Time-Dependent Friction in Rocks

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Friction experiments have been conducted on porous sandstone, quartzite, graywacke, and granite in the 20- to 850-bar normal stress range. Sliding on clean rough-ground surfaces is initially stable for this range. However, as powered rock debris accumulates on the slip surface, stick slip becomes the dominant mode of sliding. The coefficient of static friction of surfaces with gouge exhibits a highly time-dependent behavior. Static friction increases with the logarithm of the time that adjacent blocks remain in stationary contact. Over the entire range of normal stresses the static friction for 10^5-sec intervals between stick-slip events is greater than the static friction for 15-sec intervals by 6 to 10%. This behavior may be significant in understanding the mechanisms of earthquake foreshocks, aftershocks, and fault creep.

Bridgman [1936], noting the jerky motion and sudden stress drops that accompany the shearing of rocks at high normal stresses, suggested that this behavior might be a possible mechanism for the generation of earthquakes. Subsequently, stick slip in rocks has become a familiar and widely documented phenomenon of rock friction [e.g., *Jaeger,* 1959; *Byerlee,* 1967; *Handin,* 1969; *Maurer,* 1965]. *Brace and Byerlee* [1966] elaborate on Bridgman's suggestion and propose that stick slip may be an important mechanism for shallow earthquakes along pre-existing faults. In particular, they point out that this mechanism explains why it is possible to have earthquakes in fractured rock and that the stress drops for stick slip, when they are compared with those for fracturing, are more nearly in agreement with the low stress drops estimated for shallow earthquakes. It is noted, however, that the stress drops for laboratory stick slip, although they are less than those for fracturing, are still larger than those for shallow earthquakes by about an order of magnitude.

The importance of rock friction as a controlling factor of fault seismicity has been pointed out by *Burridge and Knopoff* [1967] and by *Knopoff et al.* [1969]. Using a one-dimensional discrete-element numerical model of a seismic fault along which the static friction exceeds the sliding friction, they show that many features of fault seismicity may be related to fault friction. Their results indicate that energy release and magnitude-frequency parameters may be controlled in part by variations in the static friction.

Values for static and sliding friction obtained from laboratory stick-slip experiments at moderate confining pressures have been used in numerical computations for the dynamics of faulting in a detailed two-dimensional continuum model [*Dieterich,* 1969]. Stress drops and other earthquake source parameters computed from this model agree quantitatively with values estimated for shallow earthquakes. This result overcomes the objection to stick slip as a mechanism for shallow earthquakes that arises from the large differences in stress drop observed in laboratory stick slip and estimated for shallow earthquakes. The larger stress drops occurring in stick-slip experiments arise principally from the free ends of the slip surfaces necessary in laboratory experiments but not found in earthquake-related fault motions.

Notwithstanding the considerable amount of laboratory work on this subject, much is still not understood about the parameters affecting rock friction, as is evidenced by the largely unexplained and rather frustrating lack of consistency commonly displayed by the results of friction experiments. It is becoming clear that many factors in addition to rock type and confining pressure influence the frictional properties of rocks. A number of recent studies have been directed toward delineating possible sources of variation in friction experiments. *Byerlee and Brace* [1968] studied the influence of machine stiffness and strain rate on the frictional characteristics of several rocks. Over a wide range of strain rates and machine stiffnesses they found no detectable variation in the measured parameters. *Hoskins et al.* [1968] found that varying the surface finish produced great changes in frictional characteristics. They also discovered that the amount of slip has considerable effect. For rough surfaces they found the sliding to be stable (i.e., no stress drop), the frictional resistance increasing asymptotically as slip increases. However, on surfaces with a higher degree of surface finish, stick-slip motion was characteristic of slip, even at very low normal stresses. The effect of temperature on stick slip has been studied by *Brace and Byerlee* [1970]. Preliminary experiments indicate that stick slip tends to give way to stable sliding as temperature increases.

It is interesting that these factors have previously been recognized as major determinants of the frictional characteristics of metals. The effect of these factors on metals, however, is not necessarily the same as that noted for rocks. Another possible variable in rock friction is suggested by experiments on metals at high normal stress that show that static friction is controlled by the length of time that slip surfaces are held in stationary contact [*Rabinowicz*, 1965]. The experiments in this paper were conducted to determine if rocks might also exhibit time dependency in frictional strength. These experiments demonstrate that the coefficient of static friction is time dependent under certain conditions. In particular, it is found that the static friction of surfaces separated by a layer of gouge increases with the logarithm of the duration of stick.

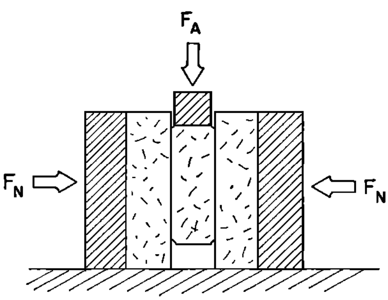

Fig. 1. Schematic diagram of apparatus.

This paper describes the experiments and discusses qualitatively the possible implications of the friction data for understanding some aspects of fault seismicity. In the companion paper [*Dieterich*, 1972] a mechanism for aftershocks based on the friction data is illustrated in greater detail and tested with the aid of a numerical model of a seismic fault.

APPARATUS

The experimental configuration used in this study falls into the general category of the direct shear friction test used extensively in engineering rock mechanics. Figure 1 schematically illustrates the apparatus. This apparatus is similar to but somewhat smaller than the direct shear apparatus described by *Hoskins et al.* [1968]. With this apparatus an inner block with planar and parallel faces is pushed between two outer blocks. The blocks have dimensions of up to 6.0 × 6.0 cm and a thickness of 1.5 cm. To ensure that the area of the sliding surface remains constant during slip, the inner block may be either larger or smaller than the outer blocks. Both configurations were used in this study with similar results.

A horizontal hydraulic jack applies the force normal to the two sliding surfaces (F_N in Figure 1). The shear stress is applied independent of the normal stress by a vertical hydraulic ram acting on a steel block to push the inner block between the outer blocks. The force developed by the vertical ram is indicated by the arrow labeled F_A in Figure 1.

Although the direct shear test in its many forms is the configuration used most frequently for friction studies in engineering rock mechanics, it is used less frequently for geophysical rock friction studies, principally because the samples are unconfined and hence the maximum stress that can be reached is limited by the crushing strength of the rock. In practice, the direct shear apparatus produces internally consistent and reproducible results. For additional details for the direct shear friction test see *Hoskins et al.* [1968] and *Jaeger and Rosengren* [1969]. These authors discuss and compare the merits and characteristics of the direct shear apparatus relative to the other common friction test arrangements.

MATERIALS AND PROCEDURE

Friction experiments were conducted on the following materials.

1. Sandstone: a porous fine- to medium-grained sandstone consisting of 90% quartz, 5% muscovite, 4% feldspar, and 1% accessory minerals.
2. Graywacke: a dense fine-grained graywacke composed of fragments of quartz, chert, and plagioclase and lithic fragments (in order of relative abundance) in a silty matrix containing abundant mica.
3. Red granite: a coarse-grained granite consisting of orthoclase, quartz, plagioclase, and amphibole (in order of abundance) and a trace of biotite.
4. Quartzite: a dense coarse-grained quartz-cemented quartz sandstone.

The materials were prepared for the experiments by sawing blocks to the appropriate dimensions with a diamond saw and lapping them to ensure that the slip surfaces were flat and parallel. The final stage of preparation consisted of lapping the slip surfaces against each other with abrasive so as to achieve the most uniform contact possible. The prepared blocks were parallel to better than 0.01 cm. After lapping, all samples were oven dried at approximately 120°C at atmospheric pressure for at least 1 hour.

Particular attention was given to the preparation of the blocks because it was found that reproducibility during an experiment was enhanced by achieving maximum nominal contact between the slip surfaces. Furthermore, the maximum normal stress that could be reached before the blocks failed by splitting or chipping increased significantly when extra care was taken in their preparation.

Because friction is sensitive to surface finish, care was also taken to control surface roughness. Two extremes in surface finish were used. Smooth surfaces were prepared by lapping with #600 silicon carbide abrasive, and rough surfaces were prepared by lapping with #80 abrasive.

With the prepared blocks a series of friction experiments was then conducted on each rock at different normal stresses. To determine if the static friction changed with time, the duration of stick was varied at constant normal stress by holding the shear stress slightly below the static friction for different time increments. The static friction at the end of a desired interval was then measured by rapidly increasing the shear stress until the block moved. In general, intervals from 1 or 2 sec to 10^5 sec were used for each experiment at a given normal stress. The lower time limit was set at the shortest increment that could be controlled and measured accurately, whereas the upper limit was determined primarily by the patience of the investigator. A few measurements were made of the static friction for stick intervals of up to 10 days.

Stick intervals during an experiment were varied arbitrarily rather than systematically (e.g., from short to increasingly longer stick intervals) to circumvent possible undesired changes of the coefficient of static friction μ_s. As an additional check against undesired variations not related to the duration of contact, a 15-sec stick interval was used as an internal standard. The static friction for this interval was checked frequently during each experiment. A change in the μ_s for the 15-sec interval resulted in a termination of the experiment. Two types of unwanted variations of μ_s occurred. In the first, abrupt and erratic changes of μ_s were always caused by failure of a block by chipping or cracking. The second type of variation arose only with experiments on blocks with rough slip surfaces. Because the frictional strength of rough surfaces increases asymptotically with displacement, experiments were done either on clean fresh surfaces or on surfaces that had already been 'run in' so that the friction had reached a stable value. A progressive increase of μ_s during one of these experiments arose when the block was not sufficiently run in.

RESULTS

In general, the over-all friction behavior observed for these experiments corroborates the findings of *Hoskins et al.* [1968]. Friction characteristics were determined primarily by surface properties and were only weakly related to rock type. However, somewhat higher coefficients of friction were found for the present experiments than were measured by Hoskins et al. The reason for this discrepancy is probably related to differences in the uniformity of contact on the slip surfaces. During preliminary experiments of this study conducted before the importance of sample preparations was fully appreciated, contact between the surfaces was not at all uniform, and lower values for the coefficient of friction were measured.

Severe stick-slip motion characterized the sliding on smooth surfaces at all normal stresses (20–850 bars). The coefficient of static friction μ_s for the smooth surfaces was quite high (0.95–1.5) and showed considerable variability. No time dependency was observed with the smooth surfaces for durations of stick ranging from 1 sec to 48 hours. This apparent lack of time dependency may not be conclusive, however, because of the high variability of μ_s.

Sliding on the rough surfaces was initially stable, the coefficient of friction increasing as displacement increased. For stable sliding the kinetic coefficient of friction μ_k equals μ_s. Slip on the rough surfaces generates finely powdered rock debris or gouge. When the surfaces are cleaned of gouge and the experiment is resumed, μ_k returns to approximately the value first measured at the initiation of slip and again increases slowly with displacement. However, if the blocks are separated but not cleaned and the experiment is repeated, μ_k decreases in magnitude only slightly and returns rapidly to the value measured before the block was disturbed. Therefore it is concluded that the asymptotic increase of μ_k accompanying slip is directly related to the accumulation of gouge.

For stable sliding on the clean rough surfaces, μ_s is equal to μ_k, and there is no detectable change in μ_s with duration of stationary contact. However, after μ_k reaches its maximum value because of slip, the static friction is very time dependent and increases with the time that the block is held stationary. This time dependency gives rise to stick slip because μ_s is greater than μ_k for finite intervals of stick. Furthermore, the time dependency and hence the stick slip on the rough surfaces clearly depend on the presence of the gouge. Stick slip was observed for all samples at all normal stresses (20–850 bars) only if there was an accumulation of gouge.

Figure 2 shows the variation of μ_s with the duration of stick on surfaces with gouge for the sandstone. Similar results were obtained for the granite, the quartzite, and the graywacke. Each plot gives the data for a separate experiment at constant normal stress. For intervals of ≥ 1 sec the data fit the equation $\mu_s = \mu_0 + A \log_{10} t$, where t is the duration of contact in seconds, μ_0 is the coefficient of static friction for 1-sec stick intervals, and A is a constant. Values for A and μ_0 are given in Table 1. The increase of μ_s with time appears to be independent of normal stress. Some idea of the reproducibility of the experiments is given by the data for sandstone at 187 and 188 bars (Figure 2, Table 1). The two experiments were done with blocks of the sandstone prepared at different times. The difference in μ_0 for the two experiments is 0.015, and the difference in A is 0.002.

Figure 3, which shows the variation of static friction with normal stress, summarizes the data from the experiments. The lower end of each bar gives the strength at the end of 15-sec stick intervals, and the upper end of each bar gives the strength at the end of 10^5-sec intervals. For the sandstone, the granite, and the quartzite the differences in frictional strength for intervals of 15 and 10^5 sec are 8, 9, and 10%, respectively. The change in the frictional strength for the graywacke was noticeably smaller (<6%). Difficulties were encountered with the graywacke because it tended to chip even at low normal stresses. Therefore the significance of the smaller increase in μ_s for the graywacke is uncertain.

Systematic experiments were not conducted for stick intervals of <1 sec because control of the experiments accurate to better than 0.2 sec was not possible with the apparatus. However, a few measurements were made with each rock for intervals of <1 sec with this relatively large timing error of ±0.2 sec. The results are of some interest. The sandstone and the graywacke move by stable sliding for stick intervals of ≤ 1 sec at all normal stresses. Hence for the sandstone and the graywacke, μ_k equals μ_0. Similarly, the granite and the quartzite show stable sliding for stick intervals of ≤ 1 sec up to 200 bars normal stress. In the 200- to 400-bar range, normal stress stable sliding occurs only if the stick intervals are less than approxi-

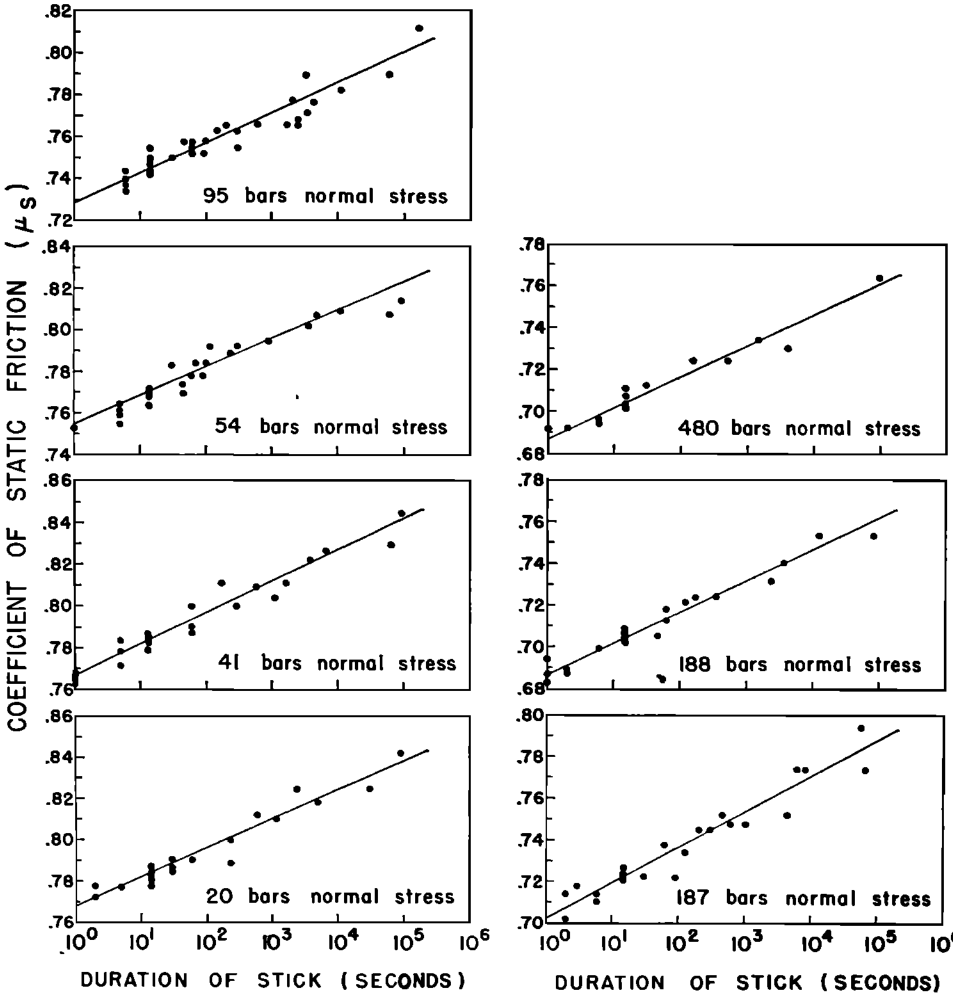

Fig. 2. Time dependence of the coefficient of static friction μ_s for sandstone.

mately 0.5 sec. Above 400 bars these rocks slide only by stick slip. The reason for the difference in behavior is not clear, but it can be noted that the sandstone and the graywacke contain several per cent mica, whereas the granite contains only a trace amount and the quartzite contains none. Also the sandstone and the graywacke have slightly lower coefficients of friction and lower values of A than the granite and the quartzite.

Possible Mechanisms for Time Dependence of μ_s

The increase of μ_s with duration of contact shown here for rocks is very similar to the time dependency observed in metals. For example, *Dokos'* [1946] data for steel at high normal stress have been shown by *Rabinowicz* [1965] to demonstrate an increase of μ_s with the logarithm of the stick interval. For metals *Bowden and Tabor* [1964] suggest a number of possible explanations for the increase of μ_s with time. These explanations are compatible with the widely accepted theory of friction that states that frictional strength is determined by the size and the strength of adhesive junctions across the slip surface. Because the formation of these junctions is controlled by localized plastic flow in the area of the contact points, one explanation is that time-dependent plastic flow increases the area of the junctions. The other possible explanations are based on

TABLE 1. Values of μ_0 and A

Normal Stress, bars	μ_0	A
	Sandstone	
20.	0.768	0.016
41.	0.767	0.015
54.	0.754	0.014
95.	0.728	0.015
187.	0.703	0.017
188.	0.687	0.019
480.	0.686	0.015
	Granite	
58.	0.708	0.021
110.	0.792	0.023
142.	0.826	0.022
180.	0.850	0.020
214.	0.833	0.025
296.	0.840	0.024
415.	0.805	0.022
465.	0.805	0.024
560.	0.785	0.021
694.	0.787	0.018
	Quartzite	
94.	0.838	0.020
250.	0.926	0.015
350.	0.897	0.025
535.	0.870	0.025
680.	0.820	0.016
850.	0.749	0.021
	Graywacke	
100.	0.834	0.013
150.	0.834	0.012
295.	0.792	0.011

the well-known observation that friction is very sensitive to surface properties. These theories state that the size of adhesive junctions remains constant but the strength of the junctions increases with time. Reasons for the increase in strength may be time-controlled breakdown of surface films or diffusion across the junction interfaces.

Which, if any, of these possible explanations for the time dependence of μ_s in metals is applicable to the observations described above for rocks is not yet entirely clear. The theories based on surface properties are vague and difficult to test. Time-controlled plastic flow in nonmetals is widely documented and seems to offer an attractive explanation of the time-dependent friction properties. Indentation hardness, which controls the area of adhesive junctions, is time dependent for metals and at least some nonmetallic materials [e.g., *Walker and Demer*, 1964].

Additional insight may be afforded by the observation that the time dependency of μ_s for rocks is apparently related to the presence of gouge. It is widely known from work in powder metallurgy and powder ceramics that strength is related to the degree of compaction and that dry compaction of powders is controlled by the duration of time that pressure is applied. This observation suggests that compaction of the gouge separating the slip surfaces is time controlled and determines frictional strength. It may be noted that the parameters that affect dry compaction processes are closely related to the physical parameters that control friction of clean surfaces. As a result, speculations in the literature on the mechanism for time-controlled compaction generally quote the explanations noted above that have been offered for time-dependent friction of metals.

In summary, the observation that the increase of μ_s with the logarithm of time is common to both rocks and metals suggests that similar processes give rise to the observed time dependency in these materials. However, additional work is required to establish which, if any, of the proposed mechanisms is applicable to rocks.

DISCUSSION

The results of these experiments, if they are applicable to natural faults, hold some interesting implications for fault seismicity. Parameters related to earthquake source motions are sensitive to both the magnitude of μ_s and the ratio of μ_s to μ_k [*Dieterich*, 1969]. These parameters include stress drop and seismic efficiency in addition to the variations of source dimensions with earthquake magnitude. The time dependence of the static friction indicates that at any point on a fault the magnitude of the static friction, and hence the stress required to cause an earthquake, and the ratio of μ_s to μ_k will be determined by the frequency of slip at that point. Therefore variation of the source parameters with frequency of slip at the earthquake source might be expected.

Of greater interest, perhaps, is the direct effect that the variation of μ_s with time might have on the over-all character of the motions on an active fault. If a fault segment is locked for some finite interval of time before an earthquake, the slipped part will be weaker immediately after the earthquake than it was before the earthquake. It is proposed that this weak-

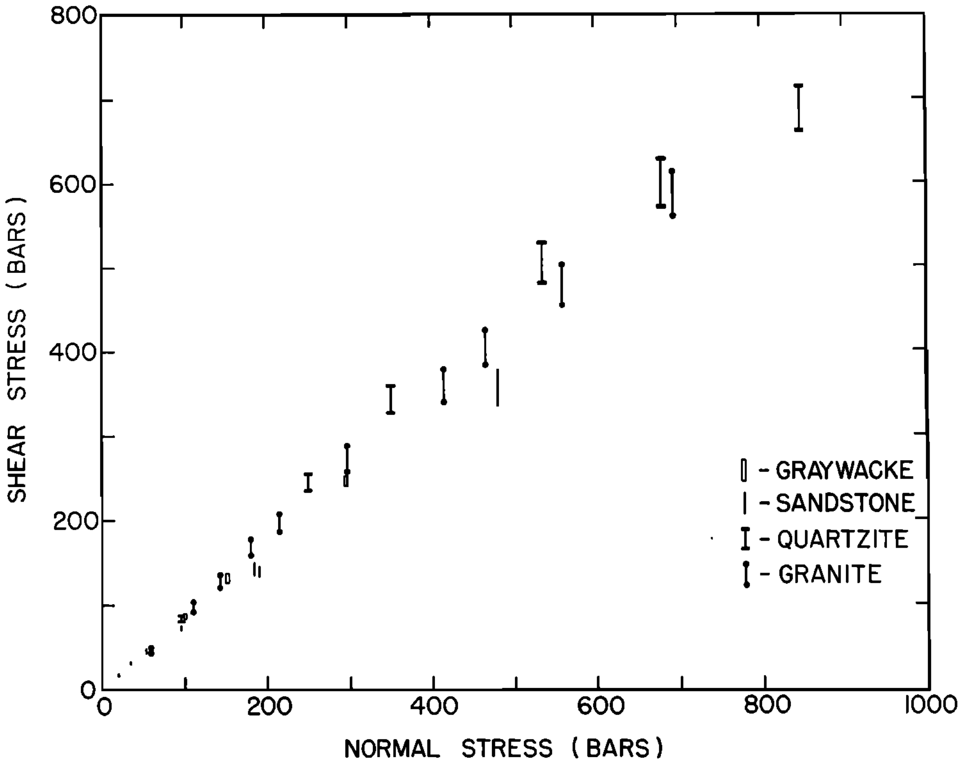

Fig. 3. Summary of experimental results. The lower end of each bar gives the shear strength for 15-sec stick intervals; the upper end of the bar gives the strength for 10^5-sec stick intervals.

ening will be conducive to additional motion on the slipped part of the fault. The additional motion might take the form of a main shock following a foreshock, an aftershock sequence, or fault creep following an earthquake, especially if there is a mechanism for stress recovery after the earthquake such as the one proposed by *Benioff* [1951]. This topic is discussed in greater detail by *Dieterich* [1972].

As regards fault creep, stable sliding occurs for all of the rocks at low normal stresses if the stick interval is ≤ 1 sec. At higher normal stresses, only the micaceous sandstone and the graywacke display stable sliding. The stable sliding observed in these experiments is at a lower stress than that required for stick slip and hence tends to persist as long as the blocks continue to move.

Acknowledgments. Barry Raleigh and Stephen Kirby generously provided advice and assistance in the construction and operation of the experimental apparatus.

Publication authorized by the Director, U.S. Geological Survey.

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(Received October 19, 1971;
revised March 9, 1972.)