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Relationship between textures and sliding motion of experimentally deformed fault gouge: Application to fault zone behavior

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ABSTRACT: The run products of many triaxial friction experiments on clay-rich and quartzofeldspathic gouges have been examined petrographically, to see if any physical differences between stable and stick-slip motion can be found that will help to identify the cause of earthquakes and/or be useful for paleoseismology. For both gouge types the transition from stable sliding to stick-slip is correlated with (1) a change from pervasive deformation of the gouge layer to localized slip in subsidiary shears, and (2) an increase in the angle between the crosscutting (Riedel) and boundary-parallel shears. A possible hypothesis to explain earthquakes based on these differences is that the localization of slip creates the potential for large stress build-ups, which are generated where the Riedel and boundary shears meet at relatively high angles. This hypothesis will be tested further experimentally, with emphasis on the Riedel shears to identify the controls on their orientation. Evidence for distinguishing physical characteristics will also be sought along locked and creeping portions of the San Andreas fault.

1 INTRODUCTION

One of the important questions in rock mechanics is the cause of earthquakes. This problem has been approached in a number of ways, including field studies, laboratory experiments, and theoretical modeling. Our approach has been to study the frictional behavior of typical fault zone materials in the laboratory. The samples tested during the friction experiments either slide stably or show the stick-slip type of motion that is considered to be the laboratory equivalent of earthquakes (Fig. 1). We have begun conducting petrographic studies of the run products of these experiments, to see if there are any physical differences between the samples that slide stably and the ones that show stick-slip motion. Tchalenko (1970) demonstrated that many of the structures developed during laboratory tests can be correlated with the structures of natural fault zones. Therefore, any physical differences that can be found between the stably sliding and stick-slip samples may help to explain earthquakes and perhaps lead to a technique for determining prehistoric earthquakes.

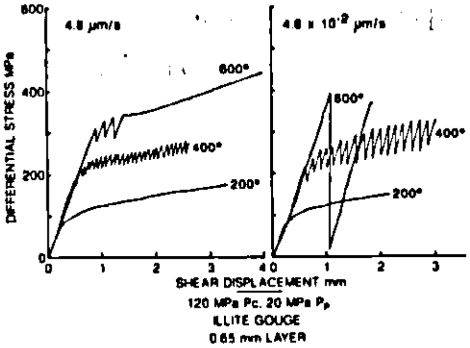

Fig. 1. Representative strength data for illite gouge.

Some previous petrographic studies have been conducted on the run products of triaxial friction experiments (Byerlee et al., 1978; Logan et al., 1979, 1981). Our work to date differs from these older studies chiefly in scale---we are investigating a number of different fault gouge materials under varying conditions of temperature, confining pressure, fluid pressure, and strain rate to try to arrive at generally applicable distinguishing features for stable and stick-slip motion. This paper compares the deformation textures developed in clay-rich and quartzofeldspathic gouges, and describes how the results possibly can be tested against actual fault zones.

2 CLAY-RICH GOUGE

Over 100 experimental run products of a gouge consisting of disaggregated illitic shale have been examined. The material contains about 70% illite, 20% quartz, 10% kaolinite plus chlorite, and trace amounts of opaque grains. The experimental samples consist of a layer of gouge 0.65 mm in initial thickness placed along a 30° sawcut surface in a granite cylinder. The experiments were run at temperatures in the range 200-600°C, sliding velocities along the sawcut of 4.8 and 4.8 x 10^{-2} µm/sec, and a variety of confining and pore pressures. Selected strength data are shown in Fig. 1, and the remainder is contained in Moore et al. (1986a). The illite-rich gouge shows increases in strength with increasing temperature (Fig. 1) as well as effective pressure (Moore et al., 1983, 1986b). All of the samples run at 200°C slide stably, but many of the higher-temperature samples show stick-slip motion. Stick-slip is more common and the stress drops tend to be larger in the experiments at the slower velocity (Fig. 1) and at lower effective pressures in the range 100-250 MPa (Moore et al., 1983, 1986b).

The deformation textures are briefly summarized here; more detailed descriptions are contained in Moore et al. (in press). Schematic drawings showing the range of textures developed in the illite gouge are presented in Fig. 2. Some samples are pervasively deformed (Fig. 2a), and the textures include a clay-mineral alignment, an array of low-angle kink bands, stretched mineral grains, and high-angle kink/fold structures. In the samples characterized by Fig. 2b, the low-angle kink bands have a more restricted occurrence; individual bands do not cross the entire gouge layer, but form short segments that are

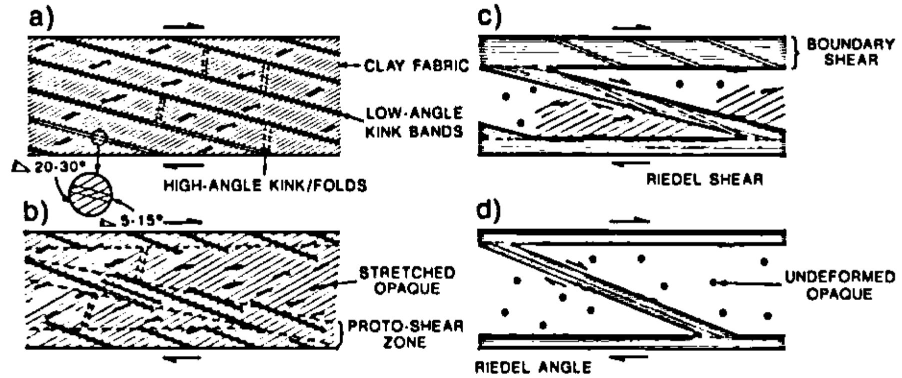

Fig. 2. Diagrammatic sketches of textural gradations in illite gouge run products. a). Deformation distributed throughout gouge. b). Deformation still pervasive in gouge, but proto-shear bands present. c). Good development of wide boundary and numerous Riedel shears; rest of gouge at least somewhat deformed. d). All deformation concentrated along narrow boundary and a few Riedel shears; rest of gouge undeformed.

concentrated along the gouge-rock cylinder boundaries and in narrow zones that cross the gouge layer at a lower angle than the kink bands contained in them. These zones of kink bands appear to represent proto-shear zones; the boundaries between the shears and the remaining gouge are poorly defined. The rest of the gouge layer still shows a clay fabric, stretched grains, and kink/fold structures. In Fig. 2c, the shear zones are well developed and relatively wide; they have sharply defined boundaries with the adjoining illite gouge that are marked by stretched opaque grains. The low-angle kink bands can still be discerned in the shears, but they are not as prominent in these samples as in those illustrated in Figs. 2a and b. At least some of the gouge between the shears is relatively undeformed. In the extreme case of localized shear (Fig. 2d), all the deformation is concentrated in narrow boundary and crosscutting (Riedel) shears, and the rest of the gouge is massive. The 600°C samples that show this end-member texture contain some lavender-colored material that is isotropic under crossed polarizers. This material occurs as one to three narrow, sub-parallel bands in the boundary shears, and some isotropic bands cross from one boundary shear to the other along a Riedel shear.

A close correlation exists between the deformation texture of a given sample and its sliding behavior, whatever the pressure-temperature-velocity conditions of the experiment. The samples with a pervasively developed fabric (Figs. 2a and 2b) slide stably, whereas the samples with localized deformation (Figs. 2c and d) show stick-slip motion if they contain Riedel shears that make an angle greater than 14° with the boundary shears. If the maximum measured angles are less than 10°, the samples slide stably, and if the largest angles are between 10 and 14°, the samples show variable behavior (e.g., 600°C, 4.8 μm/sec sample in Fig. 1). The samples with the highest-angle Riedel shears (19-23°) have the largest stress drops.

3 QUARTZOFELDSPATHIC GOUGES

For comparison with the clay-rich gouge, run products from some older experiments using a granite gouge have been examined. This gouge consists of Westerly granite which has been crushed and passed through a 0.090 mm sieve; it contains about 35% plagioclase and 25% each quartz and potash feldspar, with the remainder principally biotite, muscovite, and opaques. The quartz gouge samples of Byerlee et al. (1978) with 9 mm or more shear displacement have also been reexamined for this study. The quartz gouge is an essentially monomineralic quartz sand of about 0.6 mm maximum grain diameter. Layers of granite gouge 0.65 and 4 mm in initial thickness were used in the experiments; the quartz gouge thicknesses were 2 and 4 mm. As with the illite samples, the gouge was placed along a 30° sawcut in a granite cylinder. The experiments were run dry at room temperature, at confining pressures to 627 MPa and sliding velocities along the sawcut of 7.3 (granite) and 0.73 (quartz) μm/sec. Strength data for all the samples are contained in Summers and Byerlee (1977); selected data for the granite gouge, which are representative of both gouges, are presented in Fig. 3. The strengths of the granite and quartz gouges increase with increasing confining pressure. Both gouges slide stably at low pressures and show stick-slip motion at high pressures (Fig. 3). Increasing the thickness of the gouge layer leads to a slight decrease in the size of the stress drops but does not affect the strength at a given set of experimental conditions.

The two quartzofeldspathic gouges show some differences in texture from the clay-rich gouges, as would be expected from the different types and sizes of grains present. Kink bands and kink/fold structures, which depend on the presence of a clay fabric to form, are not developed in these samples. Instead, fracturing and crushing of quartz and feldspar grains are prominent processes. Fracturing is concentrated at the points of contact between adjoining grains, and the cracks do not have any preferred orientation. Crushed grains fill the spaces between intact grains, resulting in a compacted gouge.

The granite and quartz gouges do contain subsidiary shear zones similar to those in the illite gouge; in these samples, the shears are zones of intense grain comminution. Shear zone development and associated deformation in the quartzofeldspathic gouges show variations that are correlated with changes in the confining pressure and the sliding behavior. The textures in the 4 mm-thick samples of

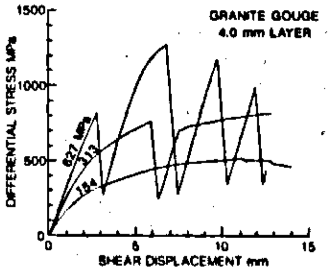

Fig. 3. Representative strength data for granite gouge at room temperature.

granite (Fig. 3) and quartz gouge will be described first. At low confining pressures where the samples slide stably, deformation is distributed across the gouge layer. Shear zones are not well developed along the gouge-rock cylinder boundaries, although in the granite gouge opaque and mica grains right at the interface are smeared out. The samples contain many Riedel shears, however, which are grouped into wide belts across the gouge layer. The gouge between the closely spaced Riedel shears in the belts shows a greater average grain size reduction than that in the wider areas separating the belts, giving the gouge a crosswise layered appearance. Stretched opaque and mica grains are found throughout the granite gouge, but the amount of elongation is greatest in the belts of Riedel shears. Individual Riedel shears in the granite gouge make angles up to 13° with the boundary of the gouge layer; angles in the quartz gouge are as high as 24°. At high confining pressures where the samples show stick-slip motion, the boundary shears are better developed, the belts of Riedel shears are much narrower and spaced farther apart, and individual Riedel shears are more sharply defined and make higher angles with the boundary shears (20° maximum in granite gouge; 33° maximum in quartz gouge). The wide areas of gouge between the belts of Riedel shears do not show much grain size reduction, and opaque and mica grains in those areas are essentially undeformed. The gouge, therefore, has a coarser-grained appearance in the high-pressure samples, which is opposite to what one might intuitively expect. The boundary shears also contain one or more narrow, subparallel bands of the lavender-tinged isotropic material, and several of the Riedel shears contain single strands.

At both low and high pressures, decreasing the thickness of the gouge layer leads to increases in the amount of grain size reduction and in the number of Riedel shears. The textural differences between the lowest and highest pressure samples are also more pronounced in the thinner samples. The orientations of the Riedel shears appear to be unaffected by changes in thickness of the gouge layer, however.

4 DISCUSSION

Although the examined clay-rich and quartzofeldspathic gouges show textural differences related to their different mineral contents and grain sizes, they share some common textural features whose occurrence and degree of development are a function of their sliding behavior. The two most significant correlations with stick-slip motion are the localization of shear and the increase in the angle between the boundary and Riedel shears. Moore et al. (1986b) also noted a correlation between Riedel angles and sliding motion for granite, serpentine, and montmorillonite-rich gouges run at elevated temperatures and 3 MPa fluid pressure. A calcite gouge examined by Logan et al. (1979) showed a decrease in strength with increasing temperature and a change from stick-slip at low temperatures to stable sliding at 400°C and above. They found that the Riedel angles in the room-temperature calcite samples were 15-20°, whereas at 400°C the angles were only 8-10°. The relation between Riedel angle and sliding motion for calcite is consistent with this study.

The different gouge types show similar trends in Riedel shear angle relative to sliding motion, but the actual size of the angle appears to vary with the mineral content. The angles measured for the illite and granite gouges are comparable and consistently lower than those in the quartz gouge. Similarly, Logan et al. (1979) found that the Riedel angles measured in a pure quartz gouge were higher than those in a pure potash feldspar gouge.

A possible hypothesis to explain the experimental results is that the localization of slip along narrow shear bands creates the potential for significant stress build-ups leading to stick-slip. The high Riedel angles would provide an impediment to continuous slip by inhibiting stress transfers where the boundary and Riedel shears meet. As observed in this study and also by Logan et al. (1979), localization of shear is a necessary but not a sufficient requirement for stick-slip motion; and the high intersection angles between Riedel and boundary shears may act as physical barriers. The higher the angle the greater the degree of obstruction to be expected, and the illite samples show a correlation between the size of the stress drops and the Riedel angles. The critical angle for motion to be measurably impeded appears to vary with the mineral content of the gouge.

Two main questions about this hypothesis deal with the Riedel shears. One question concerns the relative importance of the Riedel shears to the overall slip pattern. Consideration of the experimental samples containing isotropic material suggests that Riedel shears do form part of the main slip path. Sketch maps of the isotropic bands in two of the illite samples are shown in Figs. 4a and b. It is not known at present whether the isotropic material is glass or extremely fine-grained gouge; either material, however, is representative of concentrated slip. In each example, an isotropic band switches from one side of the gouge layer to the other along a Riedel shear. The second question is whether the Riedel shear orientations are the cause or a result of the type of sliding motion. This question cannot be answered yet, because the controls on Riedel shear

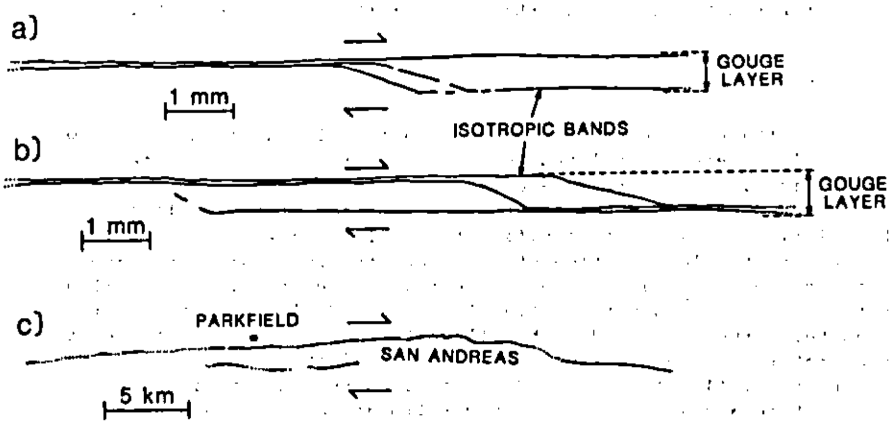

Fig. 4. a-b). Sketch maps of isotropic bands in the boundary and Riedel shears of two illite samples. The isotropic material marks the lines of concentrated slip in the samples; some bands cross from one boundary of the gouge layer to the other along Riedel shears. c). Map of surface fractures accompanying the 1966 Parkfield earthquake on the San Andreas fault in central California, from Brown and Vedder (1967).

orientations are not fully understood. Mandl et al. (1977) showed experimentally that Riedel shears correspond to Coulomb shears; and if the deformation is of the simple shear type, as is generally assumed (e.g., Tchalenko, 1970; Logan et al., 1979), the Riedel angle should equal one-half the angle of internal friction of the gouge material. This relationship does not appear to hold, however, for the changes in Riedel angle measured in the heated illite gouge (Moore et al., in press). Therefore, either the assumption of simple shear is inappropriate or some additional factor affects the Riedel angle. With respect to the latter possibility, both the sliding behavior and the Riedel shear orientation are closely related to strength. Increases in strength may cause increases in the Riedel angles, which in turn may affect the stability of motion. This possibility will be investigated further experimentally.

The ultimate goal of this research is to explain the behavior of faults such as the San Andreas, which contains both locked (stick-slip) and creeping (stable slip) segments. The conclusions reached about localization of shear in the experimental samples are applicable to the San Andreas and associated faults in California. Numerous studies show that in locked portions of these faults, motion accompanying earthquakes is localized along narrow planes in a wide fault zone (Allen, 1981, and references therein). In creeping sections, motion may either be localized or distributed across the entire width of the fault (e.g., Radbruch, 1968). The role of Riedel shears in natural faults needs to be explored. If the presence and orientation of Riedel shears can be shown to have a bearing on stick-slip motion either past or future, they would provide an important criterion for evaluating the hazard potential of various fault segments. One important question is that of scale: are Riedel shears solely small-scale features or are they major structural elements of the fault? According to Wallace (1973), they may be both; he identified en echelon fractures along the San Andreas that have the same orientation as Riedel shears and that form at scales between 1 m and 18 km. Portions of the main fault trend may correspond to Riedel shears; Fig. 4c shows the extent of fracturing associated with the 1966 Parkfield earthquake (Brown and Vedder, 1967). The fracture traces at Parkfield closely approximate the isotropic bands in the experimental samples (Figs. 4a and b). We plan to study the mapped trace of the San Andreas, to look for crossovers similar to the one near Parkfield and to see if there are differences in their orientations in locked and creeping sections. The geology at points of interest along the fault must also be examined, because of the correlation between Riedel angle and the mineral content of fault gouge; and our experimental studies must be expanded to include all gouge types observed along the San Andreas. As the opportunity permits, we will conduct structural studies of the fault at outcrop scale.

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