Frictional Characteristics of Granite under High Confining Pressure

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At high confining pressure the coefficient of friction, μ, for granite depends on the relative displacement of the surfaces. For ground surfaces, μ reaches a maximum after about 0.1 cm and then decreases to nearly a constant value after 0.5 cm of sliding has occurred. Features on the surfaces after sliding suggest that the maximum is reached when intimate contact is first established. Also, this maximum value is the same as the initial μ for perfectly mated rough surfaces. The decrease in μ from the maximum is probably caused by rolling on wear particles between the surfaces. μ decreases with an increase in normal stress, owing to a finite shear strength at zero pressure of interlocking irregularities on the surfaces. Water reduces the frictional shear strength of granite by about 400 bars, independent of the normal stress across the sliding surfaces. Brittle fracture of surface asperities may be the controlling mechanism during the frictional sliding of brittle materials such as granite. Up to the highest pressures investigated, sliding movement between the surfaces occurred with violent stick-slip. Stick-slip along a pre-existing fault may be a source of crustal earthquakes. The 'brittle-ductile' transition pressure in silicate rocks may simply be the pressure at which the frictional shear strength is equal to the fracture shear strength. In the Coulomb theory it is assumed that the strength of a rock is determined by μ and the cohesive strength. The theory does not hold for westerly granite. According to the effective stress theory, the stress required for one block of rock to slide on another in the presence of pore fluid of pressure p is given by $\tau = \mu(\sigma_n - p)$. The theory holds for granite if μ is the coefficient of friction for sliding on water-saturated surfaces and if allowances are made for the fact that μ may be a function of the effective stress across the surfaces.

INTRODUCTION

Friction plays an important role in the Coulomb criterion of rock fracture [*Jaeger*, 1962, p. 76], the modified Griffith theory of fracture [*McClintock and Walsh*, 1962], and the indentation hardness of rocks [*Brace*, 1960]. Also, friction in rocks is considered to be important theoretically in determining the magnitude of Young's modulus, the value of Poisson's ratio, and a mechanism for attenuation of seismic waves [*Walsh*, 1965*a*, *b*, 1966].

In spite of the importance of friction, it is not clear what physical processes are involved in the frictional sliding of brittle rocks because of apparently conflicting results. When the normal stress σ_n across the plane of sliding is high, the friction μ between rock surfaces ranges from 0.4 to 1.8 [*Jaeger*, 1959; *Handin and Stearns*, 1964; *Maurer*, 1965; *Raleigh and Paterson*, 1965], whereas, when σ_n is low, μ between polished surfaces of rock-forming minerals is much less, 0.1 to 0.2 [*Tschebotarioff and Welch*, 1948; *Penman*, 1953; *Horn and Deere*, 1962]. The difference in μ may be explained by differences in roughness, in that μ is low on polished surfaces and high on rough surfaces, but this explanation is complicated, because during sliding, rough surfaces become smoother and ground surfaces become rougher because of wear [*Byerlee*, 1966].

The effect that friction decreases with increasing σ_n when the confining pressure is high is not clearly understood. *Handin and Stearns* [1964] suggested that the decrease in μ for dolomite at high confining pressure occurred because the sliding surfaces became smoother. *Raleigh and Paterson* [1965] proposed that the decrease in μ for peridotite occurred because of increase in plasticity of the minerals with higher confining pressure; however, *Maurer* [1965] found that extremely brittle materials, such as granite, also show the same decrease in μ with increasing pressure.

The purpose of the present investigation was to examine the effects of roughness and confining pressure on μ and the physical processes involved in the frictional sliding (for example, plastic flow or brittle fracture) of a typical silicate rock, the westerly granite. In addition, experiments were designed to test the Coulomb criterion of rock fracture, Orowan's theory for the apparent ductility of rocks, and the effective stress theory as applied to friction.

Experimental Procedure

General. Sliding experiments were performed on three types of rock surfaces, as shown schematically in Figure 1: a ground surface as in G, a fracture surface as in F, and a fracture surface developed in virgin rock at failure as in V. An axial force was applied to the cylindrical specimens under a confining pressure σ_1, and the axial stress σ_3 was determined as a function of the axial displacement, that is, as sliding occurred on the surfaces, G, F, or V. A correction to σ_3 was made for the change in area of contact along the surface as sliding occurred.

The stresses acting on the sliding surfaces are calculated from the principal stresses as follows. The average normal stress σ_n and the average shear stress τ on the plane of the sliding surfaces is given by

$$\sigma_n = \left(\frac{\sigma_3 + \sigma_1}{2}\right) - \left(\frac{\sigma_3 - \sigma_1}{2}\right) \cos 2\alpha$$

$$\tau = [(\sigma_3 - \sigma_1)/2] \sin 2\alpha$$

where σ_1 is the confining pressure, σ_3 is the axial stress, and α is the angle that the sliding surface makes with the axis of the specimen. The coefficient of friction μ is defined as

$$\mu = \tau/\sigma_n$$

Compressive normal stress is taken as positive in this paper.

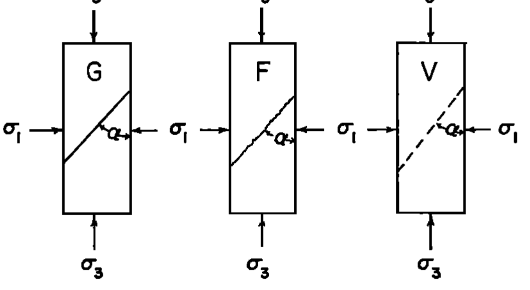

Fig. 1. Schematic diagram of friction experiments. G has a ground surface, F has a fracture surface, V is a virgin rock with the shear surface after fracture indicated by the dashed line.

Sample preparation. In the study of friction on ground surfaces (G, Figure 1), the cylinders were 3.8 cm long and 1.58 cm in diameter, with α at 45°. The sliding surfaces were ground to varying roughnesses on a surface grinder; height of asperities was determined with a profilometer, the Talysurf model 4. To ensure that the sliding surfaces were in close contact, the specimens were enclosed in an annealed copper tube (wall thickness, 0.13 mm) and then subjected to a hydrostatic pressure of about 1 kb; this added enough mechanical strength to the sample to allow ease of handling. The ends of the specimen were ground parallel and covered by hardened steel plugs; a gum rubber tube (wall thickness, 3.17 mm) held with a wire clamp sealed the ends against penetration by the pressure fluid.

The specimens with surfaces having completely interlocking asperities (F, Figure 1) were cylinders 1.581 cm in diameter and 3.8 cm long. The specimens were made by inducing a tensile failure in a large specimen and by coring cylinders from it with the fracture at about 30° to the axis; although the fracture surface was somewhat wavy, departure from a plane was only about ½ mm. The specimens were jacketed in the same way as the G specimens.

In the experiments on virgin cylinders (V, Figure 1), the fracture strength as well as the friction in granite was measured. Two sample configurations were used: one was a straight cylinder 1.581 cm in diameter and 3.8 cm long; the other was 1.581 cm in diameter and 5.08 cm long, but having a central 3-cm section reduced to a diameter of 1.11 cm. Stress concentrations were avoided at the ends of the reduced section by fillets of 0.3-cm radius of curvature. The specimens were jacketed in gum-rubber tubing.

Some experiments were made at 10 kb in another apparatus. In these, the cylindrical specimens were only 1.27 cm in diameter because the axial force required to deform larger specimens exceeded the capacity of the loading system. It was necessary in these experiments also to use polyurethane (wall thickness, 4.76 mm) for jackets because at pressures above 5 kb rubber passes through a glassy transition and fails by brittle fracture after only a small amount of strain [*Paterson*, 1964].

Apparatus and procedure. The 5-kb pressure vessel has been described by *Brace* [1964]; the 10-kb vessel was similar but modified for higher pressure. The axial force applied to the piston was measured externally by a load cell; the confining pressure was measured by a manganin coil inside the pressure vessel. The movement between the frictional surfaces was measured outside the vessel with a strain gage extensometer or DCDT transducer attached to the piston. The load cell, manganin coil, and extensometer were connected to bridge circuits, the output of which were fed into a Mosely XY recorder, model 136.

In a number of experiments the rubber jacket on the ground specimens was clamped to a hollow end plug, through which water was admitted to the sample. The water pressure in the rock was measured outside the pressure vessel with a Heise gage.

In the 10-kb vessel the piston diameter was 3.81 cm and the specimens were 1.27 cm in diameter, so that a large per cent of the force of the piston was applied to the pressure fluid, reducing the accuracy of the calculated axial stress to ±7%. In the 5-kb vessel the piston diameter was 2.54 cm and the specimens were 1.587 cm in diameter, so that the calculated axial stress was more accurate, ±2%. Both the confining and the pore pressure could be measured with an accuracy of better than ±1%.

The accuracy of the normal and shear stresses in the 5-kb experiments was ±3.5%; in the 10-kb experiments it was ±9.5%.

The calculated value of the coefficient of friction after about 0.5 cm of sliding had an error of approximately ±9%.

Experimental Results

Ground surfaces. In experiments on the sliding of ground surfaces of dry granite (G, Figure 1), the coefficient of friction μ was determined as a function of displacement for a confining pressure range of 0.7 to 2.6 kb. Samples were prepared with average heights of

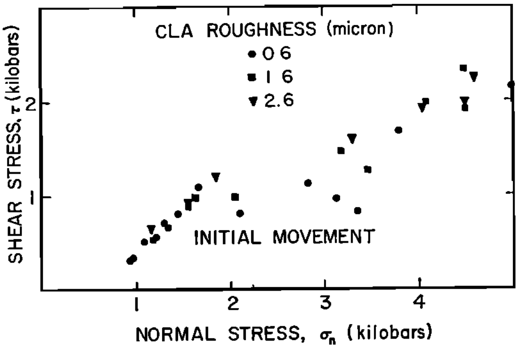

Fig. 2. Initial friction for ground surfaces.

asperities of 0.6, 1.6, 2.6 microns, as determined by profilometer.

The shear stress τ required to initiate movement between ground surfaces of dry rock is plotted against normal stress σ_n in Figure 2. The scatter in the results is due to the uncertainty in estimating the stress at which movement first starts. The finely ground surfaces (circles in Figure 2) tend to have lower values, but the results do not permit us to draw any quantitative conclusions about the effect of initial roughness on the friction.

As the surfaces move, μ reaches a maximum after approximately 0.1 cm of sliding has occurred, as illustrated in Figure 3. The results from experiments at different confining pressures all show the same characteristics.

The sliding surfaces were examined microscopically in a number of experiments in which sliding was terminated after different displacements, like the points shown in Figure 3. Within the first 0.1 cm of displacement damage to the surfaces was confined to isolated regions, as

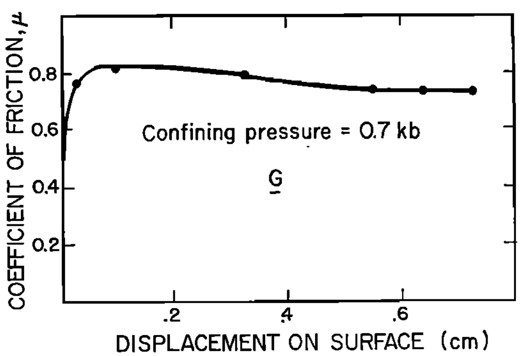

Fig. 3. μ versus displacement for ground surfaces.

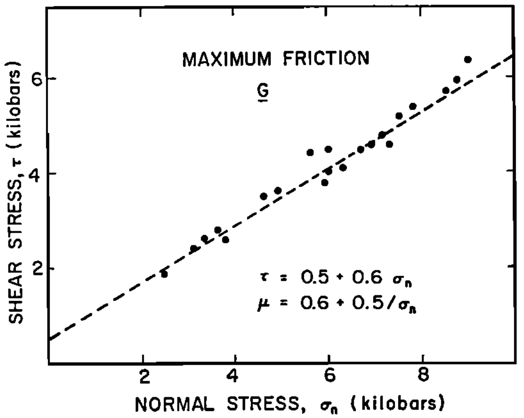

Fig. 4. Shear stress versus normal stress for maximum friction on ground surfaces.

would occur if the surfaces were not perfectly flat when they were originally placed together. At displacements greater than 0.1 cm there was damage over the whole of the surface, shown by a fine layer of crushed material. Apparently the maximum μ was reached when intimate contact was first established. For distances of sliding greater than 0.5 cm the surfaces were completely separated by loose wear particles. Under the microscope the comminuted material appeared to be finely crushed grains of the rock; the particles had optical continuity and had sharp angular edges as would be expected if the grains failed by brittle fracture. The grain size ranged from 0.1 mm in diameter down to about 1 micron.

It was found that an increase in the confining pressure σ_1 caused a decrease in the maximum value of μ. Normal stress σ_n is a more useful parameter than σ_1 in this study of friction, and with $\alpha = 45°$ they are directly proportional, $\sigma_n = \sigma_1 + \frac{1}{2}\sigma_D$, where $\sigma_D = \sigma_3 - \sigma_1$. In Figure 4 the shear stress is plotted against normal stress at the maximum μ for all the experiments on ground surfaces of dry granite; the dashed line represents the equation $\tau = 0.5 + 0.6\,\sigma_n$, τ and σ_n being measured in kilobars. Dividing by σ_n to express the equation in terms of the friction coefficient, $\mu = 0.6 + 0.5/\sigma_n$; this shows the inverse relation of μ with σ_n and approximately with σ_1.

The effect of water under pressure in the pores of the granite was also studied. The experiments were run on water-saturated samples with an average asperity height of 1.6 micron; the range of confining pressure was from 0.5 to 4.5 kb. The water pore pressures applied were 0, 1, and 1.65 kb.

The change in friction with displacement on ground surfaces in the pressure of water showed the same characteristics as it did in the dry samples: the friction rises to a maximum in the first 0.1 cm of relative displacement and then decreases slightly. In Figure 5 the shear stress is plotted against normal stress at maximum friction. The results fall about the straight line, $\tau = 0.1 + 0.6\,(\sigma_n - p)$, for $2 < \sigma_n < 10$ kb, where p is the water pore pressure in kilobars.

Interlocking surfaces. In the study of fracture surfaces with completely interlocking asperities (F, Figure 1), the range of confining pressure was from 1.1 to 10.1 kb. The angle α of the cylinders varied from 25° to 35°.

Data from a typical experiment with interlocking surfaces are plotted in Figure 6. The friction decreases from initially high values to a constant value 0.6 after about 0.1 cm of sliding has occurred. Finely ground powder was found over the whole of the surfaces after sliding. In Figure 7 the shear stress at which sliding commenced is plotted against the normal stress across the sliding surfaces. The results fall about the straight line, $\tau = 0.5 + 0.6\,\sigma_n$, for $2 < \sigma_n < 17$ kb. In terms of μ, the relation is $\mu = 0.6 + 0.5/\sigma_n$.

Behavior of unfractured granite. The compressive strength of unfractured samples of westerly granite (V, Figure 1) was found for confining pressures to 10.8 kb. Two stress-strain

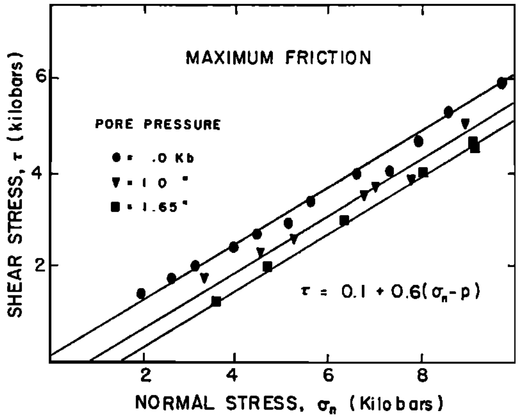

Fig. 5. Shear stress versus normal stress for maximum friction on ground surfaces of water saturated samples.

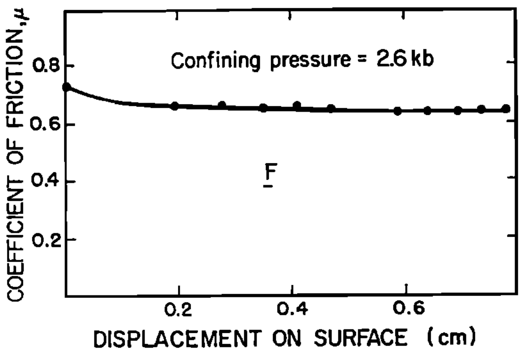

Fig. 6. μ versus displacement for mated surfaces.

curves of the granite were obtained at confining pressures of 6.6 and 10.1 kb.

In Figure 8 the axial stress σ_3 at fracture for the initially virgin samples is plotted against confining pressure σ_1. The open circles are the results from samples with a reduced central section; there is no appreciable effect due to differences in configuration of the specimens. A significant feature of the results is the nonlinear increase in σ_3 at fracture with pressure. Similar results were obtained by *Mogi* [1966] and by *Brace et al.* [1966] on westerly granite with a similar grain size.

The angle α of the shear plane was measured, and τ and σ_n at fracture were calculated and plotted in Figure 9.

Experiments were performed on two of these samples in which the sliding was continued after fracture. In Figures 10 and 11 the differential stress is plotted against the per cent of

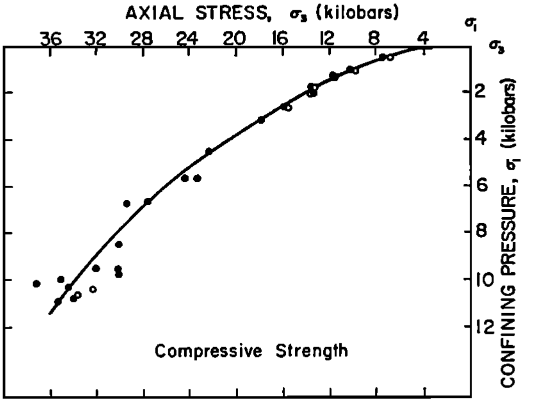

Fig. 8. Principal stresses at fracture for virgin samples of granite.

axial shortening at confining pressures of 6.6 and 10.1 kb, respectively; corrections were made for the change in the cross-sectional area with sliding. The significance of the jogs in the plot will be discussed below.

Discussion of Experimental Results

Change in friction with displacement. One striking feature of the experimental results is the change in friction on ground surfaces with the distance of sliding. Features on the surfaces after sliding indicate that the maximum friction occurs when intimate contact is first established. If this is correct, the amount of material to be sheared through to allow sliding will not differ very much from the amount for perfectly mated surfaces. The maximum fric-

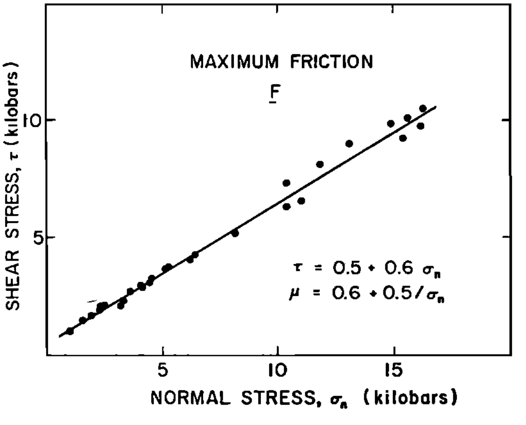

Fig. 7. Shear stress versus normal stress for initial friction on mated surfaces.

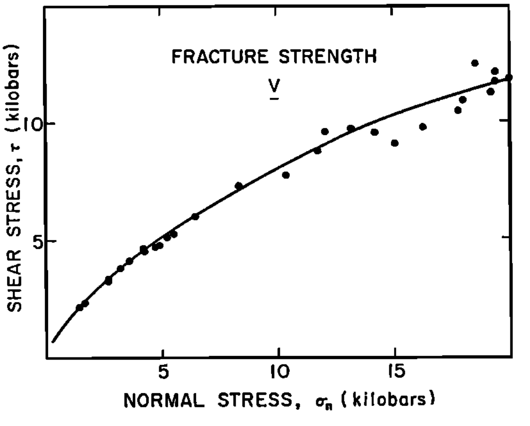

Fig. 9. Shear stress versus normal stress at fracture for virgin samples of granite.

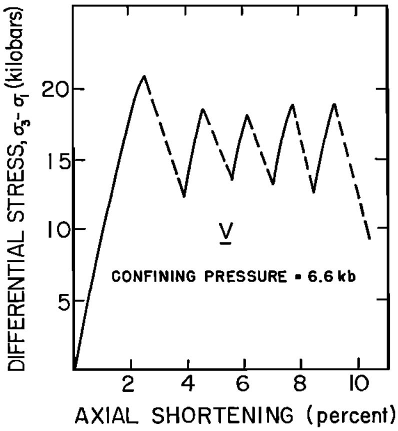

Fig. 10. Differential stress versus per cent axial shortening (confining pressure 6.6 kb) for virgin samples of granite.

tion for ground surfaces should therefore be about the same as the initial friction for perfectly mated surfaces.

The points in Figure 4 are the maximum friction for ground surfaces, and they scatter about the dashed line, which is the best fit for the initial friction for interlocking surfaces (Figure 7).

The physical processes involved in sliding when contact between the surfaces is confined to isolated regions should not differ from the physical processes when contact is made over the whole of the surface. The interlocking irregularities must be sheared through to allow sliding.

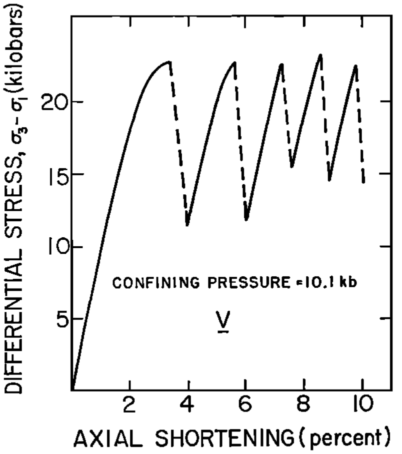

Fig. 11. Differential stress versus per cent axial shortening for virgin samples of granite (confining pressure 10.1 kb).

Why then should the friction increase with displacement? This can be explained in the following way. If the area of true contact is small, the force required to shear the asperities is less than the force required if the true contact area is large.

The frictional shear stress for perfectly mated surfaces is given by the equation

$$\tau = 0.5 + 0.6\sigma_n \qquad (1)$$

The stresses τ and σ_n are the average stresses over the real cross-sectional area, A, of the surfaces in contact. If interlocking is confined to isolated regions on the surfaces, real cross-sectional area is less than apparent cross-sectional area of contact, A_a. The apparent stresses, τ_a and σ_{na} became

$$\tau_a = (A/A_a)\tau \qquad (2)$$

$$\sigma_{na} = (A/A_a)\sigma_n \qquad (3)$$

Substitution of equations 2 and 3 into equation 1 yields

$$\tau_a = 0.5(A/A_a) + 0.6\sigma_{na}$$

If A is less than A_a, the frictional shear stress will be smaller than it would be if the apparent cross-sectional area of contact were equal to the true cross-sectional area of contact.

The decrease in μ from the maximum probably occurs because loose wear particles may roll between the surfaces.

Load dependence of friction. The results of the present study show that, when the shear stress required to cause sliding is plotted against the normal stress across the surfaces, all the points fall along a straight line with an intercept on the shear stress axis. There is no discontinuity in the data as would be expected if the physical processes involved during sliding changed from brittle to ductile behavior. The decrease in μ occurred with surfaces that were initially perfectly mated, so that a change in roughness of the surfaces with pressure could not explain the phenomena. Evidence from the present study suggests μ decreases because the interlocking irregularities on the surfaces have a finite shear strength with zero normal stress across the sliding plane. The functional relationship for μ over the stress range investigated is given approximately by

$$\tau = A + B/\sigma_n$$

where A is the rate of change in the strength of the material with an increase in the normal stress and B is the shear strength when the normal stress is zero.

Effects of water on friction. The friction of water-saturated samples of granite was found to be less than that of dry samples. A similar effect was reported by *Jaeger* [1959] on sandstone and granitic gneiss. In the present study it was found that water reduced the intercept on the shear stress axis, but that the rate of change of shear strength with an increase in normal stress was the same whether the rock was dry or wet. *Colback and Wiid* [1965] found the same effect of water on the fracture strength of virgin samples of quartzite sandstone and shale. The reason for this behavior is not exactly clear, but it seems to be related to the effect of environment on the tensile strength of brittle materials. Even though the surfaces are subjected to a shear stress it is likely that, on the asperity scale, local tensile stresses exist. In the theory of fracture of brittle materials [*Griffith*, 1924], the tensile strength T is given by

$$T = (2E\gamma/C)^{1/2}$$

where E and γ are Young's modulus and specific surface energy of the material and C is the half-length of the Griffith crack.

In the presence of water, the surface energy of a material is reduced [*Orowan*, 1944]; therefore, the tensile strength of water-saturated samples should be less than the tensile strength of dry samples.

The effect of water under a high pore pressure on the friction of granite will be discussed below.

Physical processes during frictional sliding. It is assumed that surfaces are composed of asperities and that the resistance to sliding is determined by the strength of these asperities. Three lines of evidence suggest that the asperities fail by brittle fracture rather than by plastic deformation:

1. Many metals deform plastically when the maximum shear stress reaches a critical value equal to half the yield strength in uniaxial tension. This criterion is known as the maximum shear stress criterion [*Crandall and Dahl*, 1959, p. 200]. This yield criterion is nearly independent of mean pressure.

In the experiments on the friction of granite with complete interlocking of the asperities, if the material deformed plastically, sliding would commence when the shear stress reached a critical value independent of the confining pressure of the experiment. The results show that this is not so. The frictional shear stress increases with the normal stress across the surface. It has been found that the strength of brittle materials increases with an increase in pressure; therefore, an increase in the frictional shear stress with normal stress for rocks would be expected if the irregularities on the surfaces fail by brittle fracture.

2. Extrapolation of the results found for the maximum in friction on ground surfaces to zero normal stress gives an intercept of 0.5 kb for the dry samples and 0.1 kb for the wet samples. Physically, this quantity is the shear strength of the interlocking asperities at zero normal stress. Water decreases the strength of brittle materials; therefore, the reduction in the frictional shear strength would be expected if brittle fracture of the interlocking irregularities were the controlling mechanism during sliding.

3. The material on the sliding surfaces shows no evidence of intragranular flow under the microscope. The grains are angular in shape, consistent with the concept that they were produced by brittle fracture.

The conclusion reached from this study is that brittle fracture is more likely than plasticity to be the controlling mechanism during the sliding of brittle materials such as granite.

Earthquake source mechanism. In the experiments, movement between the surfaces took place in a jerky manner (see Figure 10 and 11, for example), and, when movement ceased, the shear stress across the sliding surfaces was in most cases approximately ⅔ of the shear stress required to initiate movement. This jerky movement occurred even at a confining pressure of 11 kb, the highest pressure used in the experiments. *Jaeger* [1959] observed the same phenomenon in his friction experiments on rocks at confining pressure of 200 to 1000 bars. *Bridgman* [1936] also found that shearing of brittle materials at normal stresses up to 50 kb was accompanied by sudden shear stress drops. On the other hand, he found that the shearing of metals took place smoothly.

The phenomenon is well known to workers in the field of friction and is commonly called stick-slip motion. It has been studied extensively by *Rabinowicz* [1965, p. 94], who found that the magnitude of the force drop during slip could be controlled by the stiffness, inertia, and damping of the loading system.

Stick-slip motion along a pre-existing fault may be an explanation of the seismic source mechanism for shallow crustal earthquakes [*Brace and Byerlee*, 1966].

The observed low shear stress drop across a fault during an earthquake may occur because the stiffness, damping, and inertia of the moving fault block limits the stress drop during slip to the observed value.

Coulomb theory of rock fracture. The Coulomb criterion states that shear fracture takes place across a plane on which the shear stress τ first becomes equal to a constant τ_0 plus a constant μ times the normal pressure σ_n across the plane [*Jaeger*, 1962, p. 76].

$$\tau = \tau_0 + \mu\sigma_m$$

τ_0 is known as the cohesive shear strength, and μ is the coefficient of internal friction.

A consequence of the theory is that, at any given normal stress, the difference between the shear stress for sliding along a fracture surface and the shear stress along a fracture surface produced in virgin material at failure would be a constant that would represent the cohesive strength, τ_0, of the material.

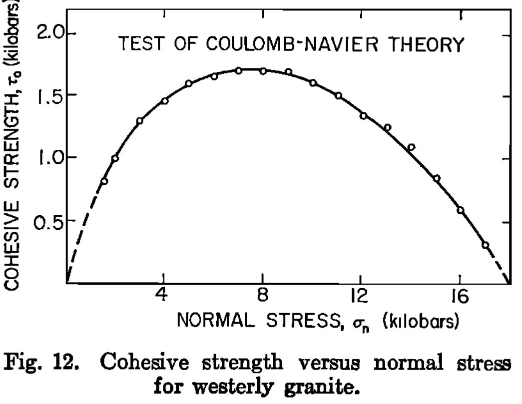

Fig. 12. Cohesive strength versus normal stress for westerly granite.

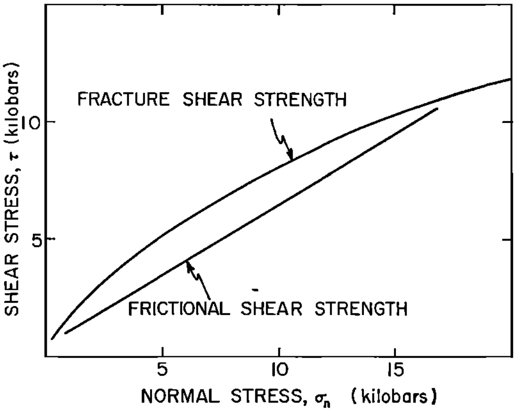

Fig. 13. Fracture shear strength and frictional shear strength versus normal stress for westerly granite.

Figure 12 is a plot of the difference between the shear stress along the fault plane at fracture and the frictional shear stress for sliding along a surface with interlocking asperities over the range of normal stresses investigated in this study. The results show that the difference is not a constant; therefore, the Coulomb criterion of rock fracture does not hold for this rock.

'Brittle-ductile' transition in rocks. Figure 13 shows the shear stress at fracture for virgin rocks of granite and the frictional shear stress for sliding on surfaces with complete interlocking of the asperities as a function of the normal stress across the sliding plane. The two curves intersect when the normal stress is about 17.5 kb. This corresponds to a confining pressure of approximately 10 kb. This indicates that at about 10-kb pressure, the axial stress required to create a fracture surface in westerly granite is equal to the axial stress required to cause sliding on the newly created surface, and the envelope of the stress strain curves should resemble those obtained with a ductile material. Figures 10 and 11 show the stress strain curve for westerly granite at 6.6- and 10.1-kb confining pressure. Movement on the shear surface took place by stick-slip, but it may be possible to eliminate this movement by increasing the stiffness, damping, and mass of the loading system [*Rabinowicz*, 1965, p. 99]. If this is so, then the only significant feature is the stress at which movement occurs. It can be seen in Figure 10 that at 6.6 kb, once nonelastic de-

formation takes place, the strength of the rock is decreased, but at 10.1 kb (Figure 11) the strength is independent of the magnitude of the strain. The criteria for ductility used by *Handin and Hager* [1957], *Mogi* [1965], *Heard* [1960], and others is that the material deforms without loss of compressive strength. In westerly granite this deformation occurs at about 10-kb confining pressure, if we accept the assumption that stick-slip motion can be eliminated by a suitable choice of deformation apparatus.

It was originally proposed by *Orowan* [1960] and more recently by *Maurer* [1965] that the apparent ductility of brittle materials may be caused by the frictional strength being equal to or greater than the fracture strength. In this investigation, experimental evidence has been obtained that tends to support the hypothesis.

Effective stress theory as applied to friction. In the effective stress theory [*Hubbert and Rubey*, 1959], it is assumed that in a porous rock the pressure of fluid within the pores produces a hydrostatic pressure in the surrounding material, and this fluid has no influence on the mechanical properties of the material.

The mathematical foundation of the theory has been questioned [*Laubscher*, 1960], but experimental evidence suggests that the theory is closely followed when applied to the brittle fracture of rocks with pore fluids [*Handin et al.*, 1963].

The theory can be applied to the problem of frictional sliding of rocks, and it predicts that the frictional shear stress τ will be given by

$$\tau = \mu(\sigma_n - p)$$

The above equation is only true if μ is independent of the normal stress across the surface. If the friction shear stress τ is given by

$$\tau = A + B\sigma_n$$

then, if the effective stress theory is correct, the equation will reduce to

$$\tau = A + B(\sigma_n - p)$$

Figure 5 shows the results of the experiments performed on granite under a water pore pressure of 0, 1, and 1.65 kb.

The lines through the points are represented by the equation

$$\tau = 0.1 + 0.6(\sigma_n - p)$$

where p is 0, 1, or 1.65 kb. There is some scatter in the data about the lines, but within the accuracy of the experiments the results are consistent with the effective stress theory.

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