Effect of Scratch Hardness on Frictional Wear and Stick-Slip of Westerly Granite and Cheshire Quartzite

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INTRODUCTION

Stick-slip is a reasonable laboratory analogue for an earthquake in the upper crust (Brace and Byerlee, 1966). A stick-slip mechanism for earthquakes is appealing because the stress drop calculated for earthquakes is much closer to the stress drop for stick-slip than for the fracture of intact rock (Byerlee and Brace, 1968). Many earthquakes are associated with pre-existing fault zones such as the San Andreas fault of California (Eaton *et al.*, 1970) and so are associated with rocks which already have sliding surfaces. In addition the dynamic behaviour of stick-slip is like that of earthquakes; the particle velocity of stick-slip is 2 to 50 cm/sec and the rupture velocity is several km/sec (Johnson *et al.*, 1973).

A mechanism of stick-slip of rock is related to the frictional wear of rock by brittle fracture (Byerlee, 1967). Byerlee (1967, 1970) proposes that asperities on surfaces in contact become locked and sliding occurs only when the asperities shear off. The static frictional force may be equated with the shear strength of the interlocked asperities.

Shearing of asperities is the mechanism of stick-slip on highly polished Westerly granite (Engelder, 1974). The initial frictional wear of highly polished Westerly granite consists of wear tracks (mainly grooves) shaped with the outline of a carrot with a tip pointing in the direction of slip of the surface containing the groove and a blunt end into which an asperity has indented (Figure 1). The groove lengths are less than or equal to the slip distance during one discrete slip or stick-slip event. The grooves are considerably shorter than total slip on a Westerly granite surface which has been subjected to several stick-slip events. Because of the shape and length of wear grooves, Engelder (1974) suggests that the grooves are generated by the ploughing of asperities

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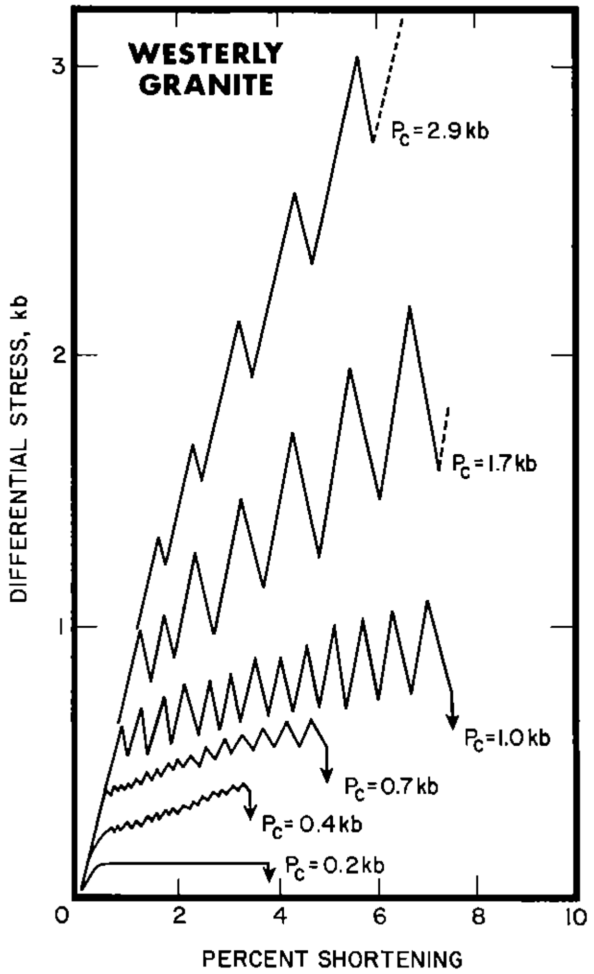

Figure 2. Differential stress versus shortening curve for the sliding of Westerly granite at various confining pressures.

Confining pressure affects the type of frictional sliding of both highly polished Westerly granite and Cheshire quartzite. For Westerly granite stable sliding occurs at confining pressures below 0.3 kb whereas stick-slip occurs above 0.3 kb (Figure 2). For each stick-slip experiment a slight to very marked increase in differential stress is necessary to initiate each successive slip. In contrast to the granite, highly polished Cheshire quartzite goes through a stable sliding to stick-slip transition at a much higher confining pressure (2.5 ± 0.2 kb).

To substantiate ideas on why the stable sliding to stick-slip transition is a function of lithology, Westerly granite and Cheshire quartzite were slid on each other at 1 and 2 kb confining pressure. Dilithologic experiments were prepared by lapping a saw cut sliding surface of quartzite against a saw cut sliding surface of granite. The effect of sliding the quartzite on the granite is illustrated in Figure 3. At both 1.0 and 2.0 kb confining pressure Cheshire quartzite slides stably on itself but when slid on Westerly granite stick-slip occurs. The differential stress necessary to initiate slip of Cheshire quartzite on Westerly granite is much less than for Westerly granite on itself.

The static coefficient of friction (μ) at the initiation of slip of Westerly granite on itself follows a slightly decreasing trend with the increase of normal stress (Figure 4). In contrast μ for Westerly granite after 0.3 mm of slip on surfaces that were initially polished increases with confining pressure. As a result of these trends the static coefficient of friction of highly polished Westerly granite varies more per unit displacement at higher confining pressure.

FRICTIONAL WEAR

Engelder (1974) shows that frictional wear on highly polished Westerly granite accompanies stick-slip and occurs only for sliding above 0.3 kb confining pressure. The same relation between wear and stick-slip occurs with the sliding of Cheshire quartzite except that wear and stick-slip occur only at confining pressures above 2.5 ± 0.2 kb.

Figure 5. Reflected-light micrograph of Westerly granite. Sliding surface displaced 2 mm at 2.0 kb confining pressure.

a result quartz grains are accented in reflected light as those grains with a high reflectivity and few tracks (Figure 5).

Initial measurements of the lengths of the carrot-shaped wear tracks on Westerly granite indicate that most are less than or equal to one slip during a stick-slip experiment (Engelder, 1974). Furthermore, wear tracks on feldspar are slightly longer than those on quartz grains (Figure 6). On either mineral the length of most tracks is less than or equal to the longest slip during a series of stick-slips. The broad distribution of track lengths for the experiments

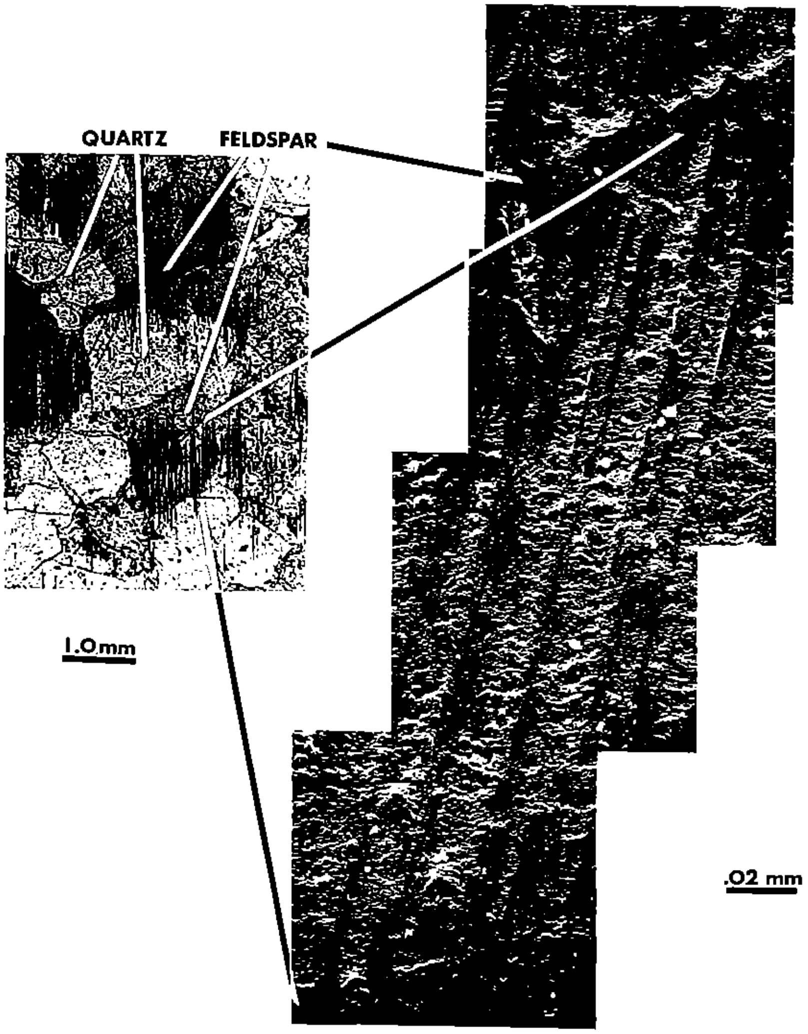

Figure 7. Reflected-light and S.E.M. micrograph of grooves in feldspar. 0.005–0.01 mm white particles in and between grooves are quartz fragments. Surface containing grooves moved toward top of micrograph.

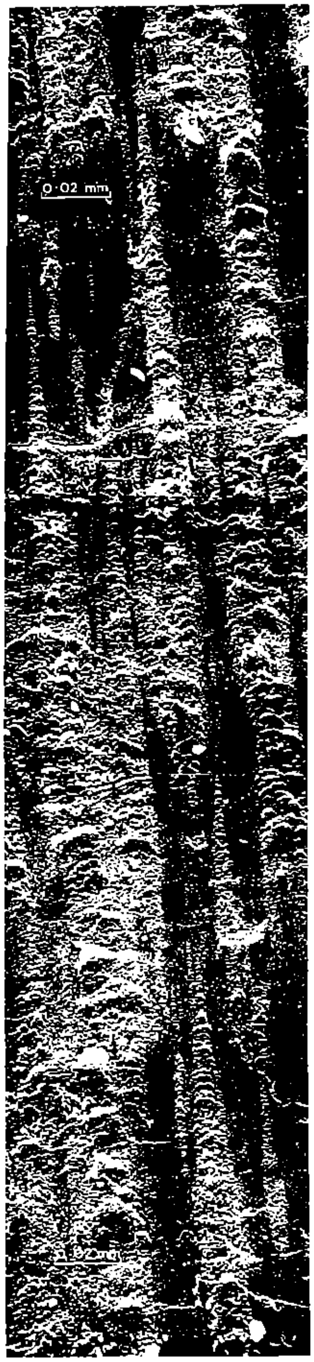

Figure 9. S.E.M. micrograph of scratches on a quartz grain caused by quartz asperities. Surface containing scratches moved toward top of micrograph.

that a large contribution to the frictional force of the highly polished granite is due to the ploughing of asperities into feldspar grains.

Speculation is necessary to explain why wear tracks occur on quartz grains of Westerly granite at confining pressures for which Cheshire quartzite slid stably and no wear tracks were generated. Edges of grains are chipped and rounded on highly polished Westerly granite and thus have been sheared during slip. Sheared grain boundaries are the location of asperities. Presumably a quartz asperity of a certain height is necessary in order to scratch quartz grains on the opposite surface. The elastic stiffnesses of plagioclase and K-feldspar vary more with crystallographic orientation than do the stiffnesses of quartz. When a normal load is applied to adjacent grains of feldspar and quartz these grains are more likely than adjacent grains of quartz to deform elastically in such a manner that a step appears at the grain boundary. Although quartz is elastically anisotropic, much larger normal loads are required before a step is generated which is equivalent in height to that expected for the boundary between a quartz and feldspar. Thus much higher normal loads are required before Cheshire quartzite starts to wear and stick-slip. Slight grain boundary asperities may also result from differential wear of quartz and feldspar during sample preparation.

The longer wear tracks in feldspar grains are believed to be due to the lower scratch hardness of feldspar. The idea is that asperities survive for a longer scratch distance because feldspar into which the asperity is ploughing is not as likely as quartz to reach the strength necessary to shear an asperity. Some feldspar grooves are longer than the distance of the longest slip during stick-slip. This is an indication that some asperities in feldspar do not shear at the initiation of slip but continue to plough through a second slip.

Asperities are more likely to shear at the initiation of a stick-slip event than during sliding. During static contact the asperities penetrate further into the grain containing the groove, thus creating a larger area of contact between the groove and the asperity. This larger area of contact results in the need for a larger shearing force for further ploughing or scratching and, so, effectively increases the strength of the material into which the asperity is penetrating. Further penetration during static contact is the result of time dependent creep of brittle materials under a point load (Scholz and Engelder, 1974).

The frictional properties of sliding surfaces are a function of the amount of wear on the sliding surface. This is illustrated by the difference between μ at the initiation of slip and μ after 0.3 mm of slip (Figure 4): μ changes more during 0.3 mm of slip at higher confining pressures. A plot of number of grooves generated per stick-slip event on Westerly granite versus confining pressure indicates that more grooves are generated per stick-slip event at higher confining pressure (Engelder, 1974). Thus the greatest change in μ for 0.3 mm of displacement and the greatest wear rate occur at higher confining pressures. The rate of change in μ is attributed to the rate of wear. Loose wear particles which are generated during wear interlock and increase the frictional strength of surfaces relative to the same surface prior to wear.

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which is also filled with loose feldspar fragments, many of which exhibit cleavage faces. Most of the grooves have a width to depth ratio which may be as large as 5:1. Grooves in feldspar reach their maximum width and depth after the asperity has travelled less than half of the length of the groove.

The effect of feldspar asperities sliding on quartz are observed by identifying feldspar on quartz surfaces (Figure 8). In this situation the feldspar seems to coat the quartz with a streak which is interpreted as remains of a feldspar asperity as it is worn off during sliding. Apparently the 'softer' feldspar adheres to the quartz and is sheared much like graphite from a pencil which adheres to paper as a pencil point is pushed over the surface.

Quartz surfaces have scratches caused by a series of release fractures which propagated as a sliding asperity presses into the quartz surface (Figure 9). In Engelder (1974) wear tracks on both feldspar and quartz were called grooves based on reflected light microscopy. To be more genetically correct the wear tracks on quartz will be called scratches because ploughing did not occur. The asperities causing these scratches are quartz because the scratches consist entirely of quartz particles; feldspar asperities are observed to wear off and are detected as a streak of feldspar on the surface of the quartz. This type of wear track is the only one found on the surface of Cheshire quartzite.

The situation for feldspar asperities on feldspar is much like that for the quartz asperities on quartz. Scratches are generated with associated release fractures and no foreign particles.

DISCUSSION

The scratch hardness of minerals on sliding surfaces affects the frictional properties of rocks. This is illustrated by considering the effect of feldspar among quartz grains. Highly polished quartz surfaces (Cheshire Quartzite) do not stick-slip below 2.5 kb confining pressure whereas highly polished quartz-feldspar surfaces (Westerly Granite) stick-slip at confining pressures down to 0.3 kb. Because frictional wear seems to be necessary for stick-slip on highly polished quartz surfaces, stick-slip will occur at confining pressures below 2.5 kb only in the presence of minerals with scratch hardnesses less than quartz. Feldspar has a lower scratch hardness than quartz and its greater susceptibility to wear promotes stick-slip of Westerly granite at confining pressures where Cheshire quartzite slides stably.

At less than 2.9-kb confining pressure Westerly granite has a larger static friction than Cheshire quartzite. Granite has three major types of wear contributing to its friction whereas quartzite has only one type of frictional wear. Quartz asperities sliding on feldspar are responsible for the increase in friction of granite relative to quartzite for the following reasons: (1) quartz asperities on quartz grains of Westerly granite should exert the same frictional force as asperities on grains in the quartzite, (2) feldspar asperities on quartz wear off and thus contribute little to the frictional strength of granite, and (3) feldspar surfaces wear much faster than adjacent quartz surfaces. The last point indicates illustrated in Figure 6 is due both to a variety of slip lengths resulting in the total slip of the stick-slip experiment and a variety of track lengths for individual stick-slip events. In addition some tracks are longer than the longest slip length. Wear tracks on the granite are not as numerous when Westerly granite slides on Cheshire quartzite at equivalent confining pressures. In this situation tracks are also less than the length of one slip during stick-slip.

A Cambridge Scanning Electron Microscope equipped for the energy dispersion analysis of X-rays is used to resolve the fine features of the wear tracks. The E.D.A.X. device permits identification of individual crystals on the sliding surface and particles associated with the abraded surface.

Three types of frictional wear tracks may be observed on the Westerly granite surface. They result from the sliding of a quartz asperity on feldspar, a quartz asperity on quartz or feldspar asperity on feldspar, and a feldspar asperity on a quartz. The identity of the asperity is revealed by the presence or absence of foreign particles within a wear track. For example, when a quartz asperity slides on feldspar, a groove is generated which contains quartz particles less than 5 μm in diameter (Figure 7). Grooves in feldspar have a rough bottom

Figure 8. S.E.M. micrograph of a track of feldspar gouge smeared on a quartz grain. Surface on which track formed moved toward top of micrograph.

The initial frictional wear of highly polished surfaces of Westerly granite and Cheshire quartzite consists of carrot-shaped wear tracks consisting of grooves, scratches and clumps of gouge. Tracks are continuously generated on the polished surface until the polish is worn off and the surface becomes covered with a layer of gouge. Initial wear tracks are distributed evenly over the Cheshire quartzite surface. In contrast the polished Westerly granite does not wear evenly; a larger number of wear tracks form on feldspar grains. As

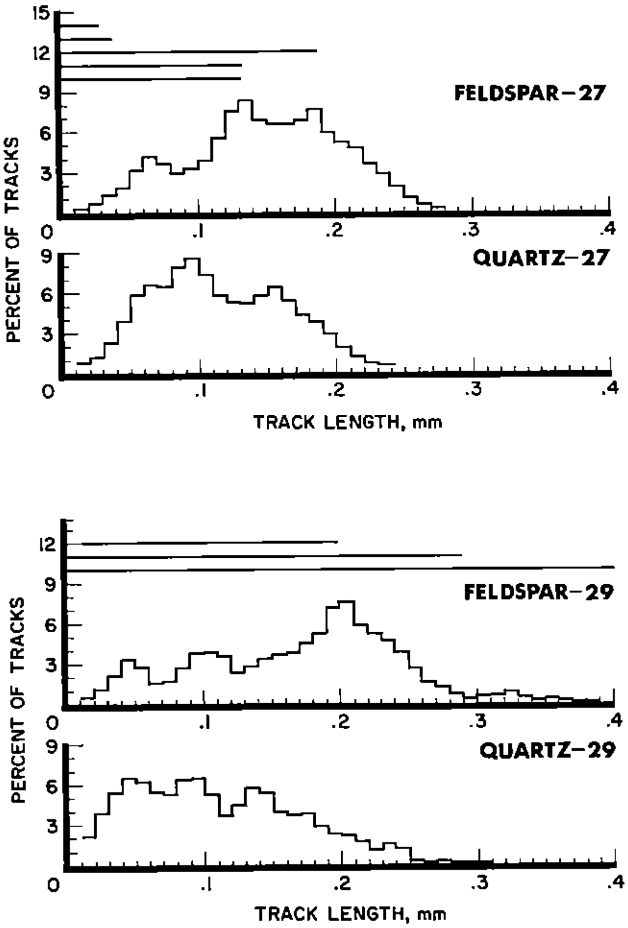

Figure 6. Histograms of percentage distribution of wear track lengths in feldspar and quartz grains on Westerly granite sliding surfaces for experiments 27 and 29 at 2.0 kb confining pressure. Number and length of individual slip lengths are indicated by horizontal lines above histograms. The top horizontal line is the first slip and the bottom the last. At least 300 tracks are included for each histogram.

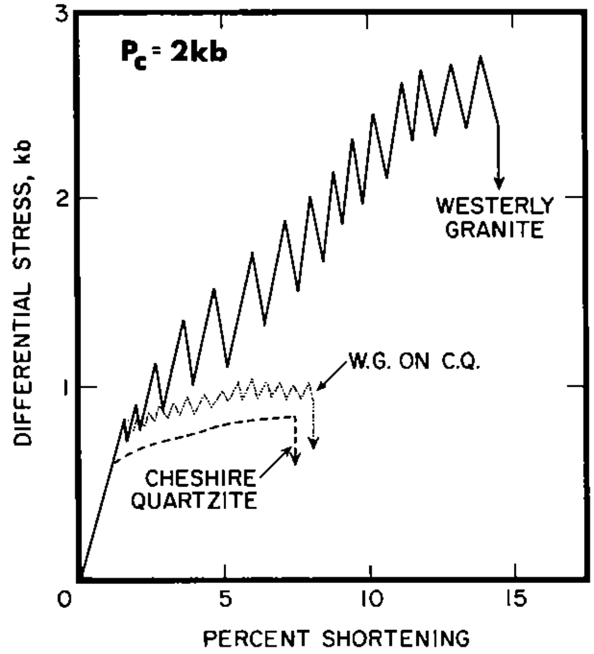

Figure 3. Differential stress versus shortening curves for various specimens at 2 kb confining pressure.

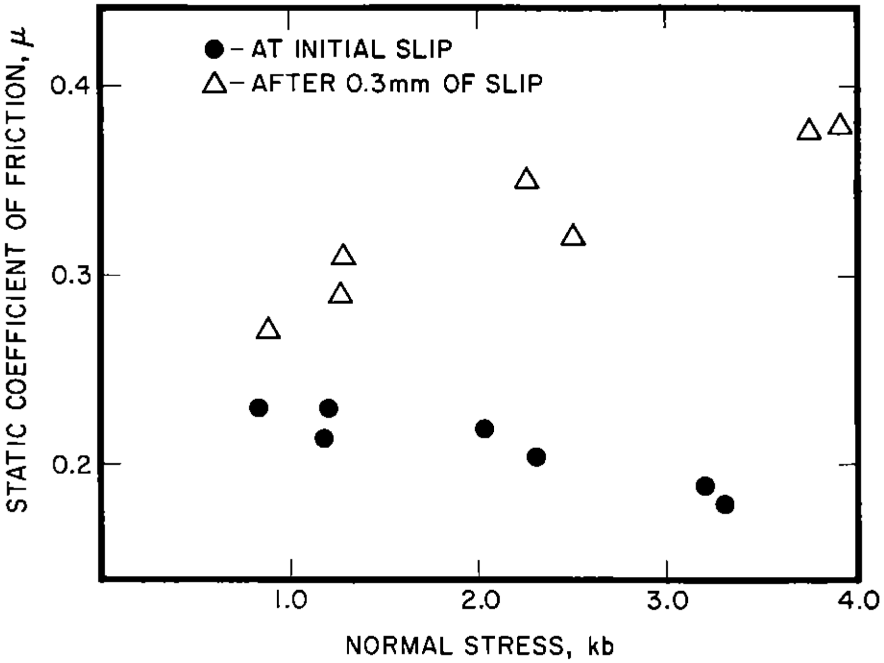

Figure 4. Static coefficient of friction of Westerly granite at various normal stresses.

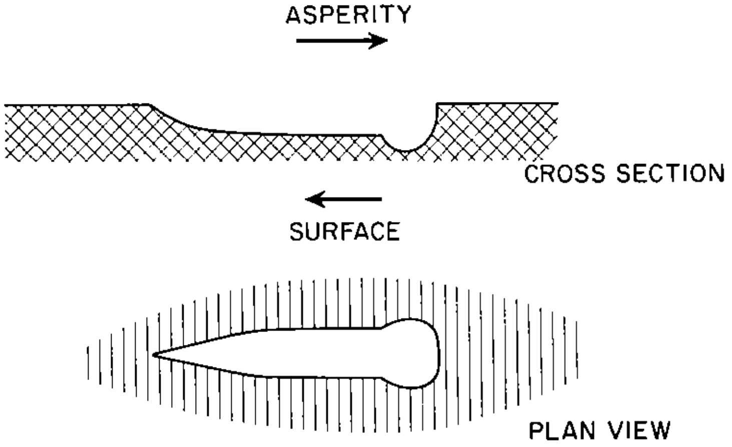

Figure 1. Schematic of an ideal wear groove in feldspar. Arrows indicate sense of slip.

that dig deeper as sliding progresses during a stick-slip event. The ploughing results in an increase in frictional resistance and impedes further sliding. Once sliding has stopped, shearing stress increases until the shear strength of the asperities is exceeded. An instability occurs with the shearing of the asperities and the surfaces slip once more.

This paper presents further observations on the mechanism of stick-slip on highly polished rock surfaces. In particular, attention is focused on the relation between scratch hardness of minerals on the sliding surface and stick-slip. The minimum normal stress at which stick-slip occurs is influenced by a difference in scratch hardness of various minerals on the sliding surface.

EXPERIMENTAL STUDIES

In order to study the mechanism of stick-slip, 1.2 cm diameter by 2.5 cm long cylindrical specimens were slid in compression on surfaces inclined at 35° to the cylindrical axis. Experimental confining pressures on the dry samples were between 0.1 and 2.9 kb with an average sliding displacement rate of 10^{-3} cm/sec. The sliding surfaces were saw cut and then hand lapped against each other to assure a good fit between surfaces. A final polish was achieved with 0.3 μm Linde A polishing compound.

The specimens used for this study are Westerly granite and Cheshire quartzite. Westerly granite consists primarily of quartz, plagioclase, and K-feldspar grains between 0.5 and 2.0 mm in diameter. Other types of grains comprise less than 2 per cent of the sliding surface area. Cheshire quartzite is monomineralic and has grain diameters up to 4.0 mm. The relative contrast in scratch hardness among minerals on the surface of granite versus the lack of contrast in scratch hardness for quartzite prompted the choice of granite and quartzite for this study.

Cheshire quartzite on Westerly granite stick-slips at confining pressures lower than the Cheshire quartzite stable sliding to stick-slip transition. This is due to granite grain boundary asperities which scratch the quartzite. Once the quartzite is scratched quartz wear particles scratch quartz and groove feldspar on the granite. The lower stress drops for quartzite on granite relative to granite on granite is due to a lower rate of wear in the former case. A lower rate of wear means that fewer asperities lock the surfaces and so the frictional strength at the initiation of stick-slip is lower.

SUMMARY

The shape and length of wear tracks indicate that the frictional instability for slip on Westerly granite and Cheshire quartzite is due to the shearing of asperities which have penetrated the sliding surface. The larger magnitude of the frictional instability on Westerly granite relative to Cheshire quartzite is due to feldspar on the sliding surface. The feldspar has a lower scratch hardness which allows more asperity penetration per unit slip. Asperity penetration and subsequent wear seem to be necessary for stick-slip and occur at lower normal stresses on Westerly granite as compared to Cheshire quartzite.

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