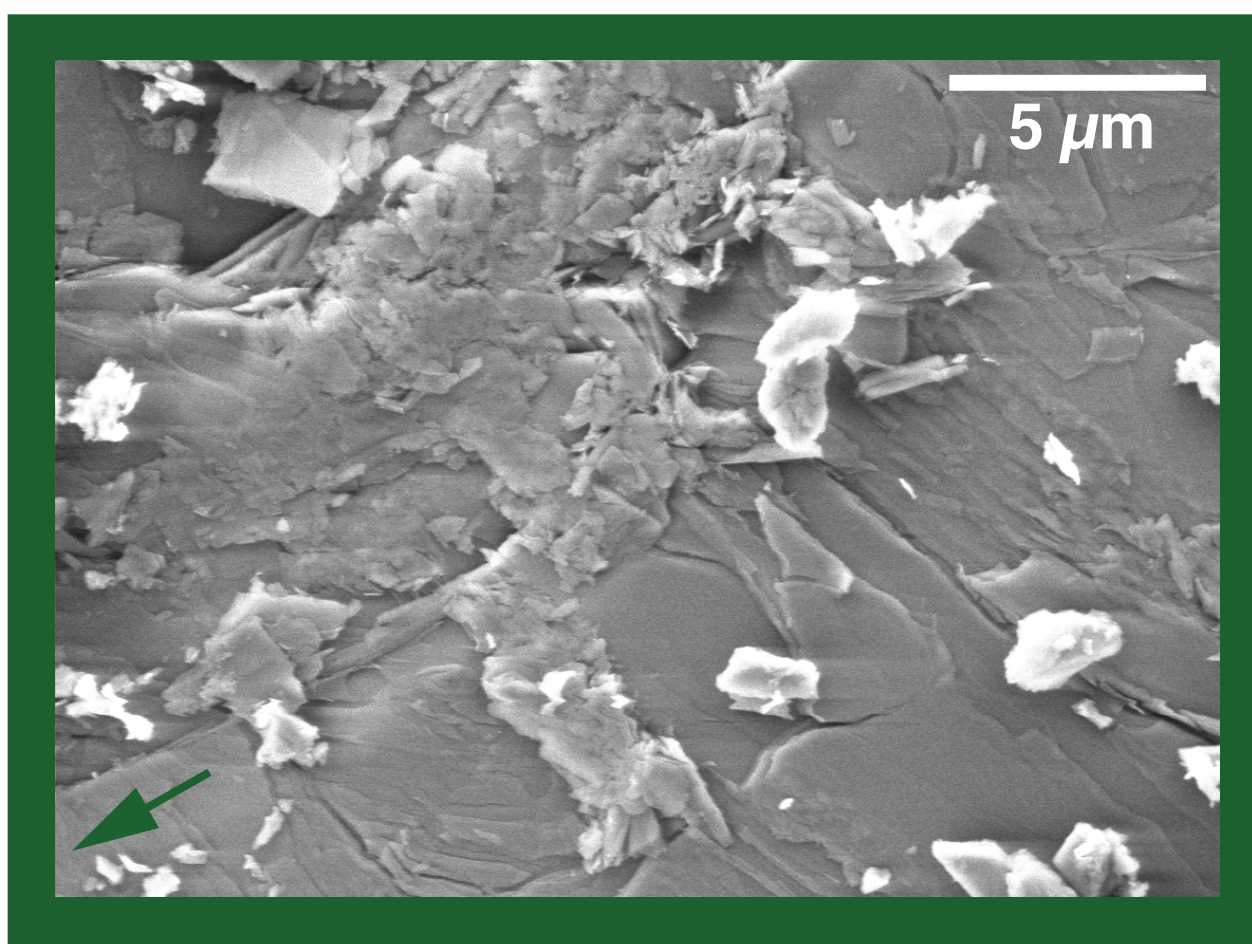
The frictional behavior of the serpentine minerals contrasts with that of brucite. Data for chrysotile are shown at left; results for lizardite and antigorite show the same trends. For serpentine minerals $\mu_{\text{dry}} \approx 0.7\text{--}0.8$. Water-saturated chrysotile is significantly weaker, because of the very large amounts of water held on the fiber surfaces. Increases in T and P cause μ of chrysotile to increase dramatically, and at the highest temperatures tested chrysotile is essentially as strong as the other common serpentine minerals. Water lubricates the shear of layer-structure minerals, and the dry strength of serpentine represents the upper limit to strength. Increases in frictional strength with increasing T and P would correspond to decreases in the thickness of water films held on the (001) surfaces. Similar high-T strength behavior has been shown for muscovite and illite, and it may be characteristic of many sheet silicates. The different behavior of brucite suggested that some other process might be involved.

Scanning Electron Microscopy

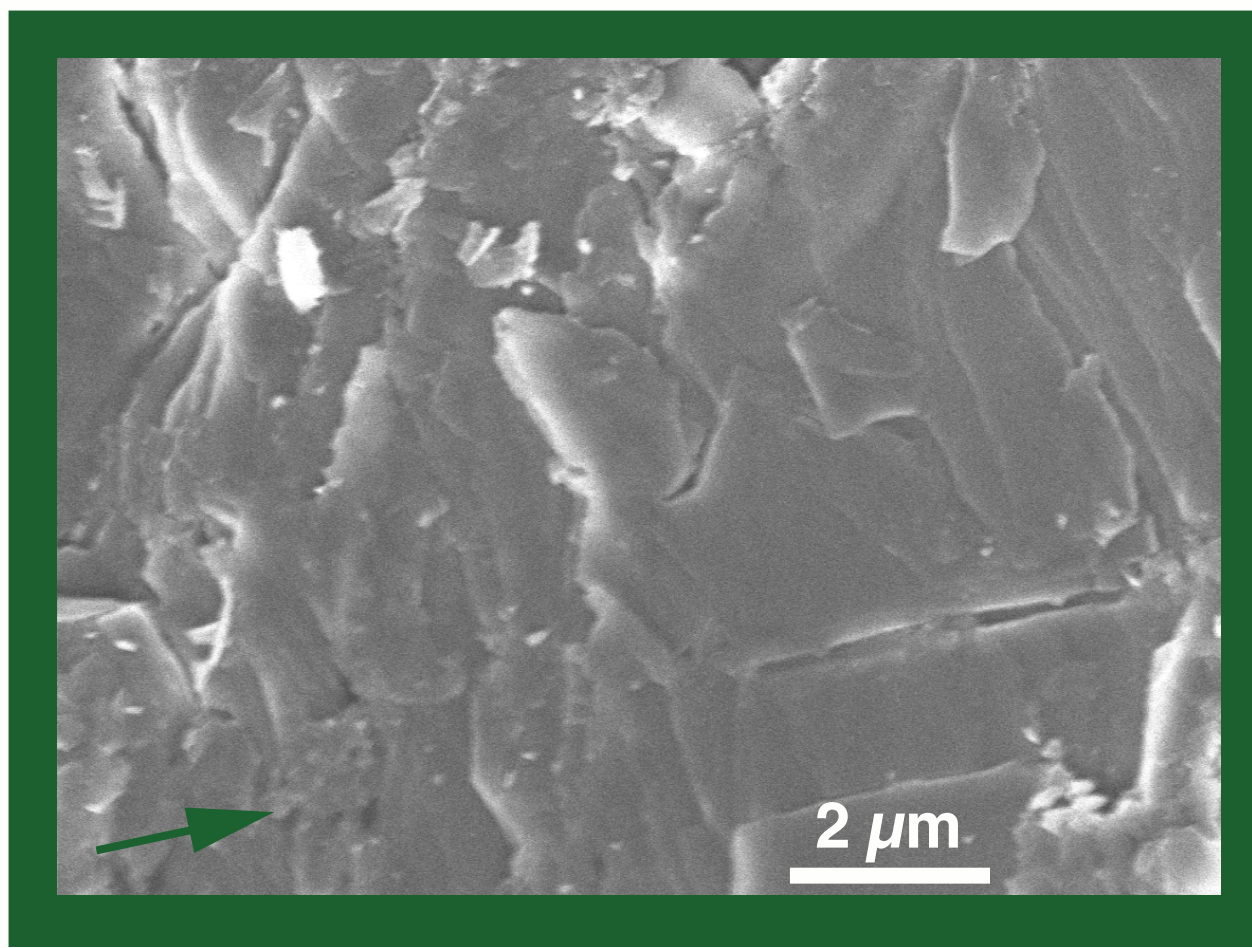


Shear of gouges composed of layer-structure minerals is localized to boundary and numerous Riedel shears. This is a boundary shear surface in the dry gouge.

Dry Brucite, 300°C



Grains in the shears rotate such that their (001) planes are parallel to the shear surface. This may explain the early peaks in strength during initial loading.

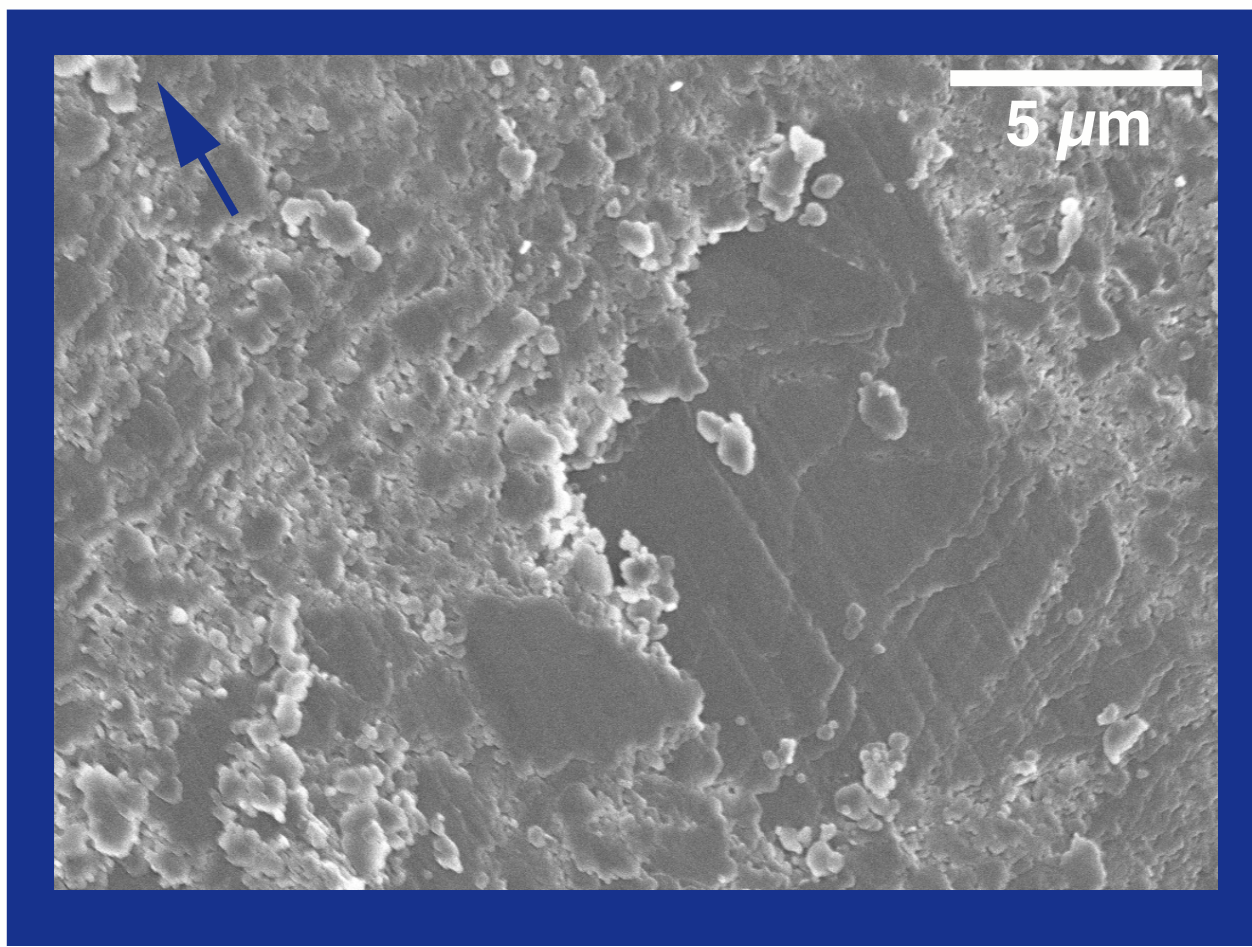


Shear of dry brucite involves grain-size reduction and spalling off of cleavage fragments. Much of the grain-size reduction may occur during the rotation of plates to form a shear plane, in this case an R-shear.

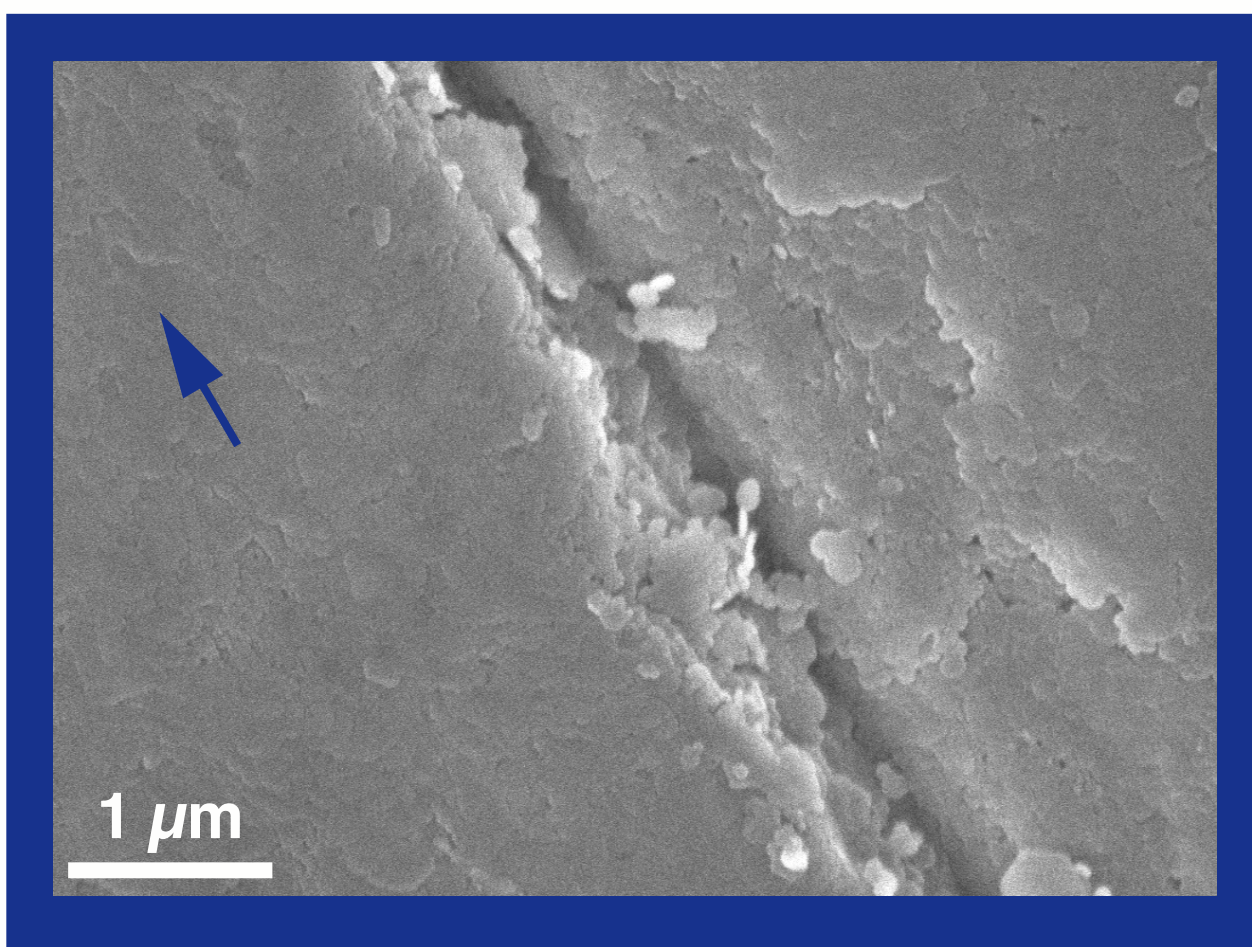
Water-Saturated Samples

All 3 experiments were run at 100 MPa effective normal stress. All SEM images (dry and wet) are of secondary electrons. All samples were quenched immediately upon jacket failure.

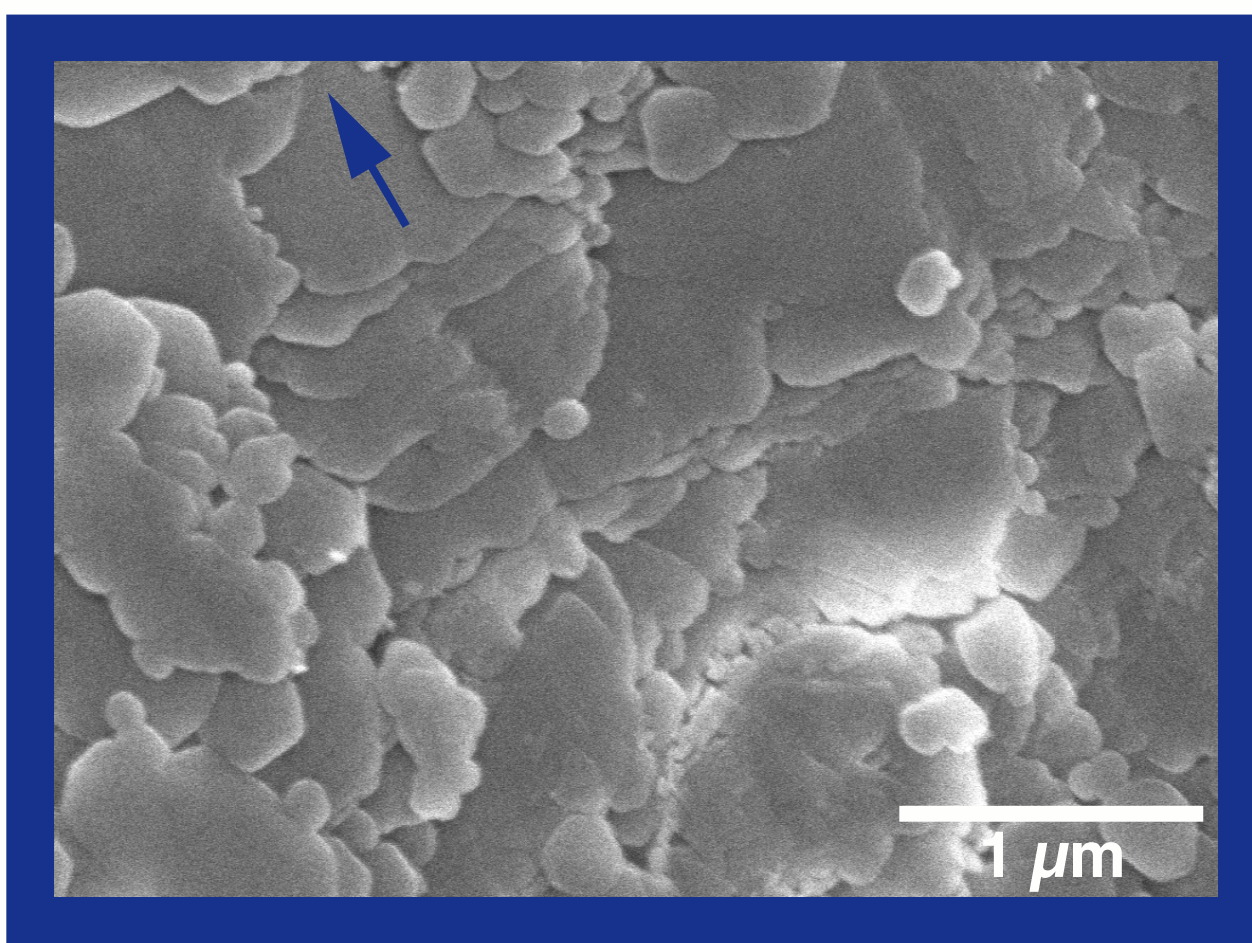
200°C



This R shear surface shows the stacking of plates along the shear. Some striated (001) surfaces are exposed. The edges of many plates are corroded and/or recrystallized.

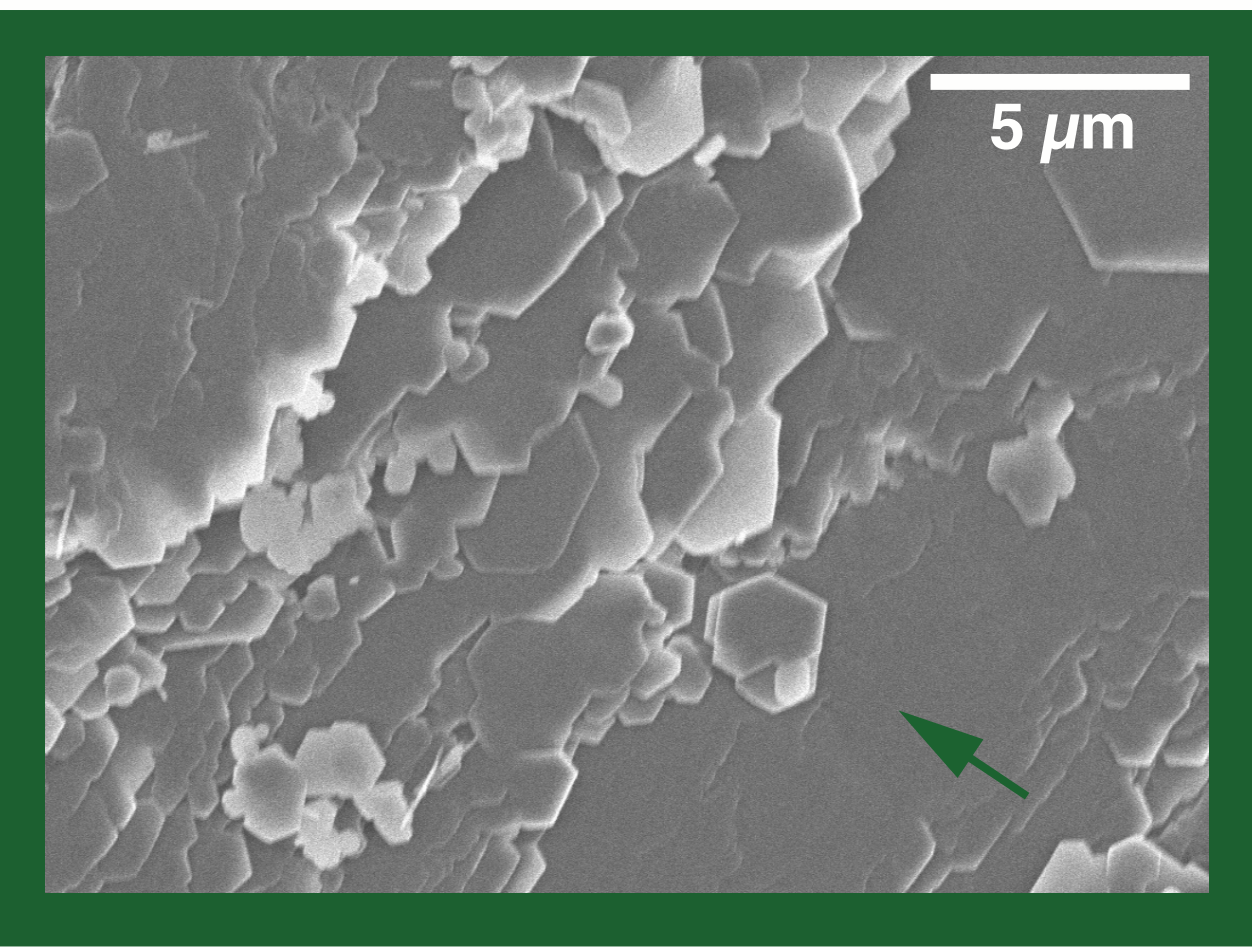


Score mark on boundary shear. Grains on the shear surface appear to have coalesced.

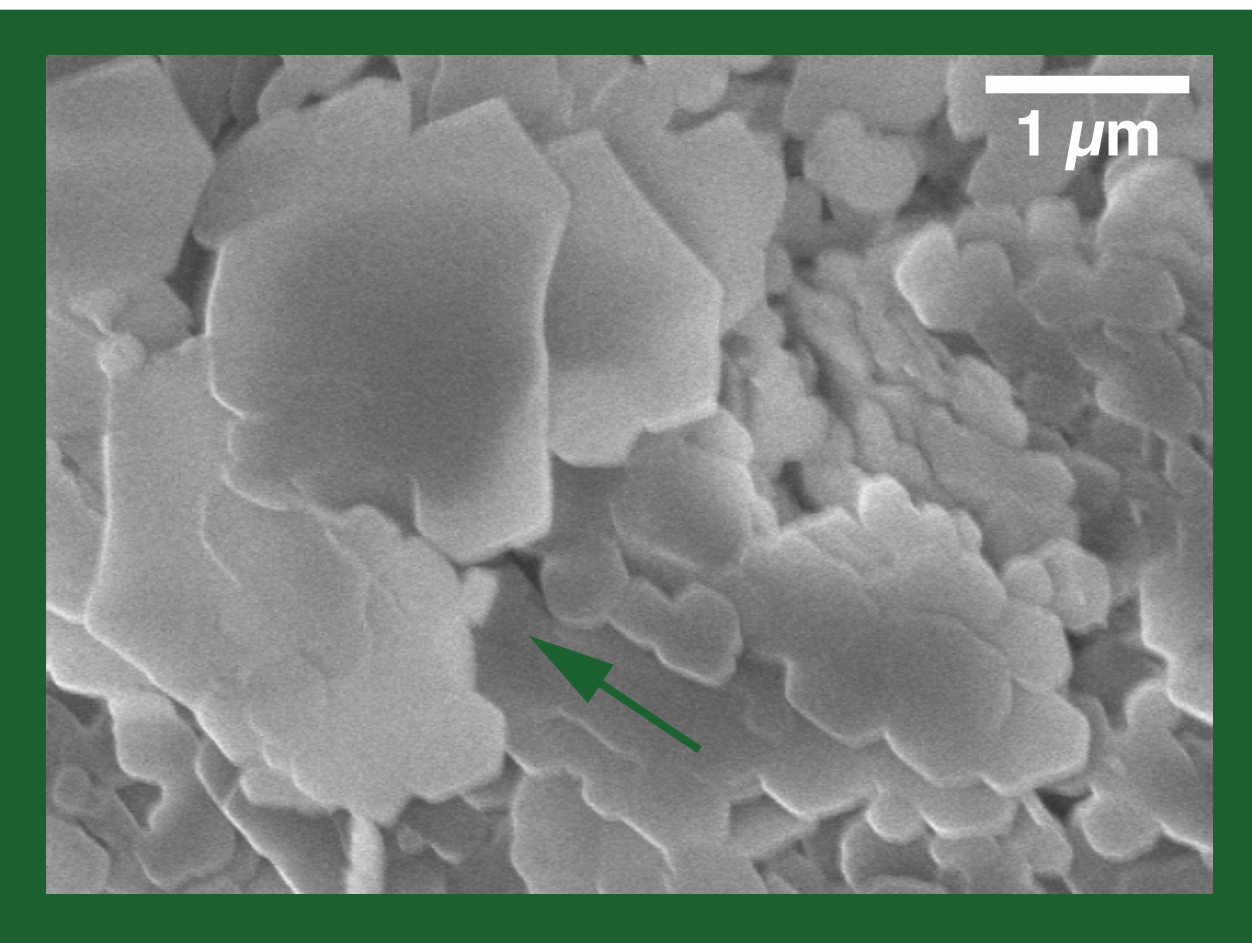


Closer view of R-shear. Minor striae may have arisen through fracturing but now look partly healed. Note euhedral crystal edges.

300°C

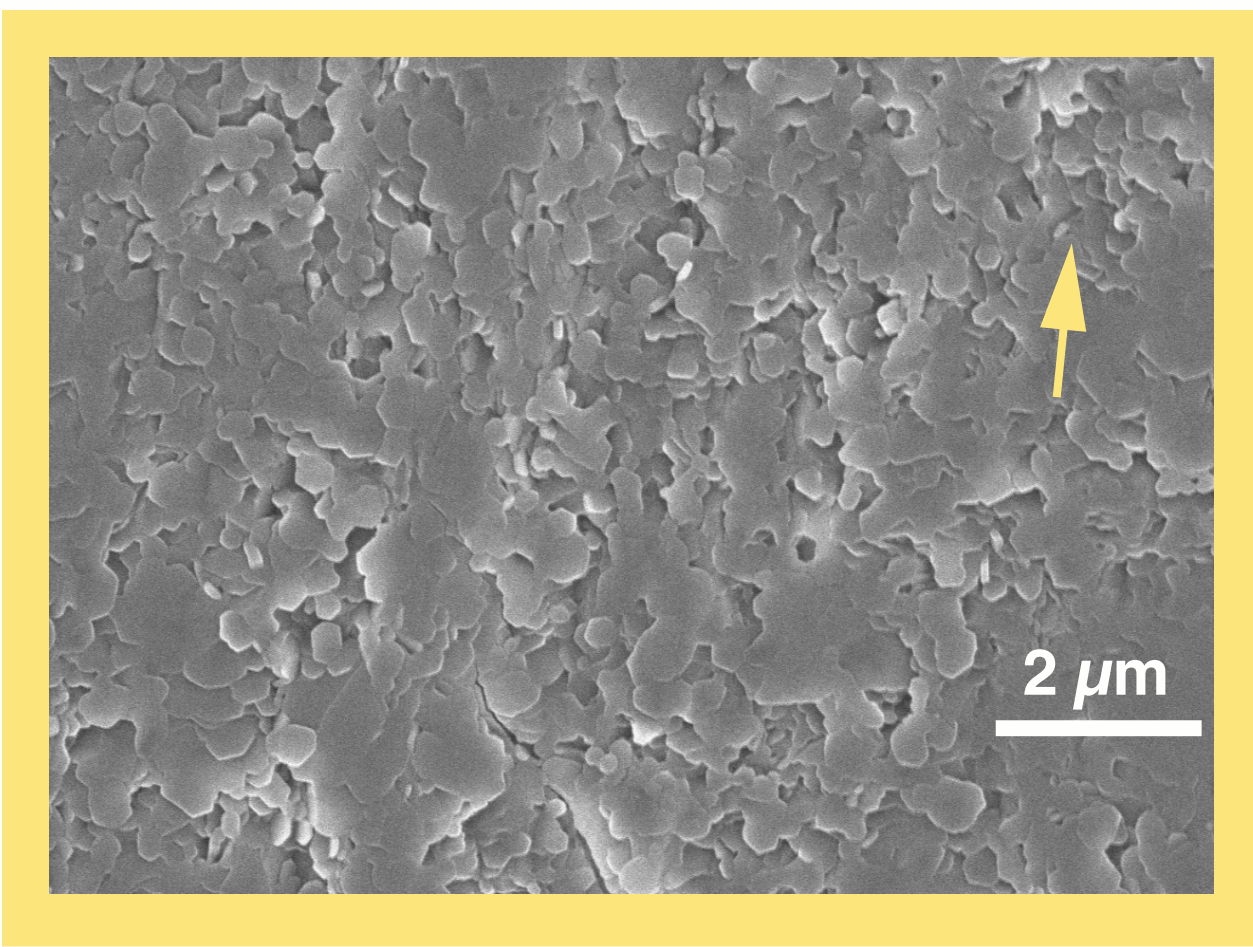


R shear near the bend to a boundary shear. The exposed edges of the crystals are on the “lee” side of the shear.

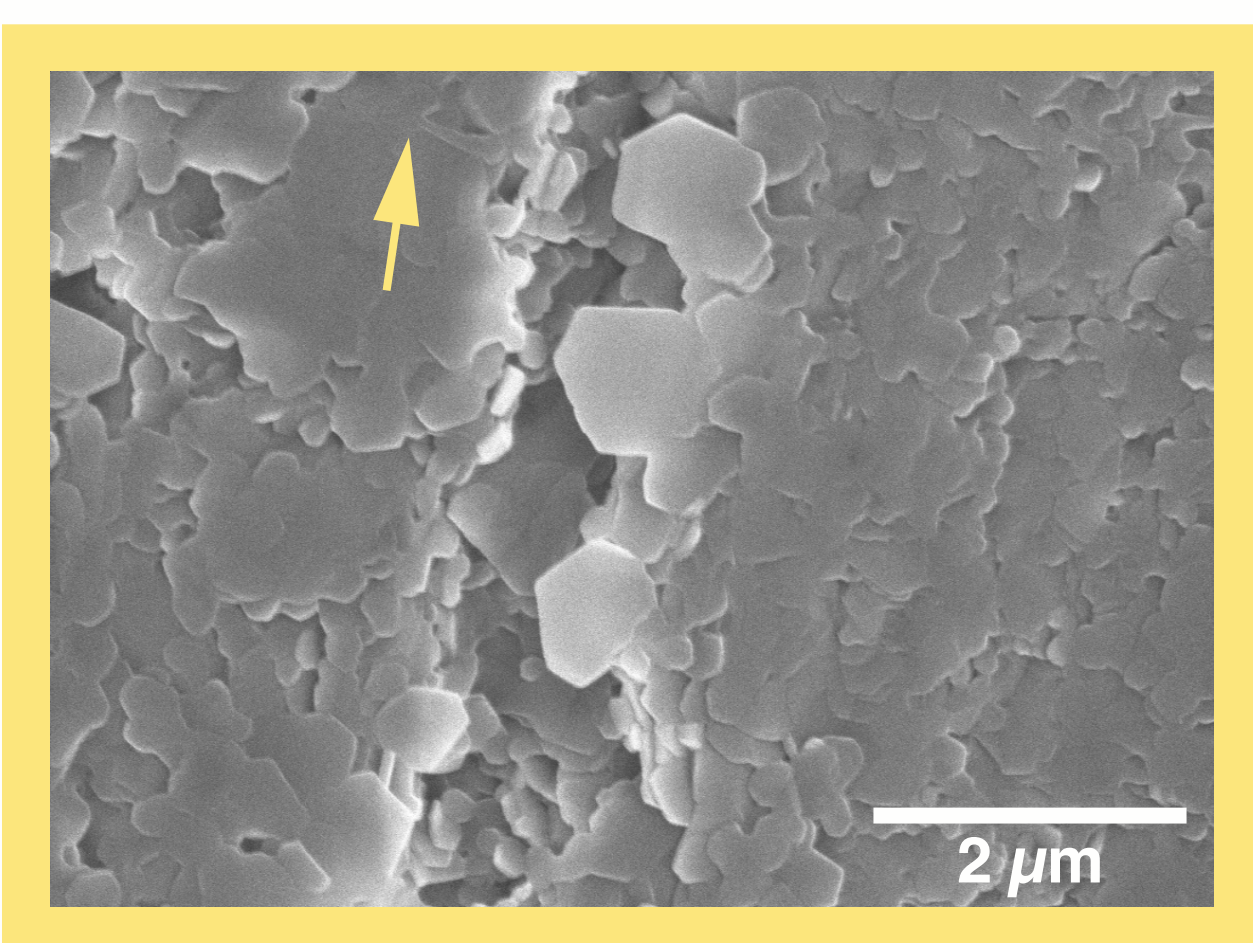


Clusters of coalesced hexagonal platelets on a boundary-shear surface are elongate in the direction of shear.

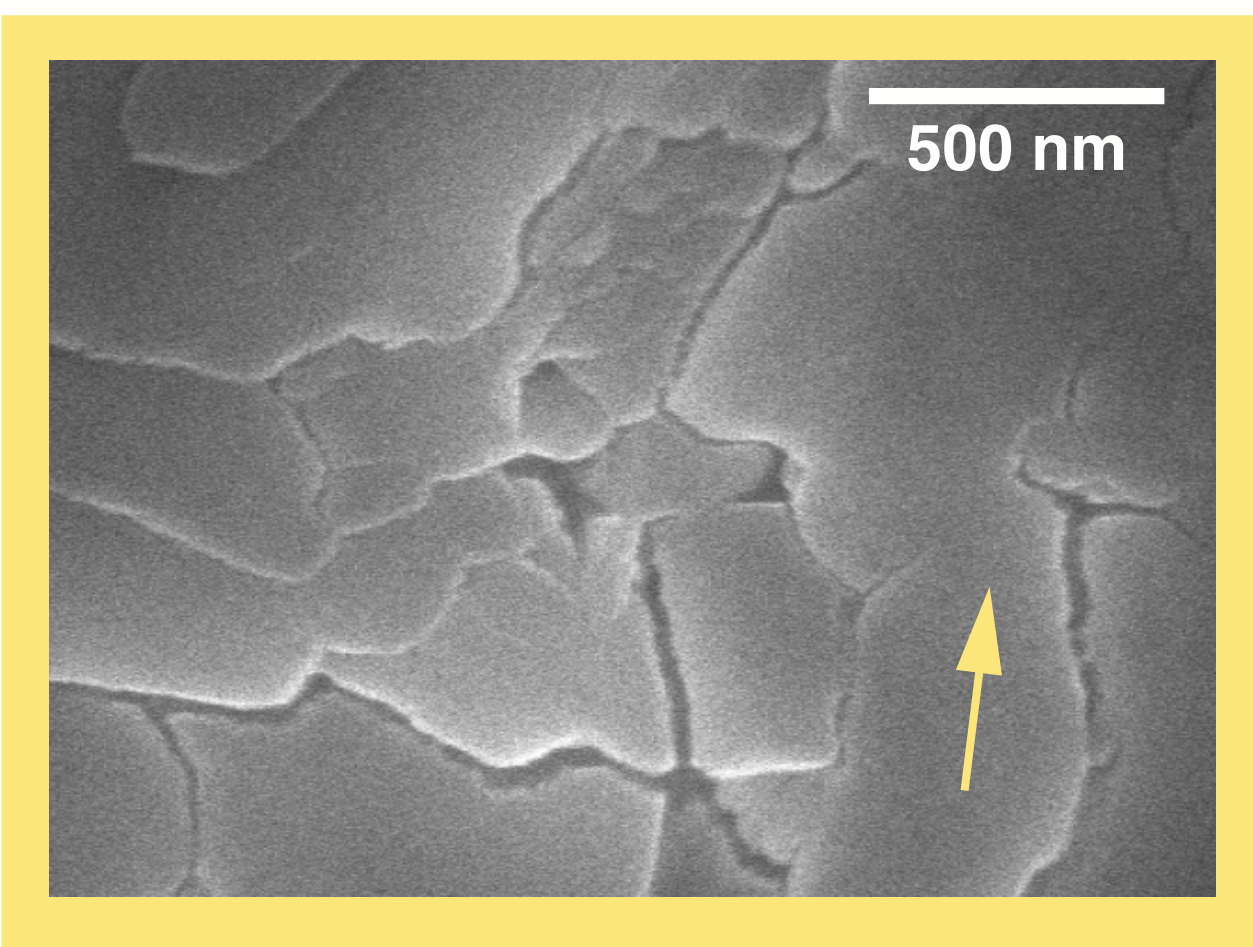
400°C



Welded grains of brucite on boundary shear surface. A shallow, $\approx 1\text{-}\mu\text{m}$ wide furrow is oriented parallel to the shearing direction.



A shallow trench on a boundary shear is being bridged by euhedral plates of brucite. An asperity on the opposite shear surface may have created the trench.

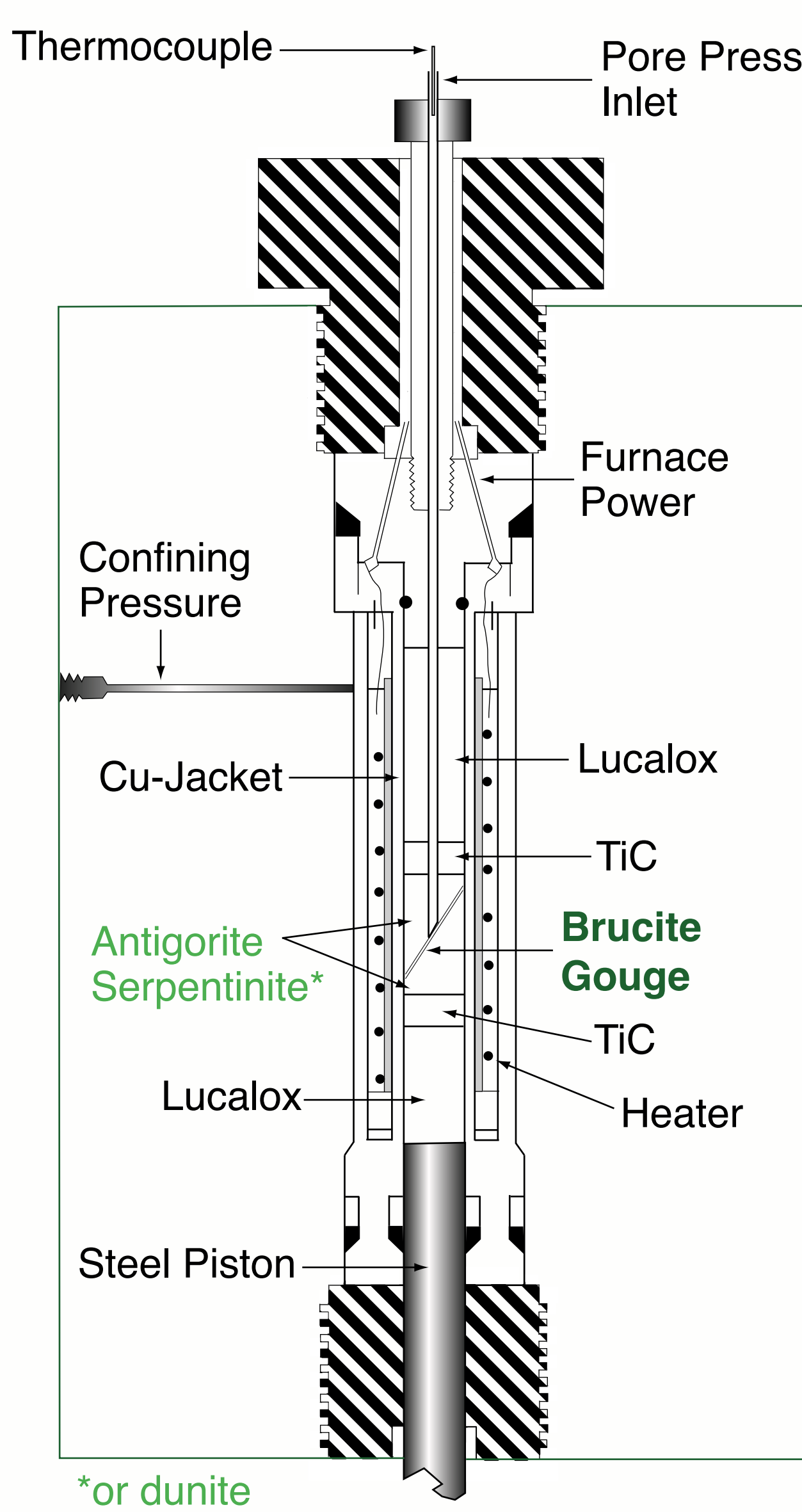


Close-up of a score mark (center) shows fractures, some of which have scalloped edges and possible minor overgrowths.

Summary

Contrasting textures of the dry and water-saturated samples suggest that a solution-transfer process may be the cause of the reduced strength of the brucite gouge at elevated temperatures. The decrease in μ with increasing effective normal stress at the higher temperatures tested may also be explained by such processes. The cause of the partial strength recovery at $T > 300^\circ\text{C}$ is not known. These results are preliminary, and further SEM examinations are planned.

Furnace Assembly



The sample consists of a 1-mm thick layer of the synthetic brucite gouge placed between the sawcut surfaces of a cylinder of dunite or serpentinite. The sample assembly is housed in an annealed Cu jacket and placed within a cylindrical furnace. The gouge layer is centered at the T maximum in the furnace. Deionized water was used as the pore fluid. Normal stress was held constant during the experiments; sliding velocities were changed at intervals during the experiments. Corrections for the strength of the Cu jackets were made to shear stress after the experiment; thus, the strength curves shown at right do not go through the origin.

Starting Material

The brucite starting material consists of clear, colorless, lamellar crystals of nearly end-member $\text{Mg}(\text{OH})_2$ from Lancaster Co., PA. The $<90\text{-}\mu\text{m}$ gouge prepared from it is shown in a secondary-electron SEM image at right.

