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The Sliding Characteristics of Sandstone on Quartz Fault-Gouge[1]

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Summary – Three types of triaxial compression experiments are used to characterize the frictional processes during sliding on quartz gouge. They are: 1) pre-cut Tennessee Sandstone sliding on an artificial layer of quartz gouge; 2) fractured Coconino Sandstone sliding along experimentally produced shear fractures; and 3) a fine-grained quartz aggregate deformed in compression. The specimens were deformed to 2.0 kb confining pressure at room temperature and displacement rates from 10^{-2} to 10^{-5} cm/sec dry and with water. There is a transition in sliding mode from stick-slip at confining pressures <0.7 kb to stable sliding at >0.7 kb. This transition is accompanied by a change from sliding at the sandstone-gouge contact (stick-slip) to riding on a layer of cataclastically flowing gouge (stable sliding). Quartz gouge between the pre-cut surfaces of Tennessee Sandstone lowers both the kinetic coefficient of friction and the magnitude of the stick-slip stress drops compared to those for a pre-cut surface alone. Stick-slip stress drops are preceded by stable sliding at displacements of 10^{-5} cm/sec. For a decrease in displacement rate between 10^{-3} and 10^{-5} cm/sec, stress-drops magnitudes increase from 25 to 50 bars. Tests on saturated quartz gouge show sufficient permeability to permit fluid-pressure equilibrium within compacted gouge in 10 to 30 seconds; thus the principle of effective stress should hold for the fault zone with quartz gouge. Our results suggest that at effective confining pressures of less than 2.0 kb, if a fault zone contains quartz gouge, laboratory-type stick-slip can be an earthquake-source mechanism only if a planar sliding-surface develops, and then only when the effective confining pressure is less than 0.7 kb.

1. Introduction

Gouge is commonly found between the walls of real faults. Thus, any attempt to characterize or model the faulting process, which may involve creep (aseismic faulting) or unstable slip (seismic faulting), must account for the mechanical properties of the fault with gouge. Most fault zones can be modelled by using three mechanical elements: a gouge zone with wall rock on both sides.

Knowledge of the mechanical properties of fault zones is based primarily on sliding-friction experiments. In contrast to natural faults with long histories of sliding and frictional wear many experimental surfaces have little or no previous frictional wear. In those experiments the frictional force is developed between two intact rocks rather than through a layer of gouge. The purpose of this paper is to report an attempt to simulate sliding after a thick layer of gouge has developed during prior large fault displacements and to determine the frictional properties of rock sliding on fault gouge.

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100 to 250 μm diameter quartz grains between halves of a 5 cm diameter by 10 cm long cylinder of Tennessee Sandstone cut and ground with an 80-grit wheel at 35° ± 0.1° to the cylinder axis (Fig. 1). Pre-cut cylinders are more desirable than mechanically fractured cylinders because the latter have rough sliding surfaces with large asperities which affect sliding characteristics enough to mask the more subtle effects of other experimental parameters. The layer of quartz on the sliding surface is cataclastically reduced to quartz gouge during the initial displacement. The experimental quartz gouge has a grain-size distribution comparable to that from natural faults (ENGELDER [10]) and, therefore, is assumed to have the same mechanical properties as the natural counterpart. A typical force-shortening curve and details of the cataclasis accompanying the curve are given by ENGELDER [15].

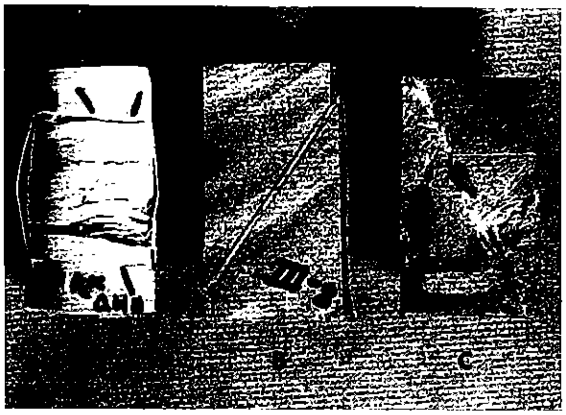

Figure 1

The three types of specimens used in this work. Specimen *a* is a compacted quartz aggregate. Shear fractures which extend between black lines drawn on the polyolefin jacket occur at about 30° to cylinder axis. Large horizontal fractures are extension fractures which resulted from extracting the specimen from the pressure vessel. Specimen *b* is a section through a pre-cut cylinder of Tennessee Sandstone with 0.12 cm thick layer of quartz gouge between sliding surfaces. Specimen *c* is a section through a cylinder of Coconio Sandstone that has been fractured to generate gouge during displacement. Long axis of each cylinder is about 10 cm

Experiments are conducted at room temperature, confining pressure to 2.0 kb, pore pressure to 1.0 kb, and slip rates between 10^{-2} and 10^{-5} cm/sec. The apparatus is described by HANDIN *et al.* [16]. The cut and ground cylinders are jacketed with heat-shrink polyolefin sleeves. The quartz grains are spread along the saw-cut by removing one half of the specimen from the sleeve and then distributing the quartz in an even layer on the sliding surface. Once the specimen half is replaced, the ends are carefully aligned. A 0.6 cm thick steel spacer powdered with MoS_2 on both sides is placed between the specimen and the pistons in order to enhance proper alignment and to decrease friction on the ends of the specimen. The reproducibility of these experiments is indicated by a series of four tests at 1 kb confining pressure in which after on the layer of gouge has a lower kinetic coefficient of friction relative to that measured for sandstone without the discrete layer of gouge.

Tennessee Sandstone stick-slips at all confining pressures in the range 0.2 to 2.0 kb (Humston [13]). However, confining pressure in the same range does affect the sliding mode of Tennessee Sandstone on quartz gouge (Engelder [15]; Figure 2). With a 0.12 cm thick layer of gouge, Tennessee Sandstone does not stick-slip above 0.7 kb confining pressure. As explained in Engelder [15], stick-slip occurs after an initial phase of stable sliding during which gouge is generated on the sliding surface. The onset of stick-slip occurs earlier in the displacement history of the specimen as the confining pressure is increased from 0.14 kb to 0.5 kb. It was expected that stick-slip would occur with even less displacement at 0.7 kb confining pressure, but the sliding is in fact stable at displacements greater than those for which stick-slip occurs at 0.14 kb. Thus, a stick-slip to stable-sliding transition is noted for Tennessee Sandstone sliding on dry quartz gouge.

In order to better understand this transition, a sequentially loaded experiment is used to investigate sliding characteristics of a single specimen both above and below 0.7 kb confining pressure. During this type of experiment the confining pressure is changed after the specimen has slid a short distance; the specimen is unloaded prior to each change in confining pressure. At the onset of a sequentially loaded experiment, gouge is generated by the initial sliding. Then the confining pressure is readjusted to the desired level. The specimen in Fig. 3 was initially loaded at 1.0 kb to generate

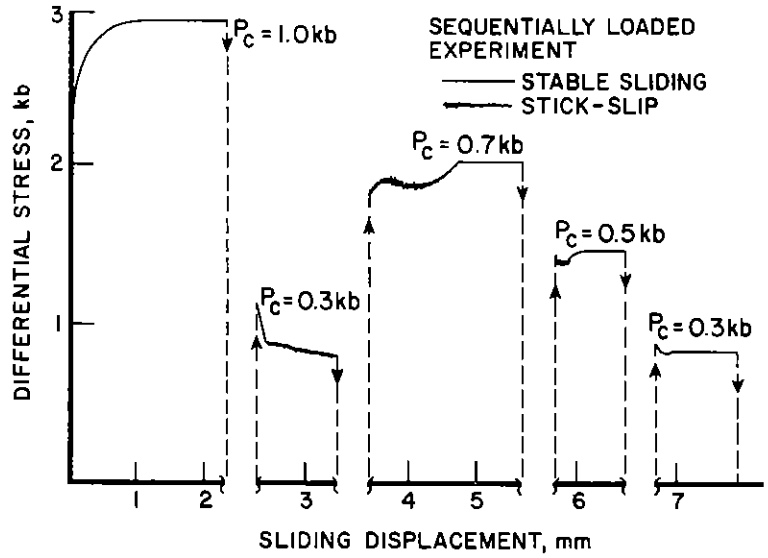

Figure 3

Effect of sequential loading on frictional sliding of a pre-cut specimen of Tennessee Sandstone with an 0.12 cm thick layer of dry quartz gouge. Confining pressure adjusted five times during the same experiment; for each adjustment the differential stress is reduced to zero and then reapplied (dashed lines)

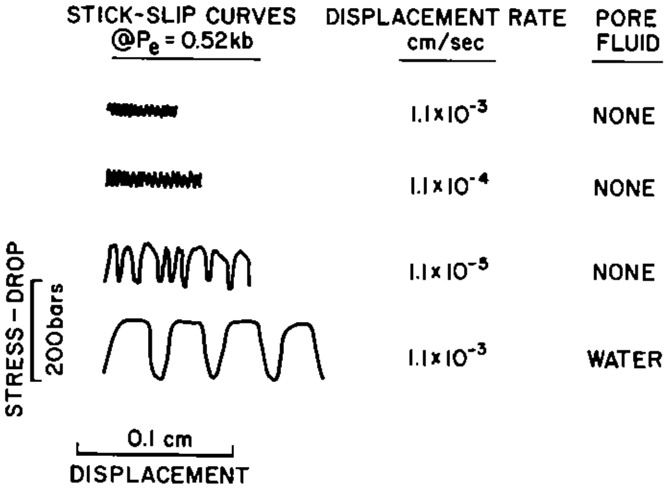

Figure 4
Diagram of the character and magnitude of stress drops for stick-slip of pre-cut specimens of Tennessee Sandstone sliding on a compacted 0.12 cm thick layer of quartz gouge. The effects of displacement rate and pore water are illustrated

Sandstone sliding on saturated quartz gouge at 0.5 kb effective confining pressure is higher than for sliding on dry gouge (Fig. 5). The two curves for saturated tests are within experimental reproducibility of each other but the curve for this dry sample is not within experimental reproducibility of the others.

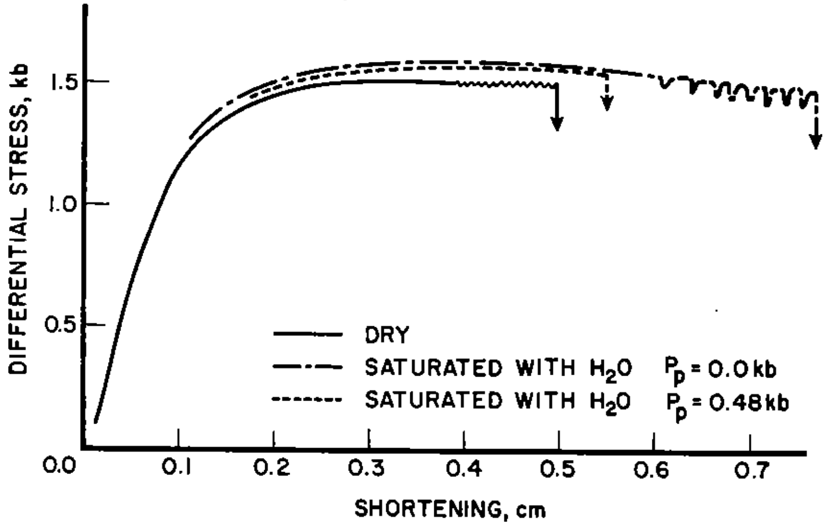

Figure 5
Differential stress-shortening curves for pre-cut specimens of Tennessee Sandstone sliding on either dry or saturated, compacted quartz gouge at an effective confining pressure of 0.5 kb. Gouge thickness 0.12 cm. Displacement rate 0.7 × 10^{-3} cm/sec

Compacted aggregates

Compacted aggregates of quartz particles, all less than 63 μm in size, are deformed to simulate the mechanical behavior of the quartz fault-gouge and thus help to explain the cause for the transition in the sliding mode. Each specimen is precompacted at 2 kb confining pressure by shortening the sample 3%. The arbitrary pre-compaction is necessary to obtain a specimen with about the same cohesiveness as that of the dry gouge after removal from the gouge zone after an experiment. These experiments are undoubtedly history-dependent, and the results should be considered with this in mind. During loading the specimen compresses nearly linearly then yields and flows by pervasive cataclasis, and finally fractures at all confining pressures (Fig. 7). During the quasi-linear portion of the stress-shortening curve, non-elastic compaction by pore collapse takes place. A positive slope after the 'yield point' always indicates pervasive cataclasis which causes the specimen to bulge with no evidence of macroscopic fracturing. Flat or negative slopes indicate fracturing along 5 to 10 conspicuous macrofractures (Fig. 1), a larger number than in intact sandstone deformed under similar conditions. More cataclastic flow precedes fracture at the higher confining pressures, as is indicated by the larger amount of shortening before fracture. The specimens fail with a slight loss of load only below 0.8 kb confining pressure. With a large number of fracture surfaces involved, slip on a single surface for a prolonged distance and the resulting macroscopic failure of the sample do not occur.

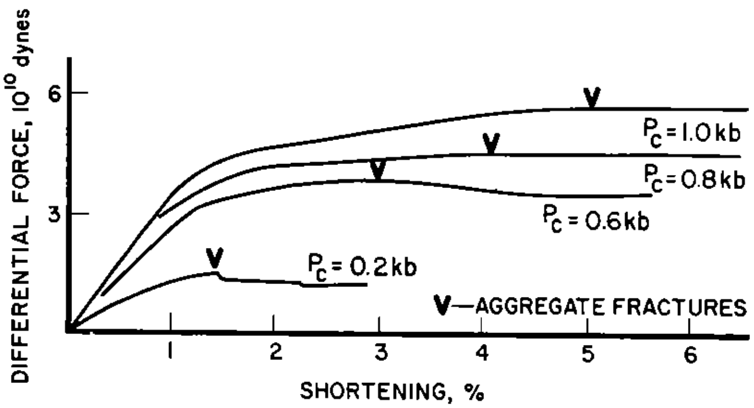

Figure 7
Effect of confining pressure on the mechanical behavior of compacted quartz aggregates composed of particles less than 63 μm

A cursory effort was given to determining the effect of strain rate on the deformation of the precompacted aggregates. The load necessary to shorten the sample 5% at 0.76 kb confining pressure decreases about 5% for each decade of decrease in strain rate between 10^{-4} and 10^{-7}/sec.

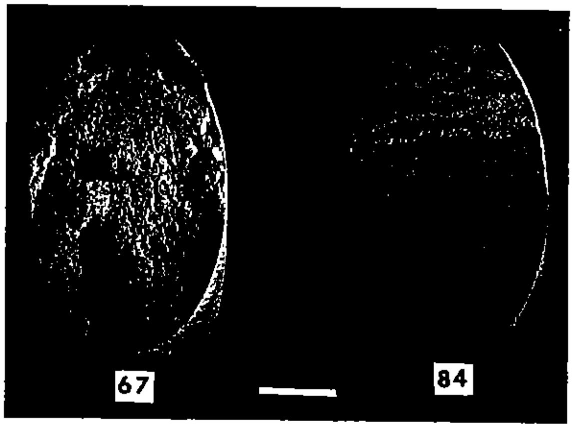

Figure 9
Photograph of indurated gouge on the pre-cut surface of Tennessee Sandstone experiment 67 formed upon continuous displacement at a rate of 10^{-3} cm/sec at 0.7 kb confining pressure. The indurated material partially spalls off the surface in large flakes. All specimens deformed at other conditions have surfaces similar to experiment 84 which is covered with patches of compacted gouge. The white banding on the surface of experiment 84 is gouge from the fine-grained bands formed within the gouge at angles 20°–30° to the sliding surface. Scale line is 2.0 cm

5. *Discussion of experimental results*

Stick-slip to stable-sliding transition

Thin section studies of the quartz gouge together with force-shortening records give clues to the mechanisms of stick-slip and stable sliding. The idea is that during stable sliding the sandstone rides on a layer of gouge which is flowing cataclastically, whereas during stick-slip the intact rock slips along the contact with the gouge layer.

In all experiments, stable sliding first occurs as the initial layer of sand is cataclastically deformed. Because cataclasis pervades this layer, shear deformation is probably distributed throughout, although banding indicates that the intensity of cataclastic deformation varies somewhat from point to point. At this stage no discrete sliding plane has developed either within the gouge or at the gouge-rock interface. Sliding involves only the scale of individual grains moving past each other. Essentially, stable sliding occurs because the intact sandstone is carried on a layer of gouge which is flowing internally by pervasive cataclasis.

As displacement progresses, stick-slip becomes the mode of sliding at confining pressures less than 0.7 kb. Stick-slip occurs when the gouge is reduced to a median grain-size of about 25 μm. It starts at smaller displacements as the confining pressure increases from 0.14 to 0.5 kb because cataclastic deformation per unit displacement is more intense at the higher confining pressure.

Most curves from stable sliding experiments have a peak which represents the ultimate strength of the specimen, followed by a negative slope which results from

Sandstone before sliding on quartz gouge, planar shear surfaces do not develop at 0.5 kb confining pressure and only stable sliding occurs. HUMSTON [13] observed that stick-slip is repressed for sliding of mismatched surfaces of Tennessee Sandstone and BLACKWELL [14] says that it occurs only when the fit between planar surfaces is good. JAEGER and COOK [18] observe that stick-slip is more likely for pre-cut surfaces than fracture surfaces. Their observation is in agreement with some tests we have conducted on Coconino Sandstone (Fig. 1). Fractured Coconino Sandstone does not stick-slip at 0.5 kb confining pressure apparently because the rough fracture surface prevents the formation of the necessary smooth sliding surfaces. However, pre-cut Coconino Sandstone does stick-slip on a 0.12 cm thick layer of gouge.

At confining pressures above 1.0 kb, the indurated gouge does not form, yet the sliding is stable. It has been established that an inflection point in the force-shortening curve indicates a change in the intensity of cataclastic deformation at the gouge-rock interface at 0.7 kb confining pressure. At 1.0 kb confining pressure the force-shortening curve has a constant negative slope, which suggests a single mode of deformation throughout the experiment. At small displacements stable sliding occurs because the intact rock is carried on a layer of gouge which is flowing by pervasive cataclasis. It follows that pervasive cataclasis probably continues to carry the intact specimen throughout the experiment. That cataclasis is pervasive above 1.0 kb is supported by the observations that cataclasis is more intense at higher confining pressures (ENGELDER [10]) and banding of gouge into coarse and fine layers is less common than at lower pressures.

BRACE and BYERLEE [19] observed a stable-sliding to stick-slip transition for faulted specimens of Westerly Granite with 0.05 cm of gouge at 1.5 kb confining pressure. Stick-slip might not have occurred below 0.7 kb because of the poor fit between the surfaces of fractured Westerly Granite. It is also possible that this stable sliding observed at 1 kb confining pressure is caused by the same mechanism which is suggested for precut specimens of Tennessee Sandstone. Owing to the necessity of using smaller specimens and the difficulties of sample preparation and jacketing, the effects of confining pressures above 2.0 kb have not been investigated systematically for Tennessee Sandstone on quartz fault gouge. BYERLEE and BRACE [9] observed stick-slip for a compacted aggregate of sand at 7 to 10 kb confining pressure. We can speculate that Tennessee Sandstone would also stick-slip on quartz gouge at some unknown higher confining pressure.

Mechanical properties of fine-grained aggregates

Fine-grained quartz aggregates have been deformed in triaxial compression to document the behavior of simulated quartz gouge without the large shear tractions which were applied during the friction tests. By our definition a rock exhibits ductile behavior when it undergoes more than 5% permanent strain before faulting. Therefore, the pre-compacted quartz aggregates have a macroscopic brittle–ductile transition below 1.0 kb confining pressure and near the stick-slip to stable-sliding transition for tional heating, fracturing of grains, and radiation of seismic waves are three principal energy sinks. Creation of new surface area by brittle fracture during cataclasis of the entire layer of gouge requires only a small fraction of this work, but the additional work expended for the creation of the bands of indurated gouge is of the same order of magnitude as that necessary to create new surface area.

Part of the work of cataclastic deformation is spent in breaking atomic bonds and creating new surfaces during fracturing of the initial sand aggregate. The work done in breaking atomic bonds (i.e., fracture–surface energy) is equivalent to the increase in total surface (Helmholz) free energy, if the surface is created by an isothermal and reversible process (INMAN and TIPLER [20]). The amount of work (W) expended to create the large surface area of the fine-grained gouge is calculated by multiplying the estimated increase in area (A) by the surface energy per unit area (γ) of quartz:

$$W(\text{ergs}) = \gamma(\text{ergs/cm}^2) \times A(\text{cm}^2).$$

In order to estimate this increase in surface energy, it is assumed that the initial sand layer contains perfectly spherical quartz grains, all 0.02 cm in diameter. The layer is initially 0.17 cm thick on 28 cm^2 of sandstone, and it has 30% porosity. If it is assumed that the gouge generated from 0.02 cm spheres consists of spherical quartz particles 2.5×10^{-3} cm in diameter (ENGELDER [10]), then the increase in surface area is about 7.7×10^3 cm^2. The surface energy for quartz as determined by the Oberimoff–Gilman method ranges from about 400 ergs/cm^2 for (1011) to 1000 ergs/cm^2 for (1010) (BRACE and WALSH [21]). Taking 500 ergs/cm^2 as a representative value, we calculate the work required to generate the new surface area as 3.9×10^6 ergs. This is only a small fraction of the total work of 2.7×10^9 ergs.

Indurated gouge is generated during the 0.1 cm of displacement beginning at about the point where the magnitudes of the stick-slip stress drops begin to decrease (i.e., at a displacement of 0.2 cm in Fig. 11), and ending at the onset of stable sliding (i.e., at a displacement of 0.3 cm). During this 0.1 cm of sliding, the shear stress increases by 50 bars. Integrating the shear force (1.4×10^9 dynes) over 0.1 cm of displacement gives an increase in work of 7×10^7 ergs. About 5% of the gouge with a median size of 2.5×10^{-3} cm is reduced to indurated gouge, assumed to consist of 2.5×10^{-5} cm spheres (Fig. 8). About 2×10^7 ergs is required to create this new surface area. This is the same order of magnitude as the increase in work (7×10^7 dyne-cm) necessary to slide the sandstone 0.1 cm during the generation of the indurated gouge. Our point is that only a small fraction of the total work expended during the whole of the frictional sliding goes into fracturing of quartz to create new surface area. However, the small increase in work just prior to stable sliding (Fig. 11) can be accounted for by the large increase in surface area during the generation of the indurated gouge.

Natural faulting process

What, if anything, do these experiments tell us about natural faults? The best field analogs that we have found are faults like the Muddy Mountain Thrust Fault

8) Quartz gouge is sufficiently permeable to permit fluid-pressure equilibrium throughout the compacted gouge in 10 to 30 sec. Thus the principle of effective stress should hold for the fault zone.

9) The fact that shallow earthquakes in pre-existing fault zones do occur at depths where effective confining pressure would exceed 0.7 kb for hydrostatic water pressure may imply that pore pressure in these zones are well above hydrostatic, although many other untested parameters may also affect the stick-slip to stable-sliding transition in nature.

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that have 3 to 30 cm of quartz gouge between sliding surfaces that are as planar as those in our experiments (ENGELDER [10]). The Muddy Mountain Thrust carries a section 4 to 5 km thick, and with a normal pore pressure, the effective confining pressure would have been 0.5 kb (BROCK [22]). This is in the stick-slip regime for sandstone on quartz gouge. However, our experiments would predict that thrust faults carrying thicker sections at normal pore pressure would slide stably.

Earthquakes are known to occur at depths in the crust where our experiments suggest that stable sliding should occur. Earthquake generation may well depend on untested parameters, including time of loading, type of gouge, temperature and surface roughness. Or it may be that seismogenic fault zones are under water pressures higher than hydrostatic.

HOSKINS *et al.* [23] and SCHOLZ *et al.* [7] observe small amounts of stable sliding prior to stock-slip stress drops. This also occurs in our tests at a rate of sliding of 10^{-5} cm/sec. These studies all suggest that if laboratory stress drops are really analogous to earthquakes, then stable sliding prior to a stress drop may be the same as aseismic creep which has preceded some large earthquakes.

6. Conclusions

1) For pre-cut surfaces of Tennessee Sandstone sliding on quartz gouge, the mode of sliding changes from stick-slip to stable sliding at effective confining pressures between 0.7 and 0.8 kb. This change in mode correlates with the macroscopic brittle–ductile transition in compacted quartz aggregates.

2) The stick-slip to stable-sliding transition is accompanied by a change from sliding of intact sandstone along its planar contact with the compacted gouge to riding on a layer of cataclastically flowing gouge.

3) The sliding-mode transition for quartz fault–gouge would eliminate stick-slip as a valid mechanism for 'locking' a fault zone in sandstone between effective confining pressures of 0.8 kb and at least 2.0 kb.

4) Compared to bare rock surfaces sliding without gouge, stress drops during stick-slip are drastically reduced by the presence of quartz gouge.

5) For pre-cut surfaces of sandstone sliding on compacted gouge at three different displacement rates at 0.5 kb confining pressure, the stress drop increases 10–15 bars for each decade of decrease in displacement rate.

6) An indurated film of gouge forms between the sandstone and an 0.12 cm thick layer of compacted quartz gouge only at about 0.7 kb confining pressure.

7) From considerations of the total work required to create new fracture surface during grain-size reduction, it is reasonable to conclude that cataclastic deformation of the gouge requires only a small fraction of the total work needed to slide pre-cut sandstone on gouge. Work expended solely for the creation of the indurated-gouge layers is of the same order of magnitude as that necessary to create the new surface area.

quartz fault-gouge. The mechanism for stable sliding as outlined above required that quartz fault-gouge be able to sustain large 'macroscopic' shear strains by pervasive cataclasis, and this is true of the precompacted aggregates at the higher confining pressures.

It may also be significant that at confining pressures below 0.7 kb, a partial drop in load follows the development of fractures in compacted aggregates. The suggested mechanism for stick-slip requires that slip occurs along a discrete plane at the rock-gouge interface. The stick-slip stress drops below 0.7 kb confining pressure and the stress drops below 0.7 kb confining pressure due to fracture of the aggregate may be manifestations of the same process. Likewise, no stress drop occurs above 0.7 kb in either the friction experiments or in the compacted aggregates which fracture only after large 'macroscopic' strains.

Effect of pore water

The presence of water increases the kinetic coefficient of friction for Tennessee Sandstone sliding on quartz gouge (Fig. 5). A saturated gouge is finer grained compared to that of a dry gouge subjected to the equivalent deformation (Engelder [10]). The generation of the finer-grained material is probably due to stress corrosion of the quartz by the water. An effect of the finer grain-size is that the actual contact area between gouge and intact sandstone is greater. Because a larger shear force is necessary for sliding on a larger contact area, the measured kinetic friction is greater.

Energy considerations for the generation of quartz gouge

About 2.7×10^9 ergs is dissipated during sliding of pre-cut Tennessee Sandstone 0.1 cm on the layer of gouge at 0.7 kb confining pressure (Fig. 11). This is the work required to overcome frictional resistance in the gouge–sandstone system where fric-

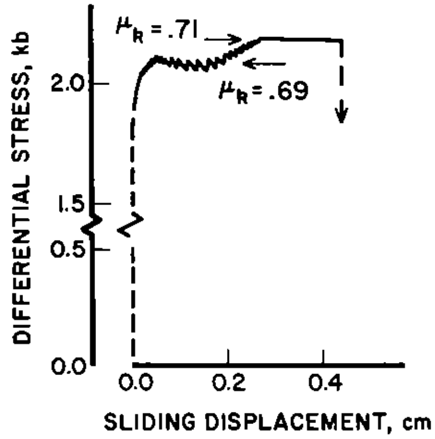

Figure 11
Differential stress-displacement curve illustrating the change in sliding mode and kinetic coefficient of friction during the generation of the indurated gouge. This is a drawing of cycle 3 of Fig. 3

decreasing load due to a decreasing contact area. If stick-slip follows stable sliding, the force-shortening curves at confining pressures of less than 0.8 kb have inflection points which occur at the onset of stick-slip (Fig. 10). The inflection point becomes more striking as the confining pressure increases.

At 0.7 kb confining pressure the inflection point represents a shift in the manner by which the rock slides on the layer of gouge. Initially, the rock is riding on a layer which is flowing by pervasive cataclasis. Beyond the inflection point the shear zone becomes restricted to the rock–gouge interface. This is indicated by the formation of indurated gouge within a restricted zone at the contact with intact sandstone (Figs. 8 and 9). Indurated gouge is found only in specimens which have been displaced beyond the inflection point at 0.7–0.8 kb confining pressure and have slid stably. The indurated gouge is a manifestation of intense cataclasis due to the sliding along the gouge–sandstone interface.

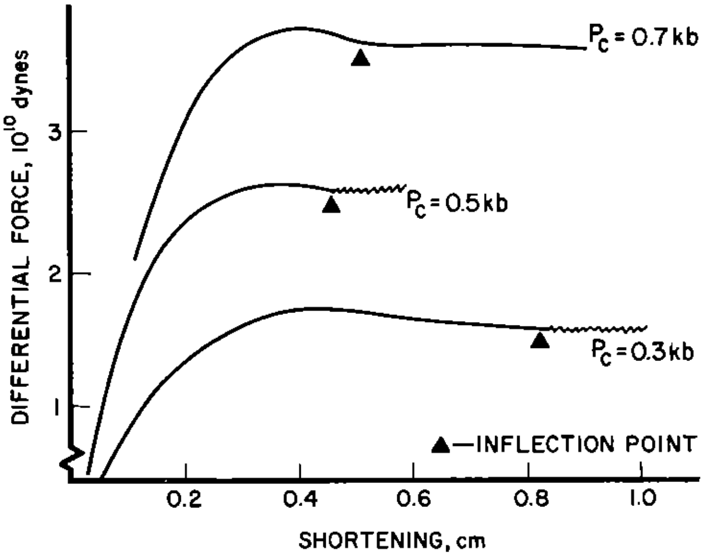

Figure 10
Differential force-shortening curves which have inflection points. The curves represent the sliding of pre-cut Tennessee Sandstone on an 0.12 cm thick layer of dry quartz gouge at a displacement rate of 10^{-3} cm/sec

At confining pressures of less than 0.7 kb, the sliding mode changes from stable to stick-slip at the inflection point. It is assumed that as in the 0.7 kb confining-pressure tests, the inflection point represents a shift from sliding on cataclastically flowing gouge to sliding along the interface. However, for unknown reasons, indurated gouge does not form at <0.7 kb confining pressure.

Other experiments also indicate that stick-slip may occur when sliding is restricted to a planar interface. When 0.1 cm deep grooves are cut into the surface of Tennessee

4 Microscopic observations

In order to further clarify the deformation mechanisms which influence the sliding of sandstone on quartz fault-gouge, thin sections of the gouge are examined petrographically. Typical gouge has a median grain size of about 25 μm and is not intact. ENGELDER [10] describes the relevant observations. 1) Cataclasis is more intense at higher confining pressures; thus the layer of quartz gouge is finer grained relative to those in lower confining-pressure tests. 2) Quartz gouge is much finer grained when it is generated in the presence of water at the same effective confining pressure.

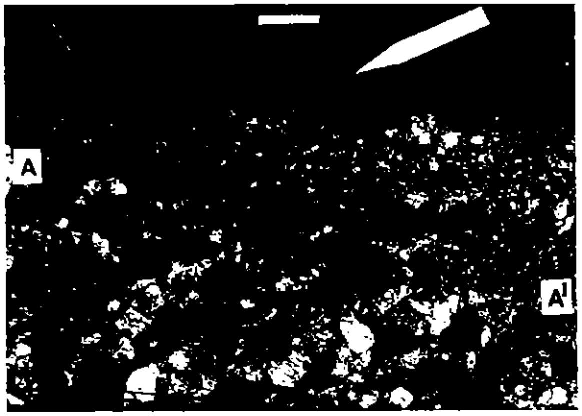

Figure 8

Photomicrograph of indurated gouge next to typical gouge. The indurated gouge (arrow) is preserved in epoxy which is used to impregnate the gouge during preparation of thin sections. The boundary (*A–A'*) between fine and coarse-grained gouge is used to infer a sense of shear of the intact sandstone on the layer of gouge. In this case the upper surface has moved to the right. Scale line is 0.02 cm; partially crossed polarized light

At confining pressures below 1.0 kb the gouge shows incipient banding with layers of coarse grained material between layers of fine-grained gouge (Fig. 8). Banding occurs at angles of 20° to 30° to the sliding surface. When banding occurs at >1.0 kb confining pressure, it tends to be parallel with the sliding surface.

A 0.006 cm thick layer of indurated quartz forms between the gouge and pre-cut surfaces of the sandstone during stable sliding at 0.7 kb confining pressures (Figs. 8 and 9). The criteria for indurated gouge are: 1) it can easily be flaked from the sliding surface, 2) it can withstand small loads without breaking up, and 3) it can support brittle fracture (FRIEDMAN *et al.* [8]). This indurated material consists of 2 to 5 μm quartz particles embedded in a matrix which appears to be isotropic and which has a refractive index of 1.518 ± 0.002. The apparent isotropy may be due to the very fine grain size and lack of birefringence or to amorphous silica which has been fused by heat generated during sliding. Transmission electron micrographs of the indurated gouge appear in ENGELDER and MCKEE [17].

Changes in porosity of the layer of gouge during a sliding friction experiment can be estimated by measuring the change in volume of the pore-pressure reservoir necessary to re-establish the original pore pressure after a certain amount of sliding has occurred. Because Tennessee Sandstone has a low permeability (0.7 millidarcys) a hole is drilled through the center of the specimen to allow easy access of water to the gouge zone. All changes in porosity are assumed to occur only within the gouge and not in the intact rock. The only detectable change in porosity occurs during the generation of the quartz gouge from quartz sand. Here the porosity is reduced from about 30 %, typical of sand compacted at 0.5 kb confining pressure, to 11 %. It remains about the same throughout the remainder of an experiment.

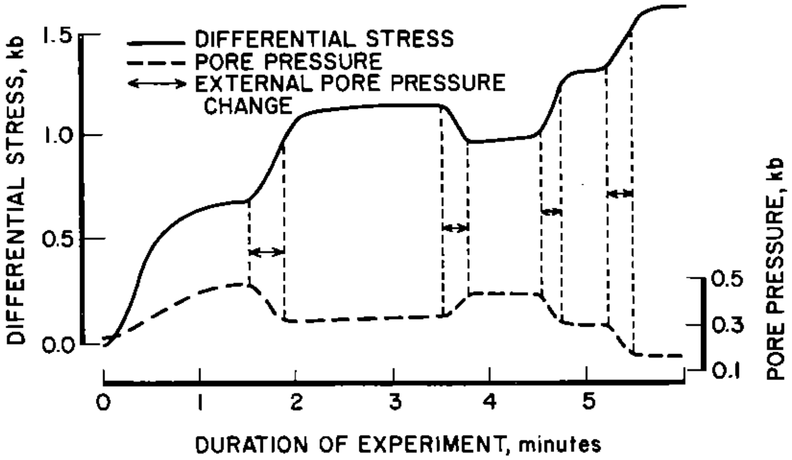

Figure 6

Curves of differential stress and pore-fluid pressure versus time for pre-cut Tennessee Sandstone sliding on an 0.12 cm thick layer of quartz gouge. Confining pressure was 0.8 kb and displacement rate was 10^{-3} cm/sec

Some idea of the effectiveness of the pore-fluid pressure and the relative short-term permeability of the quartz gouge is gained by varying the pore pressure during sliding (Fig. 6). During the initial differential loading of the specimen, the increase in pore pressure is due to the collapse of pores in the sand layer which is cataclastically deforming into a finer-grained gouge. An external pore-pressure adjustment then decreases the pore pressure to 0.2 kb. The result is an increase in the effective pressure within the specimen with a corresponding increase in differential stress necessary to maintain sliding on the quartz gouge. Likewise, an increase in pore pressure causes a decrease in both effective confining pressure and differential stress necessary to maintain sliding. Following each decrease in pore pressure of 0.2 kb over 20 sec, the differential stress continues to increase for an additional 10 sec. This indicates a small lag between the external pressure and pore pressure within the layer of gouge, but permeability is sufficient to allow rapid fluid migration within the gouge.

gouge from sand; stable sliding occurs after the gouge is generated. Whenever the specimen is reloaded at a confining pressure lower than 0.7 kb, stick-slip begins after an initial large stress drop. The sliding behavior during the first two loadings illustrated in Fig. 3 corresponds with that discovered by conventional testing where a stick-slip to stable sliding transition occurs at 0.7 kb confining pressure. This fundamental change in the sliding process occurs regardless of the previous sliding history of the specimen, provided that the confining pressures during sliding are never held between 0.7 and 0.8 kb.

The sliding of the sequentially loaded specimens at 0.7 kb confining pressure is atypical. Stick-slip occurs initially, but is then followed by stable sliding. This behavior occurs only during sequentially-loaded tests; the specimen slides stably at 0.7 kb during the entire conventional experiment. At 0.7 kb the stick-slip to stable-sliding transition seems to be a function of displacement in that a certain amount of stick-slip precedes stable sliding. Also the kinetic coefficient of friction is lower during stick-slip than stable sliding.

During the fourth and fifth cycles (Fig. 3) sliding is stable at confining pressures of 0.5 and 0.3 kb, for which stick-slip is expected. This occurs only during sequential-loading experiments. Stable sliding occurs at confining pressures of less than 0.7 kb only when preceded by slip at between 0.7 and 0.8 kb confining pressure. Slip at 0.7 kb confining pressure results in a fundamental change within the gouge that affects subsequent experiments. The gouge, deformed at 0.7 kb confining pressure during stable sliding, suppresses stick-slip at lower confining pressures, whereas the gouge deformed at 1.0 kb does not. Thus there is more than one process for stable sliding and accompanying gouge deformation.

DIETERICH [2] observes that the static coefficient of friction of rock in contact with gouge increases with the logarithm of the time of contact. A similar behavior is found for stick-slip sliding at 0.5 kb confining pressure on 0.12 cm thick quartz gouge (Fig. 4). At 10^{-5} cm/sec a small amount of stable sliding precedes the stress drop. Stable sliding may precede the stress drop at faster displacements, but the apparatus is not sensitive enough to detect it. SCHOLZ *et al.* [7] have observed stable sliding and then episodic sliding prior to stick-slip if gouge is between sliding surfaces.

An increase in gouge thickness to 0.36 cm results in a decrease in magnitude of stress drops in the stick-slip regime of Tennessee Sandstone on quartz fault gouge. At 1.0 kb this rock slides stably on all thicknesses of gouge between 0.03 and 0.36 cm. The shear stress necessary to cause stable sliding at 1.0 kb confining pressure on all thicknesses of gouge does not vary by more than the experimental error determined from four tests for sliding on 0.12 cm thick gouge. The effect of gouge thickness on the transition from stick-slip to stable sliding was not studied.

The stick-slip to stable sliding transition occurs even when the 0.12 cm thick layer of gouge is water saturated. The principal effect of the saturation is an increase of the magnitude of the stick-slip stress drops with a small amount of preceding stable sliding (Fig. 4). Saturating the gouge has about the same effect as does decreasing the displacement rate from 10^{-3} to 10^{-5} cm/sec. The kinetic coefficient of friction for Tennessee

0.45 cm of sliding displacement the mean differential stress was 3.00 kb with a standard deviation of 0.05 kb.

Cylinders of fractured or pre-cut Coconino Sandstone are also used to evaluate the frictional properties of quartz gouge (Fig. 1). In addition, 5 × 10 cm cylinders of compacted quartz particles less than 63 μm in diameter are used to study the deformation mechanisms of dry quartz aggregates at strain rates between 10^{-4}/sec and 10^{-7}/sec. The aggregate is prepared by crushing sand and sieving out all particles greater than 63 μm. The remaining particles are poured into a polyolefin jacket that is pre-shrunk to a cylindrical shell 5 cm in diameter × 10-cm long.

3. Experimental results

Friction tests

Pre-cut specimens of Tennessee Sandstone stick-slip with stress drops of more than 1.0 kb at confining pressures greater than 0.5 kb (Humston [13]). Large stress drops are observed even after a film of gouge (<0.01 cm) is generated on the sliding surface. In contrast, a 0.12-cm thick layer of gouge between sliding surfaces causes Tennessee Sandstone to stick-slip with stress drops of less than 10^{-1} kb (Fig. 2). Sandstone sliding

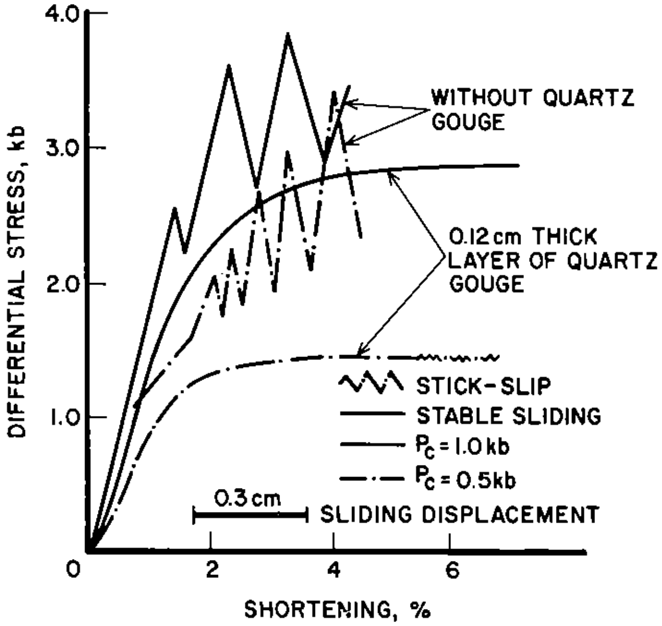

Figure 2

Differential stress versus shortening curves for the sliding of pre-cut Tennessee Sandstone with and without an 0.12 cm thick layer of quartz gouge. Specimens are deformed at room temperature, a constant rate of shortening of 10^{-4}/sec or displacement rate of 10^{-3} cm/sec. Data for Tennessee Sandstone sliding without gouge are from Humston [13]

Some of the frictional properties of rock sliding on gouge are known (BYERLEE and BRACE [1]; DIETERICH [2]), but many details are sketchy. To date observations on the changes in frictional properties with the accumulation of gouge have been limited to experiments in which a small amount of gouge had been generated during the limited displacement of an experiment (BYERLEE [3]; COULSON [4]; JAEGER [5]). In Westerly Granite the frictional force reaches a residual value when frictional wear generates enough gouge to completely separate the sliding surfaces (BYERLEE [3]). The accumulation of gouge generated during initial slip causes a decrease in stress drops during stick-slip sliding (JACKSON and DUNN [6]). Some surfaces have a stable sliding to stick-slip transition when sliding on gouge (BYERLEE and BRACE [1]; SCHOLZ *et al.* [7]). At elevated temperatures an indurated gouge or glass may form between the sliding surfaces thus further modifying the frictional force between them (FRIEDMAN *et al.* [8]). Compacted aggregates, which may simulate gouge, fracture and stick-slip at 7 to 10 kb confining pressure (BYERLEE and BRACE [9]). The coefficient of static friction of surfaces with gouge is time dependent (DIETERICH [2]).

The rate of generation of gouge with displacement is a function of several parameters. For example, quartz gouge is generated at a higher rate at higher confining pressure (ENGELDER [10]). JACKSON and DUNN [6] show that the rate of gouge generation depends on the angle of foliation to the sliding surface as well as the confining pressure. For rocks with higher fracture strengths, less gouge is generated per unit displacement between surfaces than for rocks with lower fracture strengths (COULSON [4]). DIETERICH [2] implies that the volume of gouge generated from a rough surface far exceeds that generated from a smooth one, when they are both displaced the same amount at the same normal stress.

Faults may contain any one of a number of gouges depending on the mineralogy of the country rock from which the gouge was generated. Gouge from one section in the San Adreas fault contains predominantly montmorillonite, chlorite and serpentine (NASON and TOCHER [11]). In contrast, some gouge from the Muddy Mountain Thrust contains only quartz particles (ENGELDER [10]). Gouge may also consist of carbonate minerals or of combinations of several different minerals.

2. *Experimental procedure*

This systematic study of the frictional effects of a fault gouge between intact rock is restricted to one type of gouge and, so, does not define the mechanical behaviors of all gouges. In order to document the effects of gouge, the frictional properties of the rock without gouge should be well known, and the gouge generated from that rock should be: 1) common in nature, 2) easy to work with in the laboratory, and 3) amenable to petrographic observation. Quartz fault gouge has these desirable characteristics and the frictional properties of Tennessee Sandstone are well known (LOGAN *et al.* [12]; HUMSTON [13]; BLACKWELL [14]; FRIEDMAN *et al.* [8]).

Experimental quartz fault gouge is generated by shearing a 0.17 cm thick layer of