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Friction of Rocks

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Abstract – Experimental results in the published literature show that at low normal stress the shear stress required to slide one rock over another varies widely between experiments. This is because at low stress rock friction is strongly dependent on surface roughness. At high normal stress that effect is diminished and the friction is nearly independent of rock type. If the sliding surfaces are separated by gouge composed of Montmorillonite or vermiculite the friction can be very low.

Key words: Rock mechanics; Friction; Faulting surfaces.

1. *Introduction*

It is generally accepted that crustal earthquakes are caused by sudden movement on preexisting faults. Thus an understanding of frictional sliding between rocks is an important pre-requisite to an understanding of earthquake mechanisms. In the past ten years a number of papers on the friction of rocks have been published and in this paper we review the results of the studies that pertain to the variation of friction with rock type at various pressures.

2. *General remarks on friction*

Figure 1 is a schematic diagram of a typical friction experiment. A rider of mass *m* is free to slide on a rigid flat. The tangential force required to move the rider is applied through a spring AB by moving the point B slowly to the right at a velocity *V*. If the force in the spring is plotted as a function of the displacement of the point B then

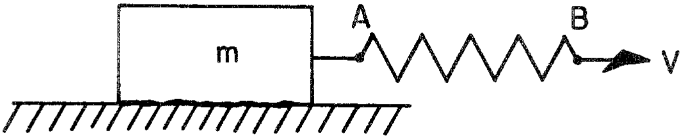

Figure 1
Schematic diagram of a typical friction experiment for explanation see text.

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typically we would obtain a curve such as shown in Fig. 2. There will be an initial elastic increase in force until the point C where the curve departs from a straight line. This indicates that there is relative displacement between the rider and flat or that the rider or flat is deforming nonelastically. At the point D a maximum is reached and the rider may suddenly slip forward and the force in the spring will suddenly drop to the point E. The force will increase again until sudden slip takes place once more at the point F. This sudden jerky type of movement is known as stick-slip. An alternative mode is stable sliding, in this case the movement between the rider and flat takes place smoothly and the force displacement curve will be continuous as shown schematically by the dotted line in Fig. 2.

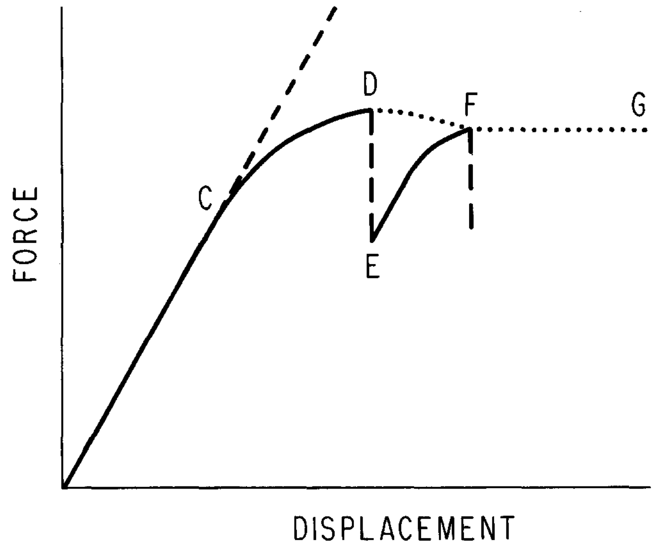

Figure 2
Schematic diagram of the frictional force plotted as a function of displacement of the rider. See text for explanations.

The force at the points C, D and G are known as the initial, maximum and residual friction respectively. There are many different types of apparatus used to study friction such as the direct shear Wang *et al.* (1975), biaxial (Scholz *et al.*, 1972), double shear (Dieterich, 1972), and trixial (Byerlee, 1967). Fortunately all types of apparatus give similar results although the structural members constituting the spring in each apparatus is not always obvious.

There are a number of ways in which the force displacement curves may differ from those in Fig. 2. For instance motion between the rider and flat may initially occur by microslip (Simkin, 1967). In this case it is extremely difficult to determine the exact point at which the force displacement curve becomes non-linear so that determination of the initial friction is subject to considerable error.

There may be a number of cycles of stick-slip before the maximum friction is reached and in some cases, particularly at high pressure, the force displacement curve flattens out so that the residual and maximum friction are identical. In other cases particularly if the surfaces are separated by a large thickness of gouge non elastic deformation commences on the immediate application of shear force and the force increases continually during the experiment so that the initial friction, maximum friction and residual friction cannot be unambiguously determined.

Some confusion also arise because many investigators simply tabulate the coefficient of friction μ without clearly stating whether it is the initial friction, maximum friction or residual friction that was measured.

μ is defined as $\mu = \tau/\sigma_n$ are whether τ and σ_n are the shear and normal stresses acting between the surfaces during sliding. If μ is not a constant, but depends on the normal stress, then a table of coefficients of friction is of little value if the normal stress at which it was measured is not also given.

In some experiments, particularly at high pressures it is found that the shear and normal stress during sliding are closely approximated by the linear law $\tau = A + B\sigma_n$ where A and B are constants. Some investigators define the coefficient of friction for this case to be B whereas the generally accepted definition would be

$$\mu = B + A/\sigma_n.$$

At very high normal stress the error introduced by neglecting the second term may be small but at low normal stress it can lead to considerable error.

This lack of uniformity in reporting friction results has led to considerable confusion. The best way to avoid this confusion would be to publish the force displacement curves for all the experiments but the amount of data that would be involved makes this impractical.

I have chosen to present the data as plots of shear stress against normal stress for each experiment and to state whether the data refers to initial, maximum or residual friction. Although this still leaves a large amount of data to be plotted it is still manageable and there is a minimum amount of confusion as to what the data represents.

3. *Experimental results*

There are three main sources of experimental data on the friction of rock: the civil engineering, the mining engineering and geophysical literature. Civil engineers are interested in rock friction because it is important in problems of slope stability in road cuts, dams, open cast mines, etc. Under these shallow conditions the normal stress across the joints and faults rarely exceed 50 bars. Mining engineers are interested in rock friction at normal stresses up to 1000 bars and apply the friction data to the solution of the design of mine openings at depths as great as 3 km. Geophysicists are mainly interested in the friction of rock at great depths in the earth. Deep focus earthquakes extend to a depth of about 700 km but unfortunately the pressures present at such a depth can not at present be simulated in the laboratory. The normal stress limit for frictional experiments that can be simply interpreted is about 15 k bars. Which is sufficiently high to cover the pressure range for crustal earthquakes.

In this paper we have maintained this division of low, intermediate and high pressure range because first the details of the friction data at low pressure would be lost if plotted on the same scale as the results obtained at high pressure. Secondly, the amount of data involved is very large and needs to be separated into manageable blocks and finally, there are different physical mechanisms involved in the sliding of rock at various pressures. For instance at low pressure the surfaces can move with respect to one another by lifting over the interlocked irregularities but at very high pressure this effect is suppressed and the surfaces then slide by shearing through the irregularities.

4. Low pressure data

Figure 1 shows the friction data for normal stresses up to 50 bars. Most of the data are from BARTON (1973), who collected the data from the civil engineering literature. Because of the great variety of rock types involved he chose to separate the data into only two classes namely igneous and metamorphic rocks and sedimentary rocks. The remaining data are from JAEGER and COOK (1973), and LANE and HECK (1973).

The straight line $\tau = 0.85\sigma_n$ on the figure is the friction obtained at intermediate pressure. It is drawn on this figure simply for reference and by no means implies that it represents a best fit to the data points.

It can be seen in Fig. 3 that there is no strong dependence of friction on rock type, at least between the two broad classifications of rocks into which most of the data are separated. The obvious features in Fig. 3 is that there is a larger scatter in the data. At these pressures the coefficient of friction can be as low as 0.3 and as high as 10. The large variation in friction is due to the variation of friction with surface roughness and BARTON (1976) has proposed that friction of rocks at low stresses can be approximated by the equation:

$$\tau = \sigma_n \tan \left[\mathrm{JRC} \log_{10}\left(\frac{\mathrm{JCS}}{\sigma_n}\right) + \phi_b\right]$$

where JRC is the joint roughness coefficient which varies between 20 for the roughest surfaces to zero for smooth surfaces. JCS is the joint compressive strength which is equal to the unconfined comprehensive strength of the rock if the joint is unweathered but may reduce to one quarter of this if the joint walls are weathered. ϕ_b is a constant. There are so many variable, whose precise value is uncertain, in the equation that its validity cannot be tested.

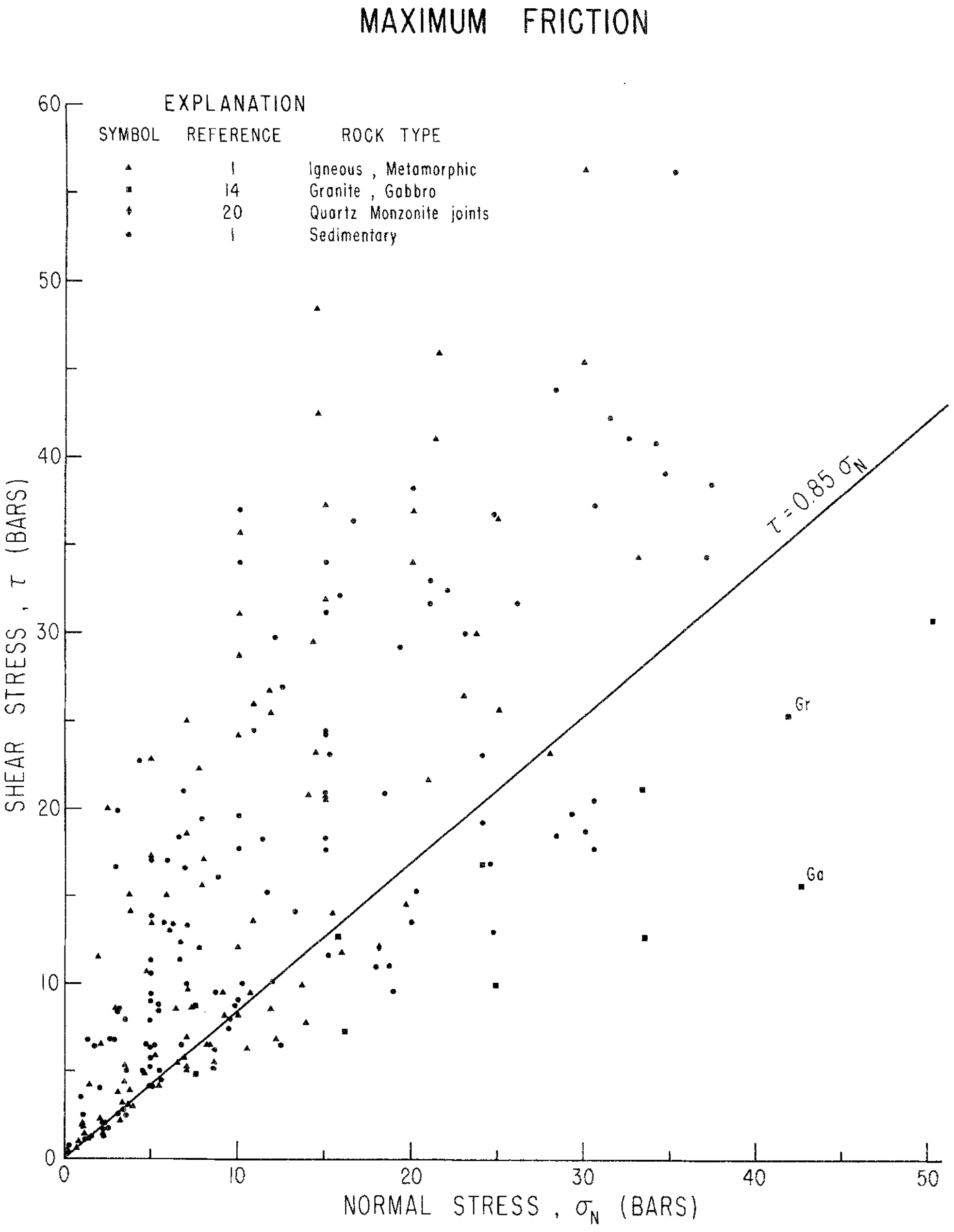

Figure 3
Shear stress plotted as a function of normal stress at the maximum friction for a variety of rock types at normal stresses up to 50 bars.

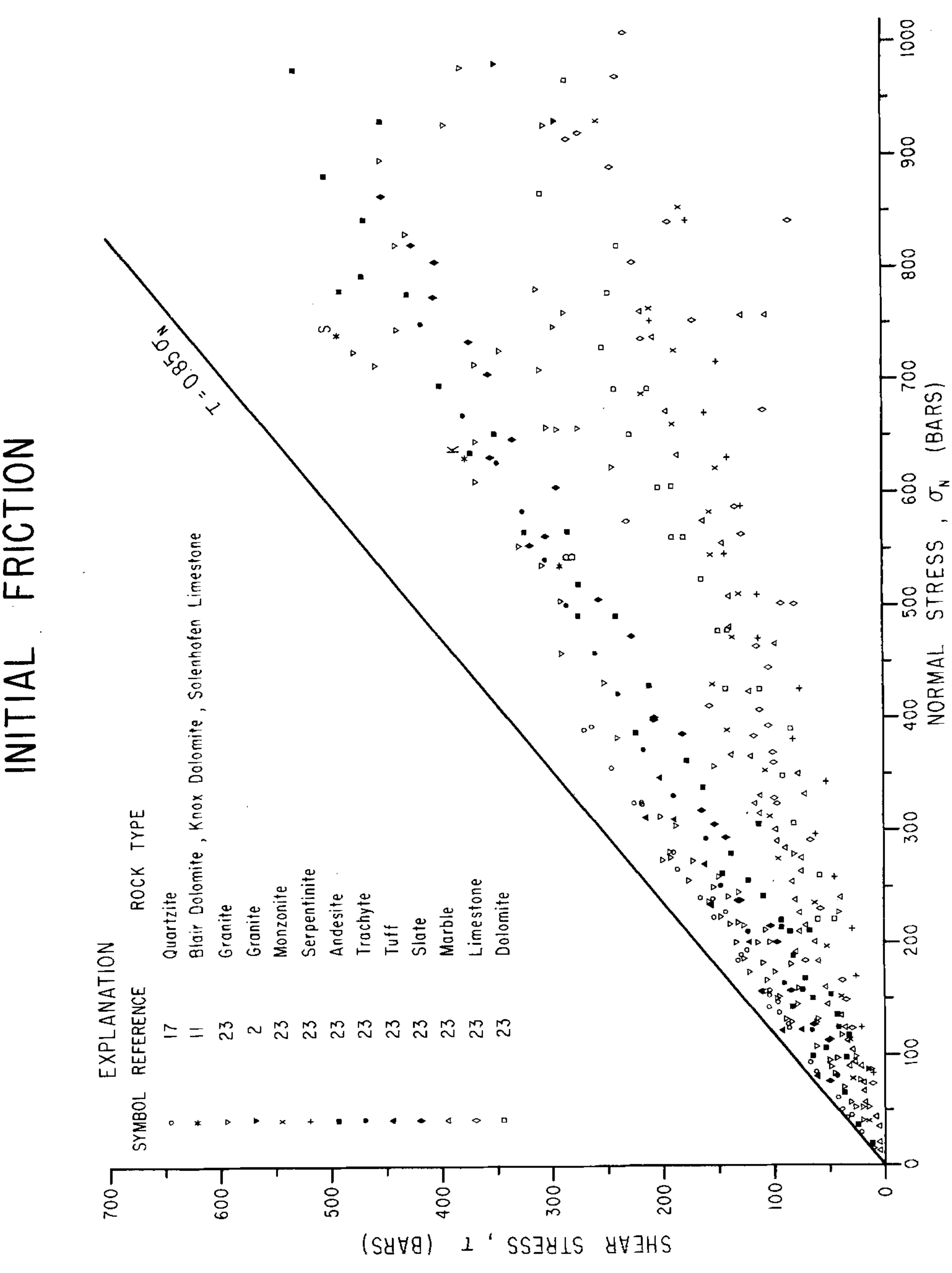

Figure 4
Shear stress plotted as a function of normal stress for the initial friction for a variety of rock types at normal stresses up to 1000 bars.

5. *Intermediate pressure data*

Figure 4 shows the initial friction data at normal stresses up to 1000 bars. The results show that there seems to be no strong dependence of friction on rock type. For instance the initial friction for limestone determined by ONAKA (1975) is close to the lower bound of the plotted data whereas the friction for the same rock type as determined by HANDIN (1969) is close to the upper bound. Also a very strong rock like granite can have about the same friction as a very weak rock such as tuff. The wide scatter in the data may be caused by variation of the initial friction with surface roughness but it is more likely caused by the uncertainty in determining precisely when movement between the sliding surfaces commences.

The maximum friction data shown plotted in Fig. 5 have much less scatter and can be approximated by the equation $\tau = 0.85\sigma_n$. There seems to be little dependence of friction on rock type. A very strong rock such as Quartzite and a very weak rock such as limestone both yield friction data that plot near the upper bound of the data in Fig. 5. Clean joints in a strong rock rock such as quartz monzonite and joints containing a weak material such as plaster both plot near the lower bound of the data shown in Fig. 5.

At these intermediate pressures the initial surface roughness has little effect on friction. Initially finely ground surfaces of sandstone, BYERLEE (1970) have about the same friction as irregular fault surfaces in the same rock type (BYERLEE, 1970).

The question that arises is why is friction at these pressures independent of rock type and initial surface roughness. SCHOLZ and ENGELDER (1976) suggest that friction of rocks can be explained by the adhesion theory of friction first proposed by BOWDEN and TABOR (1950). According to the theory, when two surfaces are placed together they touch at a small number of protuberances or 'asperities'. The normal stress at these will be very high and exceed the yield stress or penetration hardness Y of the material so that the real area of contact Ar will be $N = YAr$ where N is the normal force acting across the surfaces. At these junctions the contact is so intimate that they become welded together and for sliding to take place these junctions must be sheared through. If S is the shear strength of the material then $T = SAr$ where T is the tangentint force required to cause sliding. Combining the two equations and dividing by the apparent area of contact we have

$$\tau = \frac{S}{Y}\sigma_n$$

with metals the junctions deform plastically both in shear and in compression so that the compressive strength and shear strength are related and the coefficient of friction will be a constant independent of the strength of the material. Rocks however fail by brittle fracture and while there may be some relationship between the shear strength and compressive strength of the asperities the physical process involved during their failure is far more complex than the simple adhesion theory would predict.

Byerlee (1967) proposed that the asperities deform brittly and that for sliding to occur the irregularities on the surfaces fail by brittle fracture. A theory was developed which predicts that the friction of finely ground surfaces that only touch at the tips of the asperities should be independent of the strength of the material. The theory however has not been extended to the more general situation of interlocked surfaces, when the forces act not only at the tips of the asperities, but are distributed over their sides. Further theoretical studies of this important problem are required.

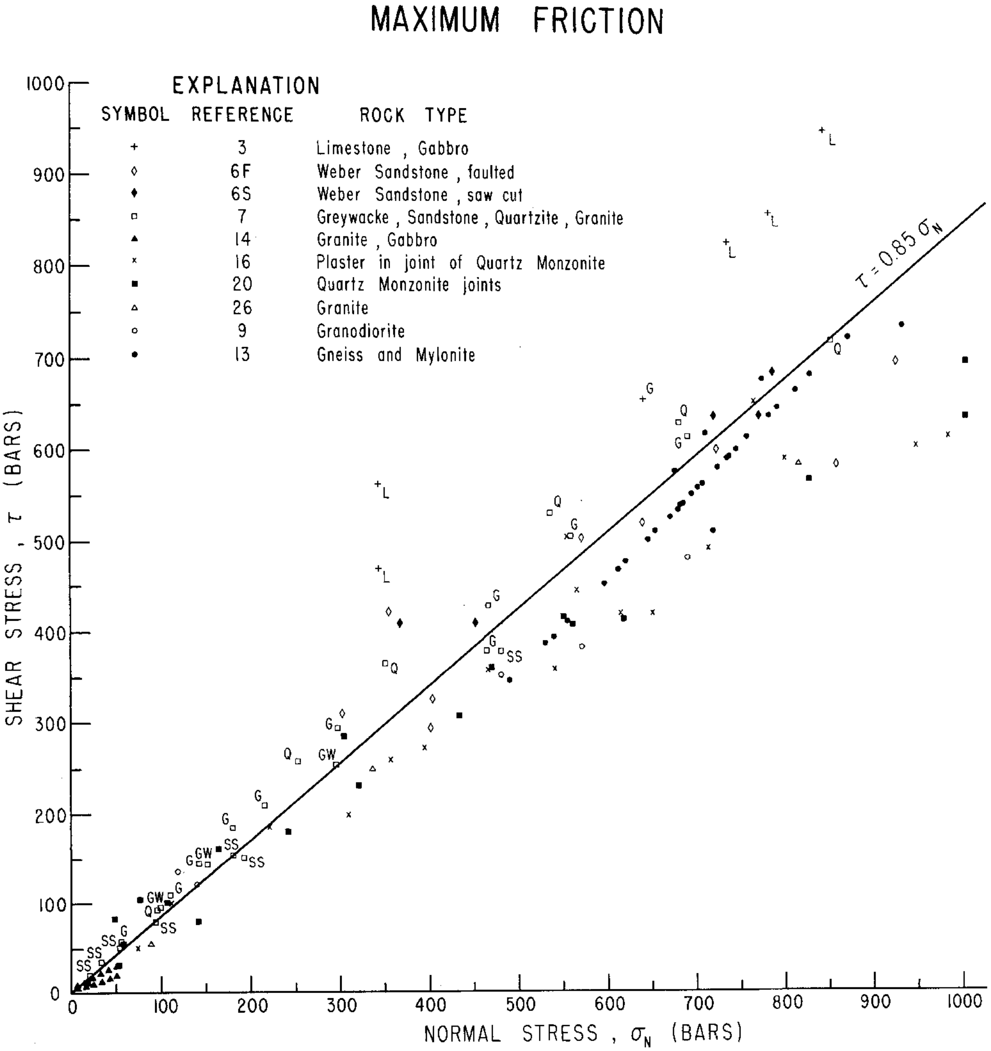

Figure 5

Shear stress plotted as a function of normal stress at the maximum friction for a variety of rock types at normal stresses to 1000 bars.

6. *High pressure data*

Figure 6 shows the initial friction in some experiments carried out at a normal stress as high as 7 k bars but the data are too few to come to any conclusions about the effect of rock type on the initial friction.

Figure 7 shows the maximum friction for a number of rock types and gouge material at pressures up to 17 k bars. If we neglect for the moment the data points obtained for sliding with gouge, then the rest of the data scatter about two straight lines.

$$\tau = 0.85\sigma_n \qquad \sigma_n < 2\ \mathrm{kb}$$
$$\tau = 0.5 + 0.6\sigma_n \quad 2\ Kb < \sigma_n < 20\ \mathrm{kb}$$

Byerlee (1968) drew a curved line through the friction data points obtained at high pressure and Murell (1965) has proposed an equation of the form

$$\tau = A\sigma_n^k$$

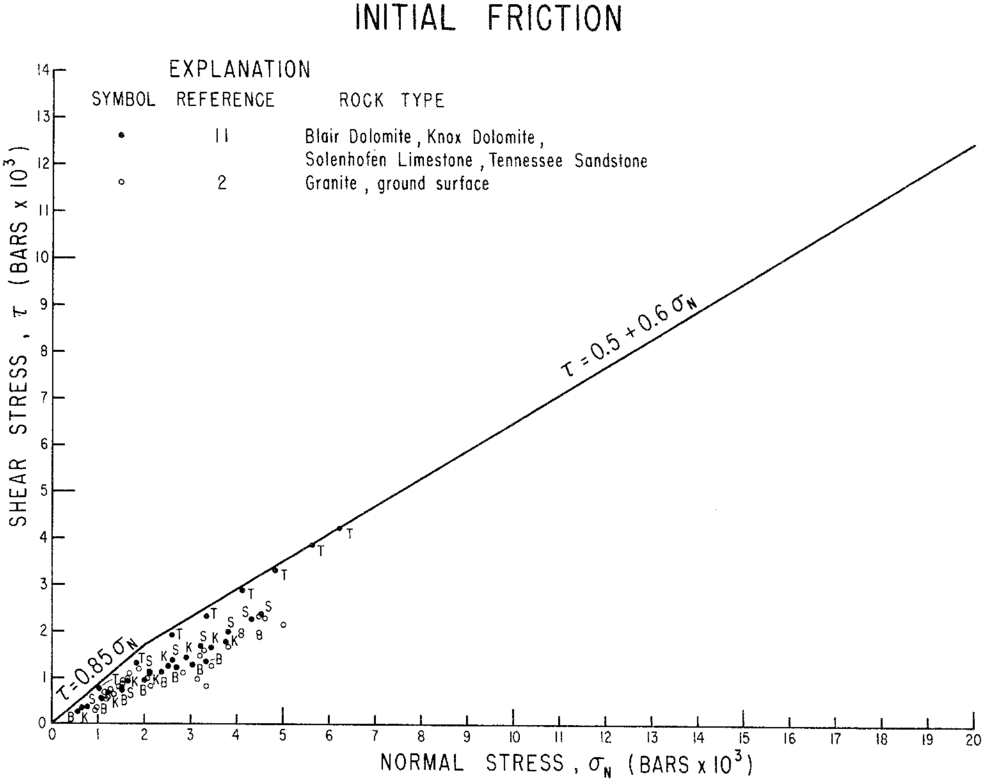

Figure 6
Shear stress plotted as a function of normal stress at the initial friction for a variety of rock types at normal stresses to 20 kb.

where A and K are constants. For most practical problems however a straight line fit to the data is sufficiently accurate and is much easier to handle analytically.

The experimental data shows that at high pressure friction seems to be independent of rock type. For example, weak rocks such as sandstone, and limestone have about the same friction as very strong rocks such as granite and gabbro.

For surfaces separated by a large thickness of fault gouge the friction is still much the same as for initially clean surfaces provided that we neglect the data for montmorillonite, vermiculite and illite. Serpentine does give, in one of the high pressure experiments, a slightly low value for friction but crushed granite and minerals such as chlorite, kaolinite and halloysite, which are normally considered to be very weak have about the same friction as initially clean surfaces of very strong rocks such as granite. Montmorillonite and vermiculite have water between the clay particles and

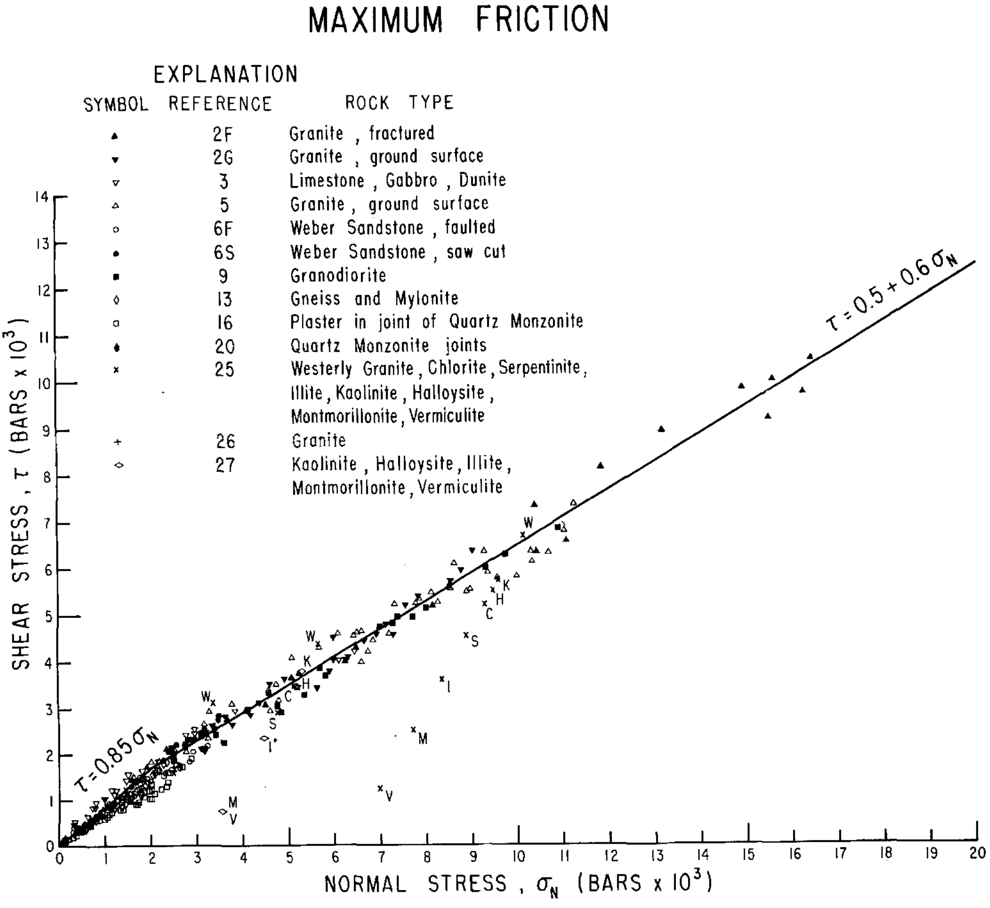

Figure 7
Shear stress plotted as a function of normal stress at the maximum friction for a variety of rock types at normal stresses to 20 kb.

SUMMERS and BYERLEE (1977) suggest that this free water may act as a pseudo pore pressure to reduce the effective pressure in the material to lower the friction. This explanation however would not be applicable for illite. WU *et al.* (1977) has suggested that during shear the minerals could become rotated until the easy slip direction becomes aligned parallel to the direction of shear but this mechanism would also be expected to operate with other platy minerals such as, chlorite, kaolinite, halloysite and serpentine but these materials have high friction. Clearly more work is required on this problem.

7. Conclusions

The experimental results show that at the low stresses encountered in most civil engineering problems the friction of rock can vary between very wide limits and the variation is mainly because at these low stresses friction is strongly dependent on surface roughness. At intermediate pressure such as encountered in mining engineering problems and at high stresses involved during sliding on faults in the deep crust the initial surface roughness has little or no effect on friction. At normal stresses up to 2 kb the shear stress required to cause sliding is given approximately by the equation

$$\tau = 0.85\sigma_n.$$

At normal stresses above 2 kb the friction is given approximately by

$$\tau = 0.5 + 0.6\sigma_n.$$

These equations are valid for initially finely ground surfaces, initially totally interlocked surfaces or on irregular faults produced in initially intact rocks. Rock types have little or no effect on friction.

If however, the sliding surfaces are separated by large thicknesses of gouge composed of minerals such as montmorillonite or vermiculite the friction can be very low. Since natural faults often contain gouge composed of alteration minerals the friction of natural faults may be strongly dependent on the composition of the gouge.

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