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Microscopic Wear Grooves on Slickensides: Indicators of Paleoseismicity

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The frictional wear of Westerly granite surfaces polished with 0.3-μm Linde A polishing compound was studied on triaxial compression specimens for slip up to 3 mm at confining pressures to 2.9 kbar. A stable sliding to stick-slip transition occurs at 0.3-kbar confining pressure. Frictional wear occurs on the polished sliding surface only when the specimens undergo stick-slip. The initial wear on the surface consists of microscopic carrot-shaped grooves whose length rarely exceeds the maximum slip accompanying one stress drop during stick-slip sliding. The preferred orientation of the carrot-shaped grooves is such that the tip points in the direction of motion of the surface containing the grooves. A groove length equivalent to individual slip distance results in a small groove length to total slip ratio (<1:5) that may be used as a criterion for stick-slip sliding. A small groove length to total slip ratio also occurs on two natural slickenside surfaces, and on the basis of the laboratory experiments these natural surfaces are thought to be samples from fault zones that were once seismically active. The experimental observation that maximum groove length closely approximates the slip during the seismic event suggests that the seismic moment of prior earthquakes on a fault may be calculated without prior knowledge of seismicity.

The current earthquake source model assumes that a discrete amount of slip occurs on a preexisting fault plane during a seismic event and that events may occur repeatedly on the same fault plane. Support for these assumptions includes the following: (1) seismic activity occurs within known fault zones instead of randomly in the lithosphere [*Barazangi and Dorman*, 1969], (2) theoretically calculated stress drops for earthquakes are considerably less than would be the case if the earthquake occurred with the fracture of intact rock [*Brace and Byerlee*, 1966], and (3) source parameters for experimentally observed frictional sliding of rocks are in many ways equivalent to earthquake source parameters [*Johnson et al.*, 1973]. On the basis of the earthquake source model, frictional wear occurs during seismic events, and therefore some well-exposed but presently inactive faults should contain outcrop features that indicate paleoseismicity. The purpose of this work is to indicate the nature of frictional wear during seismic events in natural fault zones.

Slickensides are a common manifestation of faulting in the upper crust of the earth. Striations, grooves, and steplike protuberances are all macroscopic frictional wear features that develop on slickensides [*Tjia*, 1964]. On a microscopic scale the generation of gouge by cataclasis occurs as a result of frictional wear during faulting [*Engelder*, 1974*a*]. Wear grooves on slickensides often have the shape of an isosceles triangle with very long sides that converge to a tip. Rock fragments are sometimes located at the opposite end of the groove from the tip [*Tjia*, 1964, Figure 3].

Some frictional wear features are used to infer a sense of slip on slickensides that have no features that correlate across the slickensides. The sense of slip on faults is inferred from the orientation of prod marks, tension fractures, crescentic gouges, chatter marks, and slickenside roches moutonnées [*Tjia*, 1967]. However, *Tjia* [1967] warns that triangular grooves may be ambiguous indicators of the sense of slip if they are used independently.

Experimental frictional wear of rocks has been documented by *Byerlee* [1967*a*], *Norris and Barron* [1969], *Coulson* [1970], *Dieterich* [1972], *Sholz et al.* [1972], *Jackson and Dunn* [1974], *Friedman et al.* [1974], and *LaFountain and Dunn* [1974]. All noted that a fine layer of gouge separates sliding surfaces after sliding about 5 mm. Experimentally produced wear grooves often have long sides that converge to a tip [*Jackson and Dunn*, 1974]. The tip points in the slip direction of the surface containing the groove. These grooves increase in depth and width in a direction opposite the motion of the surface containing the groove. *Coulson* [1970] suggests that some wear grooves result from Riedel shear fracturing. *Jackson et al.* [1974] suggest that grooves are generated from Hertzianlike fractures caused by a sliding asperity. Additional indicators of the sense of slip include the orientation of triangular patches of gouge on experimentally fractured surfaces [*Norris and Barron*, 1969, plate 10], the orientation of welded gouge relative to unwelded gouge, and the orientation of glass fibers [*Friedman et al.*, 1974].

Only a few attempts have been made to establish a mode of faulting (seismic versus aseismic) based on the frictional behavior of the fault material. Most notable are sliding friction experiments that indicate that the mineralogy of the rock within the fault zone may be used to infer a certain type of faulting [*Byerlee and Brace*, 1968; *Logan et al.*, 1973]. Limestone and clay minerals are commonly associated with aseismic faulting because stable sliding occurs, whereas quartz-bearing rocks may be associated with seismic faulting because of their tendency to stick-slip. However, stable sliding has been observed for rocks sliding on quartz gouge [*Engelder*, 1974*b*], and a transition from stick-slip to stable sliding of Tennessee sandstone occurs as temperature increases from 24° to 410°C [*Friedman et al.*, 1974].

Experimental Studies

Triaxial compression experiments were used in this investigation of frictional wear; 1.2-cm-diameter by 2.5-cm-long cylinders of Westerly granite were slid on saw cuts inclined at 35° to the cylindrical axis. The experimental confining pressures on the dry sample were between 0.1 and 2.7 kbar with an average sliding displacement rate of 10^{-3} cm/s. The sliding surface was polished with a series of progressively finer abrasives. A 0.3-μm Linde A polishing compound was used for the final polish. Highly polished surfaces were used in order to study surficial wear and model slickensides. An advantage of polished surfaces is that in comparison with rougher surfaces, more displacement can be achieved on polished surfaces before enough gouge is generated to cover the surface.

The experiments consisted of sliding polished specimens various distances up to 3 mm and subsequently observing the frictional wear that is unique to stick-slip. The observations were accomplished with a reflecting light microscope. Topographic variations such as wear tracks appear as dark features from which light is not reflected into the objective of the microscope (Figure 1).

Wear tracks form on surfaces during stick-slip and are absent in those instances when only stable sliding occurred. Because Westerly granite slides stably at low confining pressure and stick-slips at higher confining pressure [*Byerlee,* 1967*a*], low confining pressure experiments were used to generate specimens on which stable sliding occurred. No surface damage is observed on surfaces of highly polished Westerly granite, which slides stably at 0.1- and 0.2-kbar confining pressure. Surface wear accompanies stick-slip, which occurs above 0.3-kbar confining pressure.

Surface wear during stick-slip at low confining pressures consists of a small number of wear grooves, scratches, and clumps of gouge less than 0.01 mm in diameter. At higher confining pressures the stick-slip stress drops become larger, and the wear is more plentiful. A quantitative indication of the variation of surface wear with confining pressure is the number of wear grooves formed on the two sliding surfaces per stress drop (Figure 2). The number of wear grooves generated per stress drop approaches zero at the stable sliding to stick-slip transition. At the highest confining pressure observed, thousands of grooves form per stick-slip stress drop. Thus the generation of microscopic wear grooves on highly polished surfaces is an indication of the occurrence of stick-slip.

Wear grooves on highly polished Westerly granite narrow to a tip pointing in the direction of motion of the surface containing the groove (Figure 1). The outlines of these grooves resemble carrots and will be referred to as carrot-shaped grooves. Since not all grooves had the typical outline, individual grooves are not reliable indicators of the sense of slip. However, because carrot-shaped grooves with the correct orientation predominate on any surface, the correct sense of slip is easily determined on the basis of the preferred orientation of several grooves.

Observations with a scanning electron microscope indicate that many grooves have a width-to-depth ratio of 5 or greater and are filled with fragments less than 5 mm in diameter. Grooves in feldspar grains are deeper and as much as 15% longer than grooves in quartz grains. This difference in the character of grooves is attributed to the difference in scratch hardness between feldspar and quartz [*Engelder,* 1974*c*].

The length of individual grooves is considerably less than the total slip on the sliding surface. In order to clarify the relation between microscopic groove length and slip during the experiment the number of times that the surface slipped and distance during individual slips were varied from experiment to

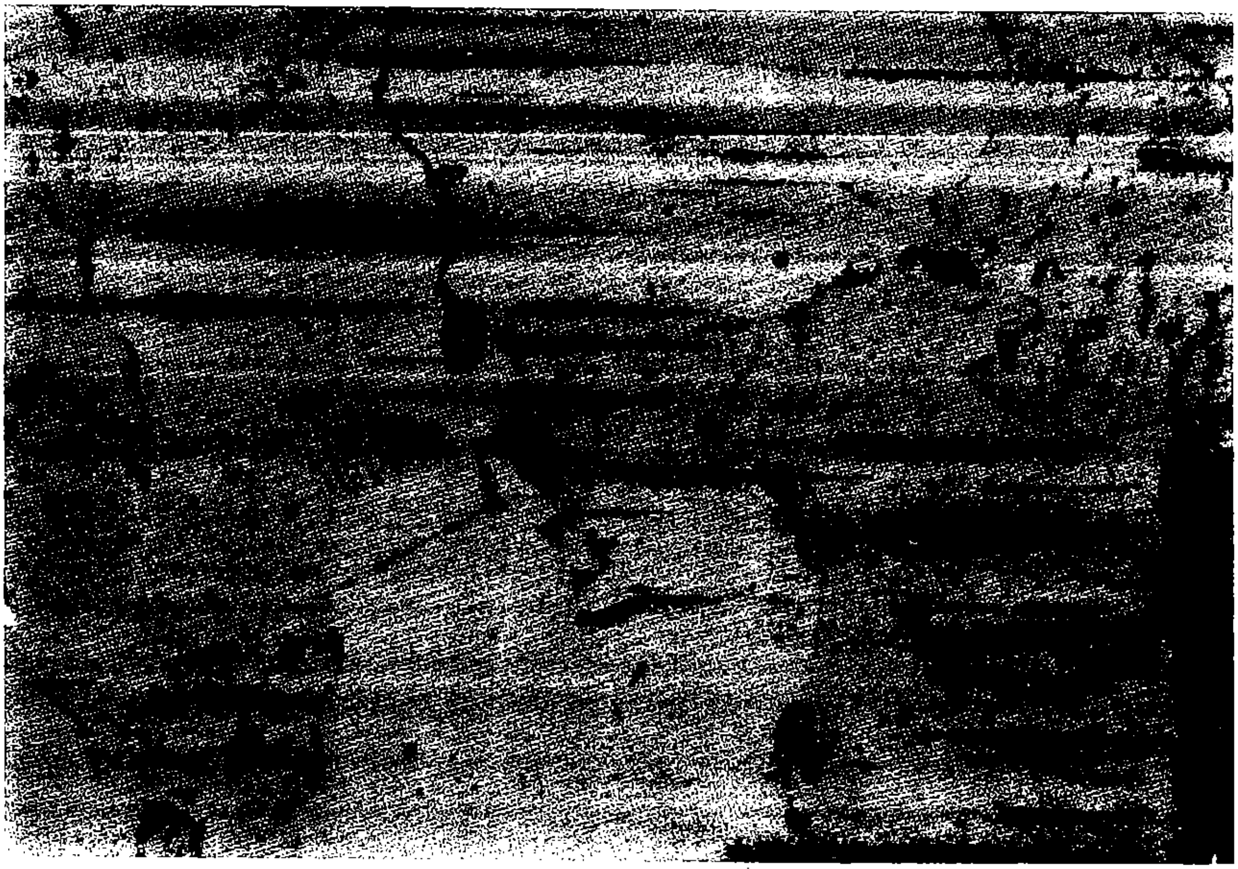

Fig. 1. A reflected light micrograph of an experimental sliding surface of Westerly granite. Grooves are about 0.2 mm long, and direction of slip of surface containing grooves is from left to right; that is, overlying surface moved from right to left. Scale line is 0.1 mm.

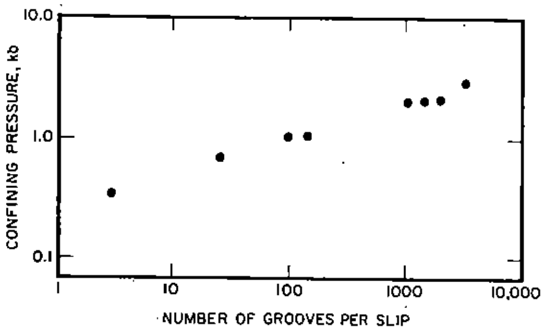

Fig. 2. Number of grooves generated on the two sliding surfaces of Westerly granite per stick-slip event versus confining pressure of the experiment.

experiment. This change was accomplished by varying the confining pressure from one experiment to the next. Most wear groove lengths are less than or equal to the length of one slip regardless of the total slip during the sliding friction experiment. For each experiment, 300 or more grooves on feldspar grains were measured from the two sliding surfaces, and their distributions are illustrated in Figure 3. Because each sample slipped a number of times with a variety of slip lengths, grooves from specific slip events could not be distinguished. A sample permitted to slip once had grooves with various lengths up to the distance of the slip. Thus the broad distribution of groove lengths for each experiment is due to both a variety of slip lengths and a variety of groove lengths for individual slips. The important point is that the mechanism causing the groove affects the sliding surface for a distance up to the length of one slip during the stick-slip experiment.

The effect of increasing the length of slip is illustrated in the two histograms for experiments at 2.9-kbar confining pressure (Figure 3). In the experiment for the top histogram, two slips occurred that were less than 0.08 mm; the groove lengths are distributed in a corresponding maximum concentration. The same maximum is observed when long as well as short events occur. In the lower histogram the groove length distribution shows a maximum that corresponds to the shorter slips of that experiment, but additional grooves have lengths up to 0.21 mm and correspond to the longer slips. The correlation of the single maximum in the top histogram and the stronger maximum in the lower histogram indicates that the groove length distribution has contributions from all slip events. However, there are a larger number of short groove lengths because short grooves are formed during long slips and not vice versa.

In samples with a large number of grooves longer than 0.17 mm the long grooves start to obliterate the shorter ones. For this reason the longer grooves are counted, but many of the short ones are not; thus the groove length maximum is not at the short end of the length scale in the case of the two histograms for experiments at 2.0-kbar confining pressure (Figure 3).

NATURAL FAULT SURFACES

On the basis of the experimental studies, microscopic wear grooves indicate (1) a sense of slip and (2) repeated slip if the groove lengths are considerably less than total slip. To search for a natural counterpart to these experimental surfaces, microscopic wear features on a highly polished slickensided sandstone with 50 mm of slip were examined. The sample comes from the Mesa Rica sandstone in the Bonita normal fault zone near Tucumcari, New Mexico [*Stearns*, 1972]. This slickenside forms within a layer of gouge up to 1 mm thick. The generation of the slickenside from intact sandstone is a two-stage process. First, a fracture propagates through the sandstone, and slip occurs along the fracture to generate as much as a 1-mm-thick layer of gouge. Then the gouge becomes cemented, but during or after cementation, one surface is polished by further slip. Slip on the polished surface of cemented gouge results in wear grooves that are carrot-shaped and orient so that their tips point toward the known sense of slip of the surface containing the groove (Figure 4). The longest grooves on the slickensided surface are 5 mm.

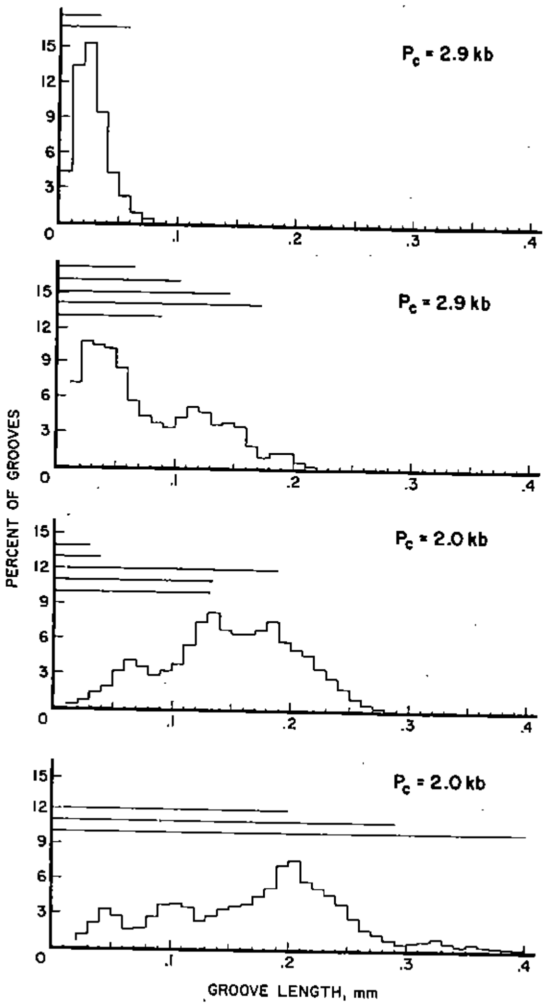

Fig. 3. Histograms of percentage distribution of groove lengths in feldspar grains on Westerly granite sliding surfaces. At least 300 lengths are included for each histogram. Number and length of individual slip lengths during the stick-slip experiment are indicated by horizontal lines above histograms. The top horizontal line is the first slip, and the bottom is the last. P_c is confining pressure of individual experiment.

Slip on this slickenside occurred a length of time after the initial generation of the fault gouge. Total offset associated with the slickenside surface and gouge layer is 50 mm. However, it is not possible to measure the amount of slip during either the initial generation of the 1-mm-thick layer of gouge or the generation of wear grooves on the slickenside. The 5-mm length of wear grooves is an indication of the minimum slip on the slickenside.

A slickensided surface with an unknown sense and amount of slip further illustrates the nature of natural microscopic grooves. The specimen comes from Tintic quartzite within the

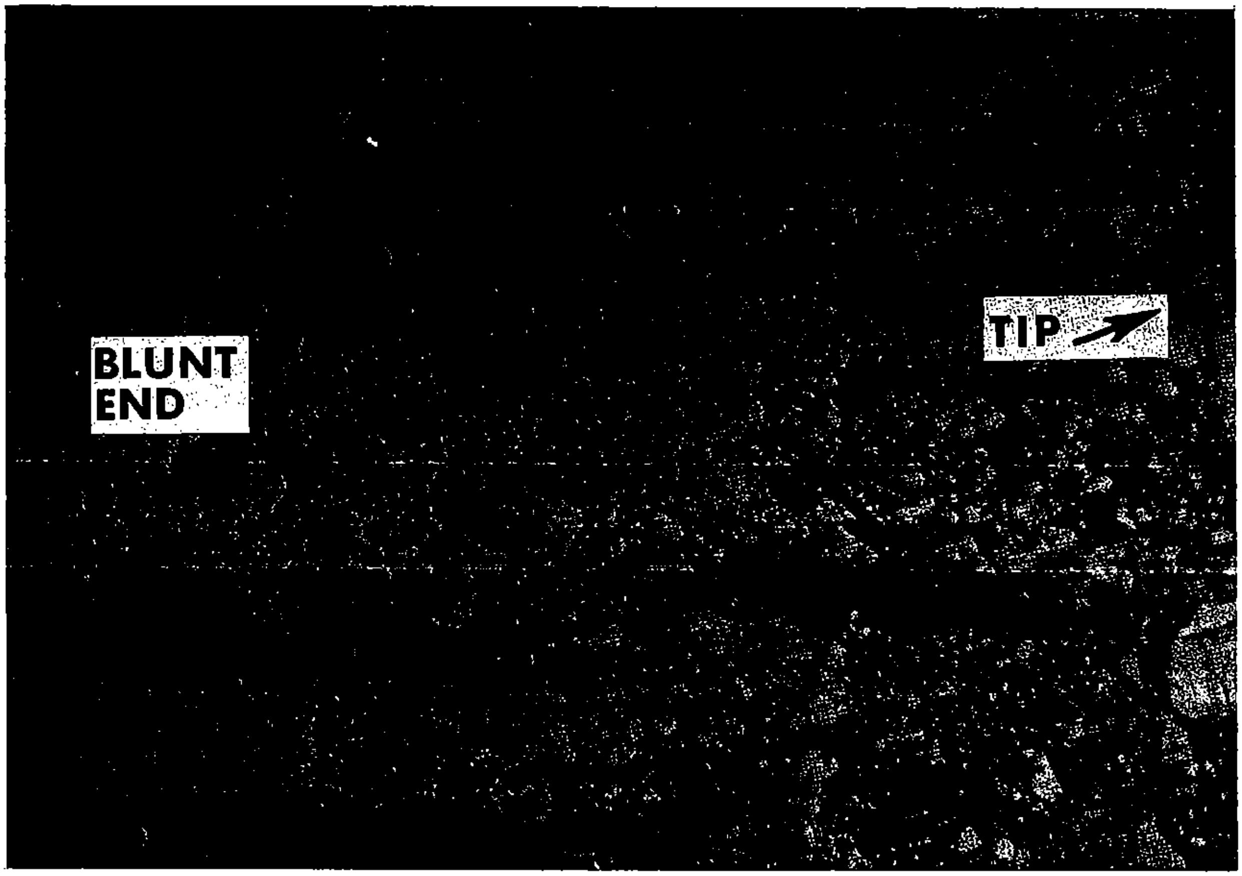

Fig. 4. A reflected light micrograph of a natural slickenside surface of Mesa Rica sandstone with wear grooves of 2 mm. Known slip direction of surface containing grooves is from left to right. Scale lines are 0.5 mm.

Eureka standard fault zone near Eureka, Utah [*Morris*, 1964]. This slickenside also forms within a layer of cemented gouge. In reflected light, many microscopic grooves are observed to terminate with a fragment or pit and have a carrot-shaped outline (Figure 5). The nature of the Tintic quartzite grooves is comparable to those illustrated by *Tjia* [1964, Figure 3]. In this case the total offset is assumed to be many times the length of the 0.5-mm microscopic grooves primarily because 0.5 mm of slip is not adequate to generate highly polished slickensides on quartzose rocks.

DISCUSSION

Stick-slip mechanism. A possible mechanism for stick-slip is that slip occurs when interlocked asperities fail brittly [*Byerlee*, 1967*b*, 1970]. Observations presented here support this idea.

The mechanism of stick-slip for highly polished Westerly granite may be inferred from the morphology of wear grooves in the feldspar grains and their relation to the length of individual slips. Grooves form because asperities on an opposite surface or gouge particles caught between surfaces plow into a surface. In other words, the sliding surface moves under the plowing asperity or trapped gouge particle, so that the resulting grooves move away from the plow in the direction of slip. Asperities or gouge particles plow deeper into the surface as slip increases. This is seen as a track that gets wider, thus deeper, from the point where plowing of the asperity initiates (Figure 1). The plowing slows and eventually stops the sliding surfaces. Shearing of asperities at the initiation of slip is a likely mechanism for the instability preceding the rapid acceleration during subsequent slip. This is indicated by the observation that grooves are terminated with a blunt end at a distance from the tip less than or equal to the length of an individual slip during the stick-slip experiment. Asperities that do not shear within grooves at the initiation of slip either continue to plow or climb out of their grooves. If asperities had continued to plow, the grooves would have been much longer than one slip length. If asperities had climbed out of their grooves, the end of the grooves would have a tip pointing in the direction of motion for asperities. In addition, the asperities that climb out of their grooves might plow a second groove in line with the first. Since in-line grooves are rare, it is believed that asperities plow into a surface only once and shear. The surfaces are again decelerated as other asperities and gouge particles plow into the opposite surfaces.

The mechanism of asperity plowing and shearing is not quite as simple as the above explanation. For one slip there are a variety of groove lengths that may be due to either the shearing of asperities before the surface is completely stopped or the initiation of plowing after a certain amount of slip has occurred. The latter explanation is more desirable, since the above description requires that some asperities slide on the surface without plowing for several slips before penetrating the surface. In addition, there are instances where grooves are longer than the longest slip (Figure 3). In this case the grooves are not terminated by a blunt end but rather have tips on both ends. This indicates that a few asperities climb out of their grooves, and so the sliding surfaces separate ever so slightly at the initiation of slip.

The asperities for the sliding friction experiments are

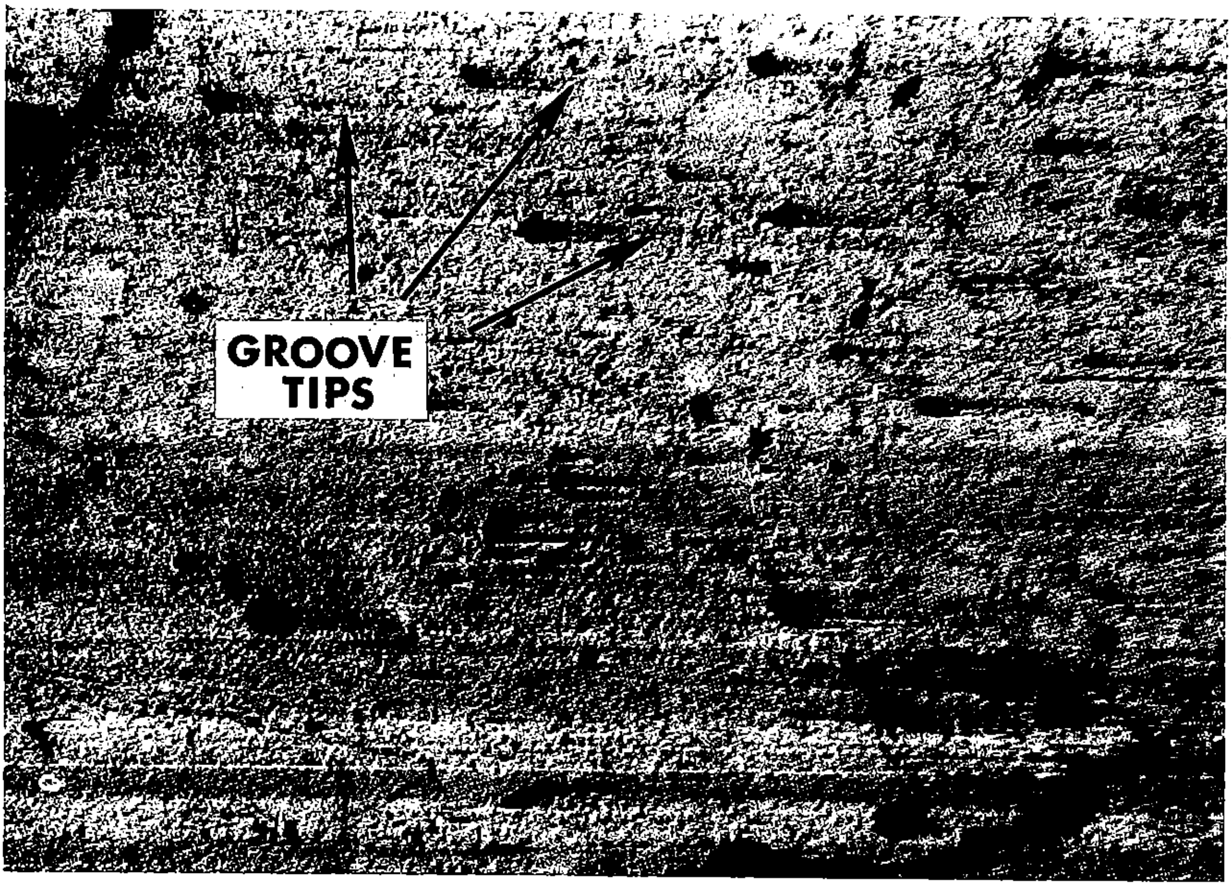

Fig. 5. Micrograph of a natural slickenside surface of Tintic quartzite in reflected light. Grooves are up to 0.4 mm long, and inferred slip direction of surface containing grooves is from left to right. Scale line is 0.5 mm.

thought to be grain edges, particularly where grains of different mineralogy are in contact. The idea is that grains with different elastic properties deform incongruously, this behavior thus creating a slight difference in height at the grain contact. The depth to width ratio of grooves, 1:5, is indicative of relatively blunt asperities as might be expected for the shape of grain boundaries. Once gouge is present between the sliding surfaces, much sharper and deeper grooves are seen in the sliding surface. For example, the grooves on the surface of Tintic quartzite slickensided surfaces are routinely deeper and terminated by fragments.

The relation between wear grooves and asperities may explain why the coefficients of static and dynamic friction differ. The frictional force opposing the initial acceleration of surfaces in static contact appears to be related to the shear strength of the asperities penetrating the opposite surface. In contrast, the frictional force during slip appears to be related to the force required to plow the grooves through the opposite surface. Because of differing frictional mechanisms it seems unlikely that the frictional forces are equal. For example, in stick-slip the coefficient of static friction is higher than the dynamic one.

Significance of microscopic grooves on natural slickensides. Total slip associated with the slickenside from the Bonita fault is 5 cm. The fraction of that slip that occurred on the slickenside may be estimated by using experimental and field data on the generation of gouge by frictional wear. For example, a 0.1-cm-thick layer of quartz gouge is experimentally generated in 0.8 cm of displacement along a fracture in sandstone at 0.5-kbar confining pressure [*Engelder,* 1974*a*]. Some shear fractures within the Bonita fault zone have not developed slickensides. Within these fractures a 0.1-cm-thick layer of gouge is generated in 1.5 cm of slip. On the assumption that 1.0–1.5 cm is a reasonable estimate of slip for the generation of 0.1 cm of gouge in the Mesa Rica sandstone of the Bonita fault, 3.5–4.0 cm of slip occurred on the slickenside surface after the gouge was generated and cemented. Thus the groove lengths on the slickenside are about an order of magnitude less than the slip on the polished surface.

Natural and experimental microscopic wear grooves have the same morphology and a length only a fraction of the total slip of the associated highly polished sliding surface. On the basis of this similarity of natural to experimental wear grooves, slip along the natural slickenside from the Bonita fault may have been of the stick-slip mode; therefore the Bonita fault may have been seismically active. The same may be said of the Eureka standard fault zone. In both cases the slip distance for seismic events may be estimated from the lengths of the longest microscopic wear grooves. The same frictional mechanism seems to have occurred during both natural and experimental sliding. This finding supports *Brace and Byerlee*'s [1966] argument that experimental stick-slip has a natural counterpart, an earthquake.

Knowledge of the length of slip $\bar{u}$ during previous seismic events based on groove length can be used to obtain a seismic moment M_0 for the earthquake [*Aki,* 1966]:

$$M_0 = \mu \bar{u} A$$

where A is the area of the fault surface, μ is the shear modulus, and $\bar{u}$ is the average displacement of one slip on the fault. The possibility exists therefore that seismological parameters of a fault may be correlated directly with frictional features of the fault. For example, the slickenside surface within the Bonita fault zone had an area of about 10^7 cm². If $\mu = 3 \times 10^{11}$ dyn/cm² and a seismic event had a displacement of 0.5 cm, $M_0 = 1.5 \times 10^{18}$. This M_0 is probably small in relation to that for an event along the main fault plane that may have an area as large as 10^{12} cm² and more than 0.5 cm of slip during a seismic event.

Macroscopic wear grooves. The literature on frictional experiments contains descriptions of wear grooves that are not compatible with the relation between microscopic grooves and stick-slip presented in this paper. For example, *Coulson* [1970] describes wear grooves generated during stable sliding. *Jackson and Dunn* [1974] describe grooves that develop on surfaces covered with gouge and have lengths that appear to be comparable to the total slip rather than the lengths of slip during individual stick-slip events. In addition to the plowing model for groove formation presented in this paper, another model is that the asperity acts as an indenter causing Hertzianlike fractures; material is then removed or compacted into the site [*Jackson et al.*, 1974]. Wear grooves may be generated during frictional wear regardless of the sliding mode. Stable sliding without frictional wear apparently occurs under special circumstances that include the necessity for well-polished sliding surfaces. Stick-slip is complicated enough that its mechanism may change with such parameters as the initial surface roughness, asperity size, or amount of uncemented gouge on the sliding surface.

Because of the complicated circumstances involved in the generation of macroscopic wear grooves, all natural wear grooves are probably not going to have the same significance as microscopic wear grooves on slickensides. Further field and experimental work is required in order to learn if there is a type of macroscopic groove on large fault planes that may be used for distinguishing seismic from aseismic faults and for estimating the amount of slip during seismic events.

SUMMARY

1. Wear grooves are found on highly polished surfaces of Westerly granite only when specimens undergo frictional sliding above 0.3-kbar confining pressure. This pressure marks the transition from stable sliding to stick-slip for these specimens of the granite.

2. The lengths of wear grooves on experimental sliding surfaces of Westerly granite are less than or equal to individual slips of a stick-slip experiment. This relation implies that slip surfaces with wear grooves considerably shorter than total slip were seismic and that the maximum slip for past seismic events of unknown magnitude and slip may be determined by the length of similar grooves on the sliding surface. Knowledge of slip of a past event permits a reasonable estimate of the seismic moment and therefore also of the magnitude of a seismic event on the fault.

3. Wear grooves on two natural slickenside surfaces have lengths considerably less than the total displacement for each surface. Hence they were probably seismic faults at one time.

4. On slickensided surfaces with a known sense of slip the preferred orientation of the wear groove tip points in the direction of motion of the surface containing the groove.

5. The shape of the wear grooves also suggests that the static friction is equivalent to the shearing of asperities at the initiation of slip. The dynamic friction may be related to the plowing of asperities into the surface to decelerate motion.

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REFERENCES

Aki, K., Generation and propagation of G-waves from the Niigata earthquake of June 16, 1964, 2, Estimation of earthquake moment, released energy, and stress-strain drop from G-wave spectrum, *Bull. Earthquake Res. Inst. Tokyo Univ., 44,* 73–88, 1966.

Barazangi, M., and J. Dorman, World seismicity maps compiled from ESSA, Coast and Geodetic Survey, epicenter data, 1961–1967, *Bull. Seismol. Soc. Amer., 59,* 369–380, 1969.

Brace, W. F., and J. D. Byerlee, Stick-slip as a mechanism for earthquakes, *Science, 153,* 990–992, 1966.

Byerlee, J. D., Frictional characteristics of granite under high confining pressure, *J. Geophys. Res., 72,* 3639–3648, 1967*a*.

Byerlee, J. D., Theory of friction based on brittle fracture, *J. Appl. Phys., 38,* 2928–2934, 1967*b*.

Byerlee, J. D., The mechanics of stick-slip, *Tectonophysics, 9,* 475–486, 1970.

Byerlee, J. D., and W. F. Brace, Stick-slip, stable sliding, and earthquakes—Effect of rock type, pressure, strain rate, and stiffness, *J. Geophys. Res., 73,* 6031–6037, 1968.

Coulson, J. H., The effects of surface roughness on the shear strength of joints in rock, *Tech. Rep. MRD-2-70,* p. 283, Mo. River Div., Corps of Eng., Omaha, Nebr., 1970.

Dieterich, J. H., Time-dependent friction in rocks, *J. Geophys. Res., 77,* 3690–3697, 1972.

Engelder, J. T., Cataclasis and the generation of fault gouge, *Geol. Soc. Amer. Bull., 85,* in press, 1974*a*.

Engelder, J. T., Coefficients of friction and their values for sandstone sliding on quartz gouge, in *Proceedings of the 3rd International Congress of the International Society of Rock Mechanics,* National Academy of Sciences, Washington, D. C., in press, 1974*b*.

Engelder, J. T., Effect of scratch hardness on frictional wear and stickslip of Westerly granite and Cheshire quartzite, in *Proceedings of NATO Advanced Study Institute on Petrophysics,* John Wiley, New York, in press, 1974*c*.

Friedman, M., J. M. Logan, and J. A. Rigerts, Glass indurated quartz gouge in sliding-friction experiments on sandstone, *Geol. Soc. Amer. Bull., 85,* 937–942, 1974.

Jackson, R. E., and D. E. Dunn, Experimental sliding friction and cataclasis of foliated rocks, *Int. J. Rock Mech. Mining Sci., 11,* in press, 1974.

Jackson, R. E., L. J. LaFountain, and M. Swain, Sliding surface features, Hertzian fractures, and stick-slip (abstract), *Eos Trans. AGU, 55,* 428, 1974.

Johnson, T., F. Wu, and C. H. Scholz, Source parameters for stick-slip and for earthquakes, *Science, 179,* 278–280, 1973.

LaFountain, L. J., and D. E. Dunn, Anisotropy and the coefficient of sliding friction (abstract), *Eos Trans. AGU, 55,* 428, 1974.

Logan, J. M., T. Iwasaki, M. Friedman, and S. A. King, Experimental investigation of sliding friction in multilithologic specimens, in *Geological Factors in Rapid Excavation, Eng. Geol. Case Hist. 9,* edited by H. J. Pincus, pp. 55–67, Geological Society of America, Boulder, Colo., 1973.

Morris, H. T., Geology of the Eureka quadrangle, Utah and Juab counties, Utah, *U.S. Geol. Surv. Bull. 1142-K,* K1–K29, 1964.

Norris, D. K., and K. Barron, Structural analysis of fractures on natural and artificial faults, Proceedings of Conference on Research in Tectonics, *GCS Pap. 68-52,* pp. 136–167, Geol. Surv. of Can., Ottawa, Ontario, 1969.

Scholz, C., P. Molnar, and T. Johnson, Detailed studies of frictional sliding of granite and implications of the earthquake mechanism, *J. Geophys. Res., 77,* 6392–6406, 1972.

Stearns, D. W., Structural interpretation of the fracture associated with the Bonita fault, *New Mex. Geol. Soc. Guideb., 23,* 161–164, 1972.

Tjia, H. D., Slickensides and fault movements, *Geol. Soc. Amer. Bull., 75,* 683–686, 1964.

Tjia, H. D., Sense of fault displacements, *Geol. Mijnbouw, 46e,* 392–396, 1967.

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