



STRENGTHS OF CLAY AND NON-CLAY FAULT GOUGES AT ELEVATED TEMPERATURES AND PRESSURES

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ABSTRACT

In order to characterize and compare the behavior of different fault gouge materials at depth, the strengths of four gouges were measured at elevated temperatures and confining pressures. The strengths of a serpentinite gouge and two clay gouges were nearly identical, despite differences both in their initial mineralogy and in their mineralogical responses to the imposed temperatures and pressures. These three gouges showed increases in strength with both temperature and confining pressure, accompanied by progressively greater degrees of induration of the samples. They also showed stick-slip behavior, that was most pronounced at the lowest confining pressures and highest temperatures examined. This contrasts with many previous studies in which stick-slip was more common at high pressures and low temperatures. The fourth gouge, derived from crushed Westerly granite, slid stably in all runs, and its strength increased with confining pressure but was unaffected by temperature. The mineralogy of the crushed granite gouge was little modified at high temperatures, and this gouge showed no significant induration during the experiments.

INTRODUCTION

The presence of gouge in a fault zone can have a significant effect on the strength and sliding behavior of the fault. Mineralogical and textural descriptions have been made of gouge materials from a number of surface localities (Wu et al., 1975; Anderson et al., 1980) and from shallow depths in drillholes (Liechti and Zoback, 1979), tunnels and mines (Wu, 1978). However, little is known about the characteristics of gouges at the greater depths of about 5-15 km, where many earthquakes are generated on faults such as the San Andreas. As an aid to understanding the behavior of fault gouge materials at depth, this paper reports the effects that temperature and pressure have on the frictional strength and mineralogy of a group of natural and simulated gouges.

GOUGE DESCRIPTIONS

Four gouges of different types were selected for study (Table 1). Clay-bearing gouges were of interest, because clay minerals are common gouge constituents at near-surface conditions (Liechti and Zoback, 1979) and because they may also be stable to considerable depths in fault zones (Wu, 1978). Accordingly, two clay-rich gouges were chosen. One of these, labeled Dry Lake Valley in Table 1, comes from the 212-235 m depth interval of a drillhole into the San Andreas fault zone near Hollister, California (Liechti and Zoback, 1979). The gouge in this depth interval contains approximately 80% clay minerals, of which about half are montmorillonite and mixed-layer clays; the remaining 20% consists principally of quartz and plagioclase. The second clay-rich gouge

was prepared by disaggregating an illitic shale from Fithian, Illinois, which contains moderate amounts of fine-grained quartz, chlorite and kaolinite in addition to illite (Table 1).

TABLE 1
Gouges Used in This Study and Their
Approximate Modal Compositions

Gouge	Composition
Dry Lake Valley, 212-235 m depth in drillhole near Hollister, Calif.	About 80% clays, 20% quartz and plagioclase (Relative proportions of clays: montmorillonite and mixed-layer clays 50%, kaolinite 30%, chlorite 10%, illite 10%) (Analyses in Liechti and Zoback, 1979.)
Serpentinite, San Andreas fault near San Carlos, Calif.	All chrysotile
Illite, from illitic Shale, Fithian, Ill.	illite 70%, quartz 20%, chlorite + kaolinite 10%
Westerly granite gouge	plagioclase (35%), potash feldspar (25%), quartz (25%), biotite + muscovite + chlorite (10%), epidote + calcite and fluorite + opaques (5%).

The third gouge, a serpentinite collected from a trench in the San Andreas fault near San Carlos, California, provided a non-clayey, sheet silicate gouge for comparison with the first two samples. X-ray diffraction analysis of this gouge showed only the presence of a serpentine mineral, identified as chrysotile using the method of Whittaker and Zussman (1956). The fourth gouge, prepared from crushed Westerly Granite, provided still greater contrast since it consisted principally of quartz and feldspars, with a maximum of 10% sheet silicate minerals (Table 1). This prepared granite gouge would have properties close to those of natural granitic and gneissic rock flours from the San Andreas in southern California (Anderson et al., 1980). With the exception of the Dry Lake Valley gouge, the gouge materials were passed through a 170 mesh (90 μ m opening) sieve to eliminate any large grains.

PROCEDURE

The experimental assembly (Fig. 1) was similar to other high-temperature designs for triaxial strength tests (e.g., Stesky et al., 1974; Lockner et al., 1982). The sample consisted of a layer of gouge 0.65 mm in thickness sandwiched between 30° polished sawcut surfaces in a granite cylinder 19.0 mm in diameter and 41.3 mm long. The gouge-filled cylinder was placed within an annealed copper jacket between titanium carbide end plugs and Lucalox insulators. The space between the copper-jacketed sample assembly and the surrounding resistance heater was loosely packed with boron nitride, which is a poor electrical and a good thermal conductor.

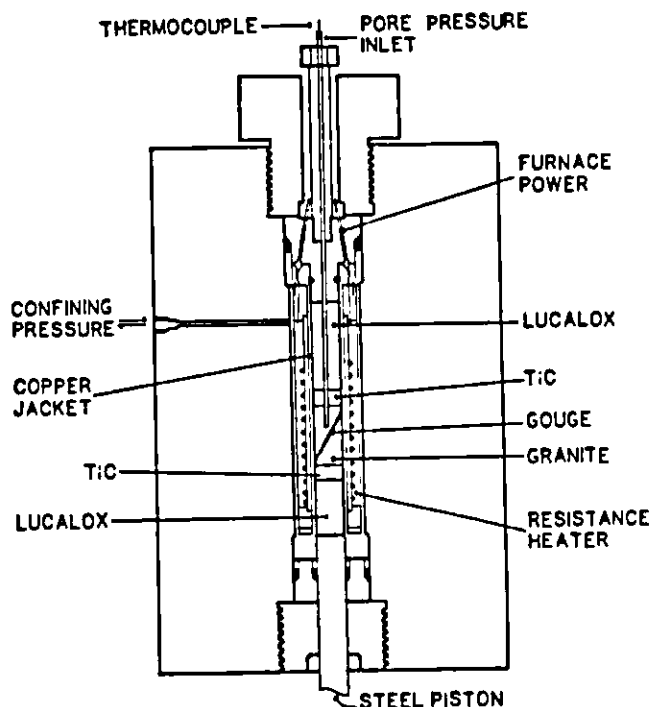


Figure 1. Experimental assembly.

Experiments were run at confining pressures of 1 and 2.5 kbar and temperatures of 200°, 400°, and 600°C. All experiments were conducted at a strain rate of 10^{-4} /sec, that is, an axial shortening rate of 4.1×10^{-3} mm/sec. In addition, a pore pressure of 30 bars was maintained in all runs, to ensure that the samples were fluid-saturated throughout the experiments and also to prevent the build-up of pore pressure through mineral dehydration reactions. Pore fluids were introduced to the sample along a central inlet that was extended almost to the gouge layer by means of a hole drilled partway through the upper granite cylinder.

Both sawcut granite pieces were presaturated with deionized water, to reduce the time required to equilibrate the pore fluid in the sample. Temperatures were monitored by a thermocouple inserted along the pore pressure inlet. Pressures and strains were computer-controlled and -recorded; force and displacement measurements were made outside the pressure vessel using a load cell and displacement transducer.

Following loading of the sample into the pressure vessel, confining and pore pressures were applied, and after that the temperature was raised to the desired value. All samples were then held at temperature and pressure for 16 hours before the differential stress was applied.

RESULTS

Friction Strengths and Sliding Behavior

Figures 2-4 plot effective differential stresses against axial compression for the four gouges at each temperature. All the experimental results were verified in repeated runs but, for clarity, a single representative curve for each gouge was selected and plotted in the figures.

At a given set of temperature and confining pressure conditions, the three sheet silicate gouges supported nearly identical stresses within the experimental uncertainties. The only noticeable difference was at 600°C and 2.5 kbar, where the serpentinite gouge was slightly weaker than the others. These three gouges showed strength increases with both temperature and confining pressure as well as strain hardening with continued sliding. For the most part, the sheet silicate gouges slid stably in the experiments at 200°C. However, as temperature was increased, these gouges showed a progressively greater tendency to stick-slip behavior, with both the frequency of occurrence and the magnitude of the stress drops being larger at the lower confining pressures.

The crushed granite gouge showed strain hardening similar to the three sheet silicate gouges, but its behavior in other respects differed from the rest. The granite gouge slid stably at all conditions, and although its strength increased with increasing confining pressure, no temperature dependence was observed. As a result, the positions of the granite gouge curves are identical in each of Figures 2-4. At 200°C, the granite gouge was considerably stronger than the others. However, this difference in strength diminished as temperature was increased, until at 600°C the strengths of the clayey gouges had completely overtaken that of the granite gouge.

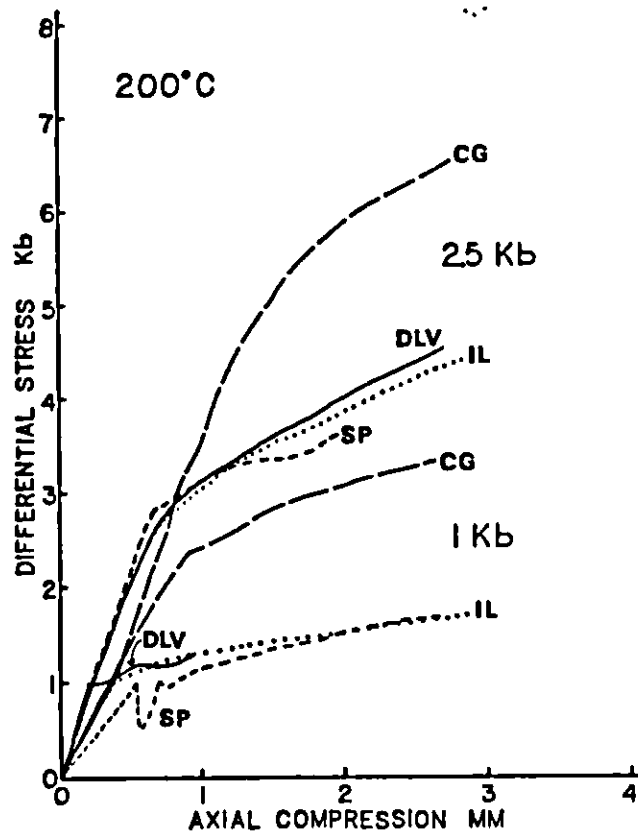


Figure 2. Plot of differential stress against axial compression for sliding experiments at 200°C. Symbols: CG - crushed granite gouge; DLV - Dry Lake Valley gouge; IL - illite gouge; SP - serpentinite gouge.

Mineralogical Changes

The granite gouge was little affected either mineralogically or texturally by the elevated temperatures and pressures of the experiments. X-ray reflectances of the minor amount of chlorite in Westerly gradually disappeared with temperature increase, but those of all other minerals were unchanged relative to each other. Physically, the granite gouges retained their granular character, with even the 600°C run products disaggregating fairly readily.

In contrast, the clay and serpentinite gouges showed progressively greater degrees of lithification with temperature increase. At 200°C, run products of these three gouges were compacted but not hardened; but at 600°C they had the appearance and hardness of slates, the Dry Lake Valley gouge being especially well indurated. The low-temperature clay and serpentinite gouges separated readily from the surrounding

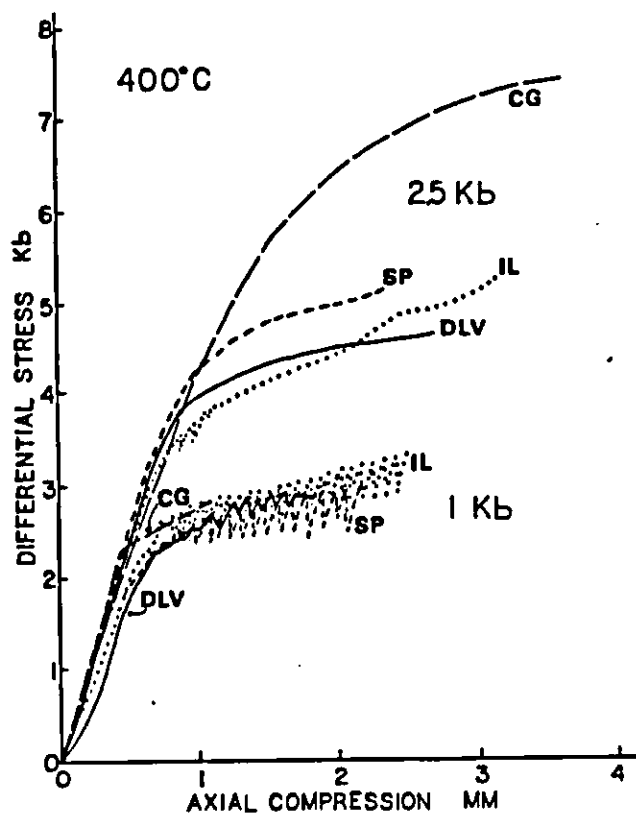


Figure 3. Plot of differential stress against axial compression for 400°C experiments. Symbols as in Figure 2.

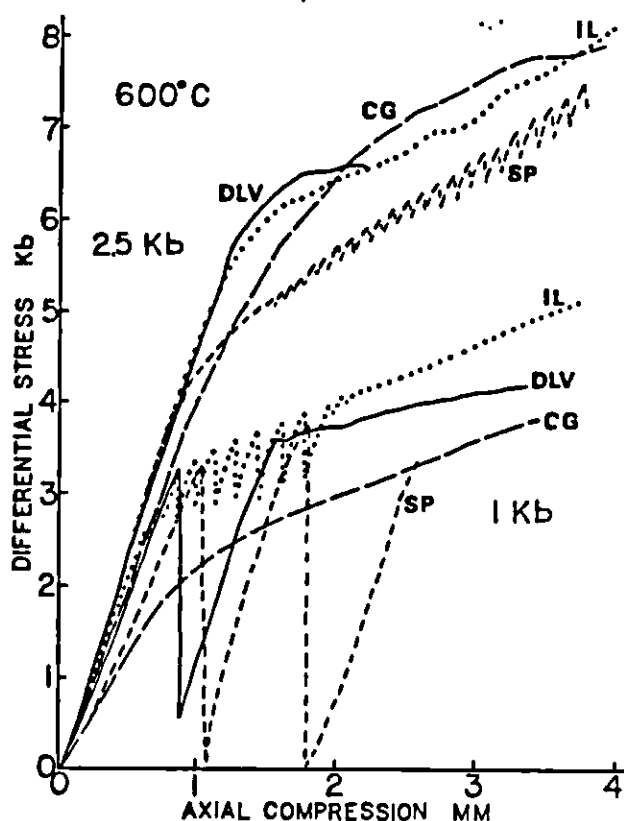


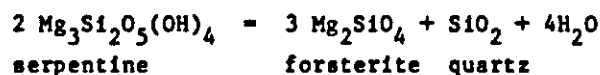
Figure 4. Results of 600°C friction experiments. Symbols as in Figure 2.

granite cylinder, whereas the high-temperature run products were welded to the sawcut surfaces. X-ray diffraction analysis of the run products of these three gouges showed a number of mineral changes with increasing temperature-pressure conditions that are illustrated in Figures 5-7 and briefly described below.

Serpentinite

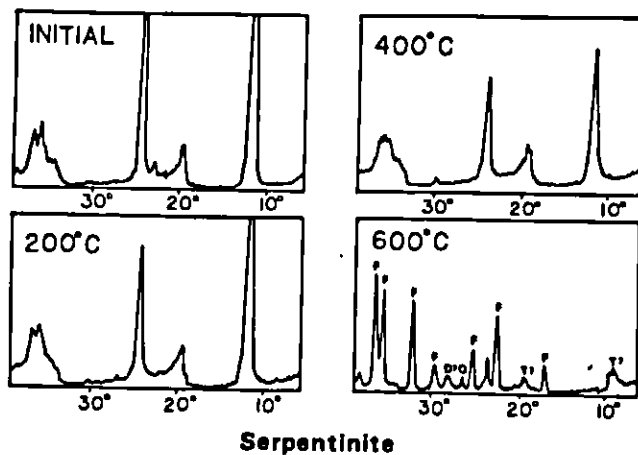
X-ray diffraction patterns of the starting material and run products at different temperatures are shown for the serpentinite gouge in Figure 5. No pressure-related changes in X-ray intensity in runs at a given temperature were observed; and the high-temperature patterns in the figure are representative of both pressures tested. Except for a slight decrease in the height of the 25° 2θ peak, the 200°C traces were unchanged from the starting material. At 400°C, all serpentinite peak intensities were noticeably reduced, possibly caused by the loss of reflections from poorly crystalline

material. At 600°C the serpentinite mineral underwent the following dehydration reaction:



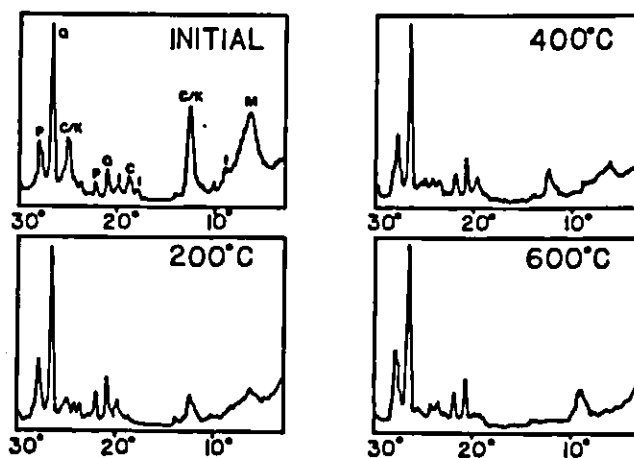
Well developed forsteritic olivine dominated the 600°C traces in Figure 5. A few additional peaks, possibly representative of talc and diopside, also appeared.

The observed dehydration reaction is a common one for serpentinite and occurs in air at about 600°C (Deer et al., 1966). However, in their high-temperature strength experiments on serpentinite, Raleigh and Paterson (1965) obtained somewhat different reaction products. In one case, part of the serpentinite apparently altered to forsterite, and then the remaining serpentinite reacted with the forsterite to produce talc. In other, brucite-bearing samples, serpentinite and brucite reacted to give forsterite alone.



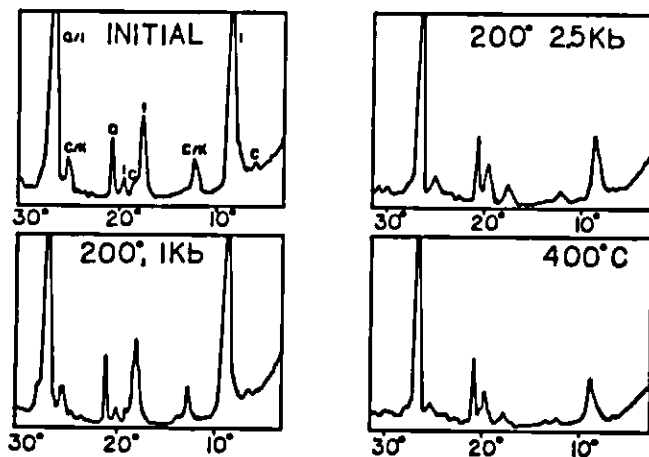
Serpentine

Figure 5. Summary of changes in X-ray diffraction patterns with increasing temperature for the serpentine gouge. Symbols: F - forsteritic olivine; Q - quartz; T - talc; D - diopside. Diffraction patterns are the same for the two confining pressures at a given temperature.



Dry Lake Valley

Figure 7. Effect of temperature on X-ray diffraction patterns of Dry Lake Valley gouge. Symbols: M - montmorillonite; Q - quartz; C - chlorite; k - kaolinite; I - illite; P - plagioclase.



Illite

Figure 6. Changes in X-ray diffraction traces with temperature and pressure increase for the illite gouge. Symbols: I - illite; C - chlorite; k - kaolinite; Q - quartz.

Illite

The initial trace for illite in Figure 6 shows the predominating illite and quartz peaks and the lesser chlorite and kaolinite peaks. As temperature increased, most of the clay peaks decreased in intensity relative to quartz; but the pattern of change was somewhat different from the other gouges. In this case, the largest decrease in most clay mineral peak intensities occurred between the 1 and 2.5 kbar runs at 200°C. However, one illite peak, that at 4.5 Å (2θ = 19.5°), nearly doubled its height in that interval. As with serpentine, the general decreases may in part be related to the loss of poorly crystalline materials. The increase in the one illite peak may reflect some structural modifications accompanying heating. The illite peaks showed no further changes at temperatures above 200°C, but the chlorite and kaolinite peak intensities continued to decrease. Unlike the serpentine gouge, no new minerals were formed in any of these runs. Quartz peak intensities were unaffected by the temperature changes.

Dry Lake Valley

X-ray intensities of clay minerals in the Dry Lake Valley gouge showed a variety of changes with increasing temperature (Fig. 7) but no measurable pressure-related differ-

ences at any given temperature. At 200°C the intensities of all the clay mineral peaks decreased, with the single exception of the 4.5 Å illite peak, which increased as it did in the illite gouge. The chlorite/kaolinite and montmorillonite peak intensities decreased again at 400°C and disappeared completely at 600°C. The 10 Å peak, located at around $2\theta \approx 9^\circ$, showed no changes between 200° and 400°C; however, at 600°C its height more than doubled. The decreases in montmorillonite intensity are caused by the progressive removal of interlayer water. At lower temperatures this process apparently was incomplete, causing no noticeable augmentation of the peak at 10 Å, which is the basal spacing of the collapsed montmorillonite structure. More thorough dehydration at 600°C produced the observed increase of the 10 Å peak.

DISCUSSION

Gouge Strengths

Comparison to Other Studies

Few previous studies at elevated temperatures have been made of the frictional strength of gouge materials. In one of these, Logan et al. (1981) measured increases with temperature to 300°C of the strength of a chlorite and a Dry Lake Valley gouge, which is consistent with the strength increases reported here. In addition, they found no significant temperature-related changes in the strength of a quartz gouge in the range 25° to 300°C, with the result that the clay gouge strengths increased relative to the quartz gouge at 300°C. A large number of room-temperature friction studies on gouges are available for comparison. Summers and Byerlee (1977a, b) delineated three groups of gouges on the basis of their strengths. A crushed granite gouge had the highest measured strengths and expanding clay gouges (montmorillonite, vermiculite) the lowest. Gouges consisting of non-expanding clay minerals such as illite, chlorite, and kaolinite had intermediate strengths. The pressure-related changes in strength of the crushed granite gouge (Figs. 2-4) are consistent with the results of Summers and Byerlee (1977a, b), and the 200°C illite and serpentinite gouge strengths also correspond reasonably well to the strengths of similar gouges at room temperature. The 400°C and 600°C strengths of these two sheet silicate gouges, however, are greater than those of their room-temperature equivalents. Even at 200°C, the montmorillonite-rich Dry Lake Valley gouge is substantially stronger than a pure montmorillonite gouge at room tempera-

ture. Morrow et al. (1982) also found that montmorillonite-rich gouges are considerably stronger than ones consisting solely of montmorillonite. The 200°C Dry Lake Valley gouge strengths are similar to and the 400° and 600°C strengths higher than those of the room-temperature, dry, montmorillonite-rich gouges examined by Morrow et al. (1982).

Stesky (1978) gathered together the results of sliding experiments on jointed, faulted, and sawcut samples for a number of different rock types, including granites and slates. The measured strengths are essentially independent of temperature to 400°C, and the results delimit a relatively narrow field, indicated by dashed lines in Figure 8. For comparison with Stesky's (1978) compilation, the shear and normal stresses of both initial and maximum friction were calculated at each confining pressure for the gouges of this study. To simplify the diagrams, gouges with similar strengths were grouped together. All the granite gouge experiments were put into one group, because this gouge's strength was unaffected by temperature. The 200°C clay and serpentinite gouges formed a second group, and the same gouges at 400°C formed a third. The 600°C serpentinite gouges were separated from the 600°C clay gouges, because of differences in strength at that temperature.

Initial friction (Fig. 8a) was measured at the position on a given stress-displacement curve where it departed from a straight line, corresponding to a change from elastic to non-elastic deformation during sliding (Byerlee, 1978). In several cases, it was difficult to determine unambiguously the position of this elastic yield point, and a range of initial friction values was obtained for some groups, as indicated by the elongate circled areas in Figure 8a. With the exception of the 600°C serpentinite group, the maximum values of initial friction at the two confining pressures for each group were connected by a curve of the form $T = A\sigma_N + B$ in Figure 8a. The appropriate stress envelope for the 600°C serpentinite gouges at 1 and 2.5 kbar confining pressure, not drawn in Figure 8a to reduce clutter, would be $T = 0.18\sigma_N + 1.03$.

In nearly all the experiments of this study, stresses were still rising when the runs terminated, usually because of jacket failure. Therefore, true maximum friction strengths were not reached. As a result, for each group of gouges in Figure 8b, only the highest measured strength at each confining pressure, corresponding to the run with the greatest amount of axial compression before failure (about 4 mm), was plotted and the points were connected as in Figure 8a. The 600°C serpentinite maximum stress envelope, not drawn in Figure 8b, is nearly coincident

with the granite curve ($\tau = 0.73\sigma_N + 0.22$). It should be emphasized that these strengths are the maximum observed strengths of the gouges and may be somewhat lower than the true maximum values.

Looking first at initial friction (Fig. 8a), the 200°C clay and serpentinite strengths are much lower than the rock friction strengths compiled by Stesky (1978). However, the 600°C clay gouge strengths fall well within the rock friction field and those of the granite gouge are near its lower strength limits. The observed strain hardening of the gouges with continued sliding (Fig. 8b) increases all the gouge strengths relative to the rock friction field, so that even the 200°C clay and serpentinite gouges are only slightly weaker than the sawcut or faulted rock samples.

The strength of serpentinite apparently shows a greater temperature dependence than many other rock types. Raleigh and Paterson (1965) found that both the ultimate strength of serpentinite and its subsequent sliding

strength following failure decreased continuously as temperature was increased, with the decreases especially rapid above 500°C. Thus, for the serpentinite gouge, both the increase in strength with temperature to 400°C and the lack of decrease between 400° and 600°C are different from Raleigh and Paterson's (1965) results.

Controls of Gouge Strength

It is significant that the strengths of the three sheet silicate gouges were the same at a given temperature despite the differences both in their initial mineral assemblages and in their mineralogical responses to high temperatures and pressures. The presence of expanding clays in one gouge did not affect that gouge's strength relative to the others. This similarity of strengths contrasts with some room-temperature studies on mixed-clay and serpentinite gouges (Chu et al., 1981; Morrow et al., 1982), in which the samples tested had different strengths.

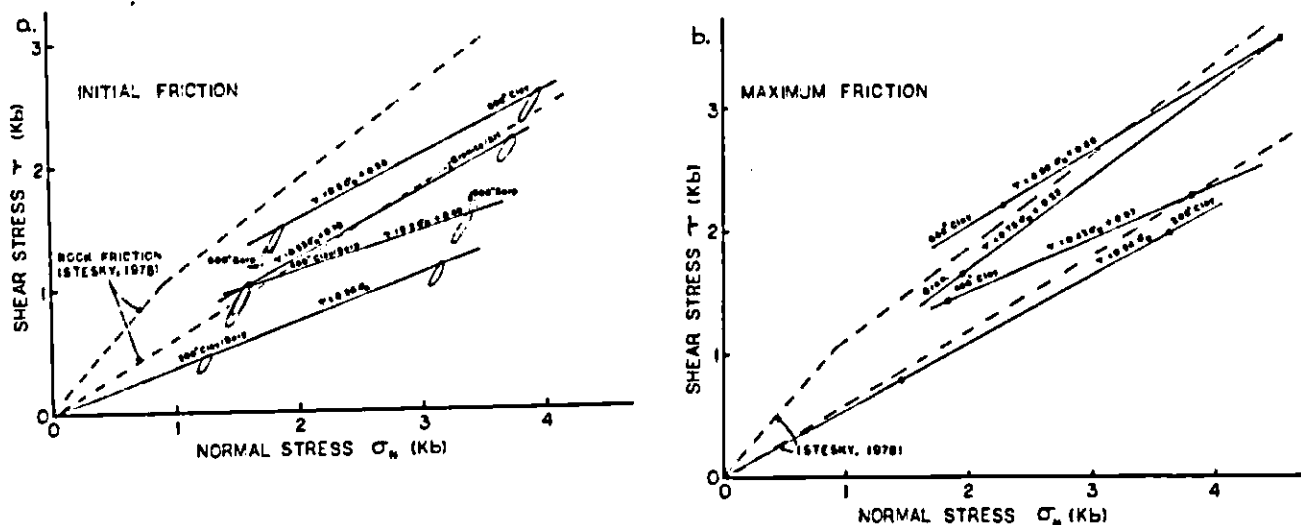


Figure 8. a). Ranges of shear and normal stresses of initial friction for different groups of gouge materials. The maximum stresses for the two confining pressures of four groups are connected by lines whose equations are as shown. b). Maximum observed friction of the crushed granite gouge, of the clay and serpentinite gouges at 200° and 400°C, and of the clay gouges at 600°C. The 600°C serpentinite strengths are essentially identical to the granite strengths. Because stresses were still rising at the time of jacket failure, the true maximum strengths should be higher than plotted here. For comparison, the field of sliding strengths for a number of different rock types without gouge (Stesky, 1978) is shown.

Chu et al. (1981) found a possible direct relationship between gouge strength and grain size. However, Morrow et al. (1982) could find no correlation between strength and either grain size or mineralogy.

Whatever the causes of such variable clayey gouge strengths at room temperature, they were superseded at higher temperatures by some common factor that gave such gouges the same strengths at a given set of physical conditions and that caused temperature-related strength increases to the point where the gouge strengths were equivalent to rock friction strengths (Fig. 8). This factor may be their progressively greater degrees of lithification at higher temperatures and pressures. The exact processes involved in lithifying the sheet silicate gouges during the experiments are not well understood. However, the important factor contributing to their similar strengths appears to be the progressive development of a slaty fabric and slaty hardness from a mineral aggregate principally composed of platy minerals, whatever their mineralogy. At 600°C, the serpentine mineral altered to olivine and quartz, neither one a sheet silicate mineral. As a result, the 600°C serpentinite gouge strengths were no longer the same as those of the clay gouges. In the time of the experiments, the granite gouge was compacted but not indurated at high temperatures, and its strength was unaffected by temperature change.

At 200°C, the sheet silicate gouges were not well indurated, and their strengths were similar to room-temperature clay strengths and also much lower than that of the granite gouge. Possible causes for the low-temperature differences between the granite and phyllosilicate gouges include the effects of mineralogy and grain size. A gouge composed of hard minerals such as quartz and feldspar would be much stronger than one consisting principally of soft, platy minerals, other conditions being the same (Summers and Byerlee, 1977a). Grain size analyses of the four gouges were not made. However, even though the sieved granite, serpentinite, and illite gouges had the same maximum grain size, on the average the granite gouge was probably coarser-grained than the gouges rich in clay-sized particles. Because of this, the higher strength of the granite gouge at 200°C would be consistent with the observations of Chu et al. (1981) that gouge strength increases along with grain size. However, the apparent size dependency described by Chu et al. (1981) is also open to a mineralogical interpretation, because the sand- and silt-sized fractions of the Dry Lake Valley gouges they tested are principally composed of quartz and plagioclase. The strong, coarse-grained gouge (#320) studied by them may have contained

sufficient amounts of hard minerals to form a framework of interlocking grains that controlled the gouge's strength.

Sliding Behavior

Although some contradictory experimental results exist regarding the conditions favoring stick-slip (e.g., Olsson, 1974; Engelder et al., 1975), for the most part the temperature-pressure relationships of stable and unstable sliding are as shown at the top of Figure 9 (from Stesky, 1978). Stesky et al. (1974) studied the sliding behavior of fractured and faulted rocks of many different kinds, without gouge, at elevated temperatures and pressures. They found that, at low temperatures, stick-slip was favored by higher pressures; at high pressures, stick-slip gave way to stable sliding as temperature was increased. The specific pressure-temperature relationships in Figure 9 (top) are for sliding on granite surfaces (Stesky et al., 1974; Stesky, 1978), and included in the compilation are experiments run with and others without a pore fluid pressure. With other rock types, the transitional zone shifts to either higher or lower temperatures, depending perhaps in part on the brittle-ductile transition temperatures of important minerals in the rock samples (Stesky et al., 1974).

Most previous, room-temperature friction studies on gouge materials are consistent with the low-temperature portion of Figure 9, top. Summers and Byerlee (1977a, b) measured increases with pressure both in the tendency to show stick-slip behavior and in the magnitude of the stress drops of a diverse group of gouges, including crushed Westerly granite, crushed Ottawa sandstone, muscovite, illite, kaolinite, halloysite, and chlorite. Pure montmorillonite and vermiculite gouges were the only ones that slid stably at all examined pressures. Increasing the thickness of the gouge layer led to increases in the pressures required to initiate unstable sliding (Byerlee and Summers, 1973).

The granite gouge slid stably in all our experiments. Such behavior is consistent with the trends summarized by Stesky (1978) (Fig. 9, top), except perhaps at 200°C and 2.5 kbar confining pressure, where unstable sliding might have been expected in some runs. However, sliding modes of the clay and serpentinite gouges (Figs. 2-4) are very different from these other results, as illustrated in the lower part of Figure 9. The tendency to stick-slip for these gouges increased with temperature throughout the range examined, with the frequency and magnitude of stick-slip events being greatest at the lower confining pressures.

There is some evidence that unstable sliding may be a common characteristic of sheet silicate gouges at elevated temperatures. In experiments conducted at 1.5 kbar confining pressure, Logan et al. (1981) found that a montmorillonite-bearing Dry Lake Valley gouge and a bentonite gouge slid stably at 25°C and unstably at 300°C. Other experiments described by Logan et al. (1981) contrast with the trend shown in the lower part of Figure 9. For one thing, they found that a chlorite gouge slid stably at both low and elevated temperatures. In addition, their bentonite gouge showed an apparent transition back to stable sliding at 450°C. Differences in experimental conditions, for example heating time and pore fluid pressures (their samples were vented to the atmosphere), may account for the few discrepancies between the two sets of experiments.

Explanations of the stick-slip relationships shown at the top of Figure 9 have emphasized the locking of asperities on sliding surfaces (Byerlee, 1970) and the interlocking of grains in a gouge (Summers and Byerlee, 1977a). As confining pressures are increased in room-temperature experiments, stick-slip motion is promoted because sliding must take place by fracturing through the asperities or gouge grains rather than by sliding over them. A similar fracturing mechanism may be responsible in part for stick-slip motion of the heated phyllosilicate gouges. In the time of the experiments, the major effect of heating on these gouges was to promote their lithification. Sliding would then take place by fracturing through the hardened mineral aggregate, which would favor stick-slip. The granite gouge, which lacked this pronounced induration, also lacked the temperature-related development of stick-slip.

Other factors also must influence the development of stick-slip in the heated phyllosilicate gouges. For one thing, it might be expected that high confining pressures would have the same effect at high temperatures as at room temperature, that of increasing both the amount of compaction and the tendency to stick-slip. However, at any given temperature, sliding was more stable at the higher confining pressures. This suggests either that pressure has a different effect on sliding mode at high temperatures, or that some unknown, opposing factor is involved that outweighs the effects of pressure. Heating time may be an important control on sliding behavior, longer times tending to re-stabilize sliding (Logan et al., 1981). With respect to expanding-clay gouges, which slid stably in all room-temperature experiments (Summers and

Byerlee, 1977a, b), high-temperature dehydration accompanied by loss of the generated fluids will raise the effective stress level of such gouges, thus favoring stick-slip (Logan et al., 1981). The probable correlation between earthquakes and experimentally observed stick-slip motion makes it important to investigate more thoroughly the controls of sliding behavior in the phyllosilicate gouges.

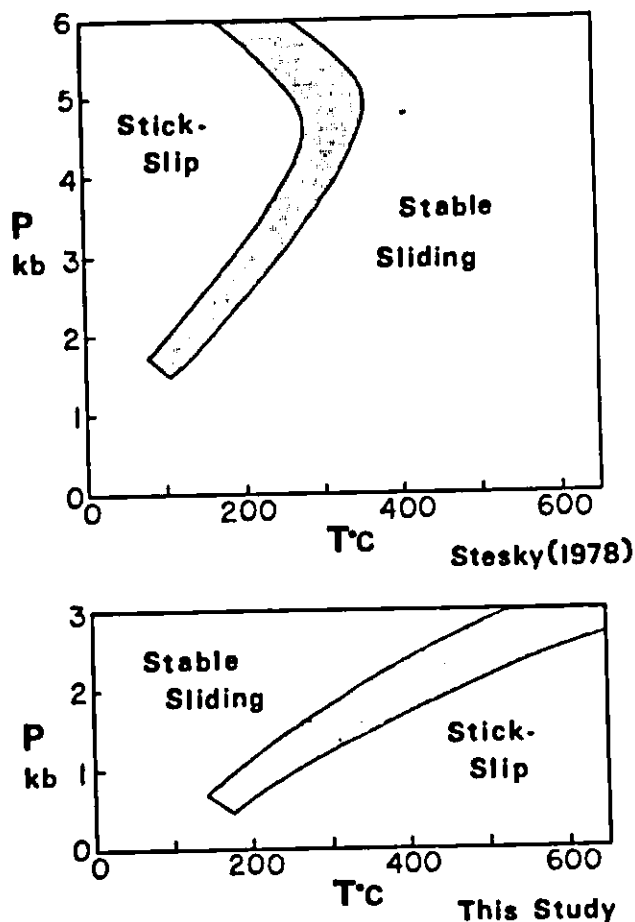


Figure 9. Top. Relationships between temperature, pressure and sliding behavior for faulted and jointed surfaces in granite (modified from Stesky, 1978). The same relative trends are shown by other rock surfaces, but with different transitional temperatures. Bottom. Summary of sliding behavior of sheet silicate gouges of this study.

Application to Fault Zones

The results reported here have some significance to the interpretation of fault zone behavior at depth. At temperatures to 200°C (Fig. 2; see also Summers and Byerlee, 1977a), gouges rich in quartz and feldspars are considerably stronger than ones composed principally of phyllosilicate minerals. However, higher temperatures tend to reduce the influence of mineralogy on the friction strength of fault gouge. Other factors being equal, then, gouge strength would become more homogeneous at greater depths, whatever the mineralogic heterogeneities. In addition, the differences in strength between a clay gouge-bearing fault zone and a fault trace without gouge would diminish at high temperatures. Of course, certain complications could arise with respect to localized transient heating accompanying slip (Raleigh, 1977), which would lead to strength increases of any phyllosilicate gouges located along the shear zone.

On the San Andreas, earthquakes are limited to the upper 20 km of the crust (Brace and Byerlee, 1970). In addition, the energy released by earthquakes in northern California increases rapidly to depths of 6 km and decreases as rapidly below that level (Byerlee and Summers, 1975). The greater stability of sliding on rock surfaces at high temperatures (Fig. 9, top) has been invoked to explain the restriction of earthquakes to the upper crust (Brace and Byerlee, 1970). The sliding behavior of the clay and serpentinite gouges of this current study also is consistent with earthquake observations in California. In this case, however, increased temperature promotes stick-slip and increased pressure, at least between 1 and 2.5 kbars, favors stable sliding. Lithostatic pressures would be about 1.6 kbar at the critical 6 km depth described by Byerlee and Summers (1975), which would be within the field of stick-slip sliding for the high-temperature gouges (Fig. 9, bottom). To conform with earthquake observations on the San Andreas, down to depths of about 6 km the effects of increasing temperature may outweigh those of pressure, leading to stick-slip events. As depths and pressures increase further, the clayey gouges would show progressively more stable sliding behavior.

In contrast to the sheet silicate gouges, the granite gouge slid stably in all the high-temperature experiments. This suggests that at least under some conditions the distribution of earthquakes along a fault could be influenced by mineralogy. However, under other conditions the granite gouge also may show stick-slip. Lithification of the

phyllosilicate gouges may have been a factor in the occurrence of stick-slip at high temperatures. Similarly, cementation lithification of quartz-bearing gouges produced by solution and redeposition of silica from pore fluids could cause such gouges to exhibit stick-slip motion (Angevine et al., 1982). Longer reaction times, higher pore fluid pressures, and a different pore fluid composition might promote such lithification reactions in the granite gouge, thus increasing the possibility of stick-slip during sliding.

Changes in time, fluid pressure, and fluid composition also may have considerable effects on the properties of the phyllosilicate gouges. High fluid pressures, which may affect the sliding stability of the phyllosilicate gouges, may be produced when water released during dehydration reactions cannot escape the fault zone. Time and fluid composition are other potentially important variables. In the short time of the experiments, dehydration was the principal effect of heating on the clays. With additional time and appropriate fluid compositions, mineral reactions could occur such as the alteration of montmorillonite to illite and chlorite. Other reactions could produce non-phyllosilicate minerals, changing the textural character of the gouge. Such mineralogic changes could have a major effect on strength, as was observed with the serpentinite gouge at 600°C. As can be seen, considerably more work is needed to investigate the variables not treated as yet.

CONCLUSIONS

- 1). The strengths of a group of phyllosilicate-rich gouge materials increased with temperature and confining pressure. At a given set of physical conditions, these gouges had identical strengths, despite their different mineralogies. At temperatures of 400°C and above, the maximum measured stresses supported by these gouges were comparable to those obtained during rock friction experiments conducted without gouge layers.
- 2). The strength of a crushed granite gouge increased with confining pressure but not temperature. Up to 200°C, this gouge was significantly stronger than the other examined gouges, but the differences decreased at higher temperatures.
- 3). The phyllosilicate gouges exhibited stick-slip motion at high temperatures, with the stress drops occurring at the lower examined confining pressure (1 kbar). This sliding behavior is consistent with the distribution and magnitudes of earthquakes with depth in California.

4). The crushed granite gouge slid stably at all examined temperatures and pressures. The differences in sliding behavior between this gouge and the others suggest that under certain conditions the mineralogy of a fault zone may control the distribution of earthquakes.

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