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MECHANICS OF CRUSTAL EARTHQUAKES

by

W.F. Brace, Principal Investigator

Department of Earth & Planetary Sciences
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FINAL TECHNICAL REPORT

December 1, 1971

Sponsored by

Advanced Research Projects Agency

ARPA Order No. 1579

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Contract Period: 11/17/70-11/16/71

Project Officer: James J. Olsen
Twin Cities Mining
Research Center.
Twin Cities, Minnesota
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SUMMARY

This report includes the work accomplished and results achieved during the twelve month period of the contract. The report is in four parts: Parts I and II give the results of analytical studies, and Parts III and IV give the results of measurements at high temperature, as well as a review of the effect of all known physical parameters on stick-slip.

The theory of stick-slip is developed, based on the concept of a static and dynamic coefficient of friction. The dynamic coefficient is assumed to be independent of displacement and to depend wholly on normal stress across the surface. It is also assumed to be velocity-independent. The theory predicts that the stress drop during stick-slip is independent of machine stiffness. The displacement during stick-slip is by contrast directly proportional to the machine compliance. Two series of experiments with different fault angles would serve to evaluate the dynamic coefficient of friction.

Stiffness has been suggested as an important parameter in frictional behavior of rocks. Stiffness is calculated for a long, shallow, vertical surface fault of finite depth, which has slipped with a uniform stress drop over the surface. It is found that stiffness for typical source dimensions is several orders of magnitude lower than stiffness in typical laboratory high pressure experiments. As stick-slip is

probably enhanced in softer systems, stick-slip observed in the laboratory will probably also be observed under geologic conditions, other factors being comparable.

Frictional sliding on sawcuts and faults in laboratory samples of various silicate rocks is markedly temperature-dependent. At pressures from 1 to 5 kb, stick-slip gave way to stable sliding as temperature was increased 200° to 500°C. The particular temperature of transition to stable sliding varied with rock type.

Stick-slip on pre-existing faults has been suggested as one source of crustal earthquakes. We review current laboratory studies of stick-slip to note factors which determine whether sliding is stable or unstable in laboratory samples, point out ways in which the laboratory experiment may not model the situation in the earth, and emphasize areas in which further laboratory study is needed.

The most important factors which determine whether sliding will be unstable (stick-slip and earthquake-producing) or stable (stable sliding or fault creep) include mineralogy, porosity, effective confining pressure, temperature and thickness of fault gouge. In general, stable sliding is enhanced by high temperature, low effective pressure, high porosity, thick gouge, and the presence of even small quantities of minerals like serpentine and calcite.

It is still not clear just how well the laboratory experiment models a seismic region in the earth. This is in part because both the detailed geometry of natural seismic

faults and factors like gouge thickness are not well-known. Also, it has not yet been possible in the laboratory to study the characteristics of a fault in which slip is limited to part of the surface, as is the case in a typical seismic area. The laboratory experiment also does not correctly model the real situation in which normal stress, temperature, and effective pressure may vary along the fault surface.

In addition to design of experiments in which the above features are included, work should be done both on the theory of stick-slip and on a better understanding of the physical characteristics of rocks responsible for observed differences in sliding behavior.

PART I

An analysis of stick-slip on rock surfaces in
the laboratory

Pierre-Yves F. Robin

ABSTRACT

The theory of stick-slip is developed, based on the concept of a static and dynamic coefficient of friction. The dynamic coefficient is assumed to be independent of displacement and to depend wholly on normal stress across the surface. It is also assumed to be velocity-independent. The theory predicts that the stress drop during stick-slip is independent of machine stiffness. The displacement during stick-slip is by contrast directly proportional to the machine compliance. Two series of experiments with different fault angles would serve to evaluate the dynamic coefficient of friction.

INTRODUCTION

Stick-slip is a type of relative motion between two surfaces in contact, under the action of shear stresses. It is characterized by jerky movements, separated by intervals during which no significant relative displacement occurs. This effect has been studied in metals (1, 2, 3)

and, more recently, in rocks (4, 5, 6). Stick-slip in metals has usually been interpreted in terms of two coefficients of friction, one static and one dynamic. However, because the experimental systems used were dynamically complex, the problem of deducing the value of the dynamic coefficient of friction from the observed motion has not yet been solved (7). On rock surfaces, stick-slip has also been interpreted as the result of a dynamic coefficient of friction smaller than a static one (8). It is also possible, however, that stick-slip results from random variations of the average coefficient of friction as the two surfaces move by each other.

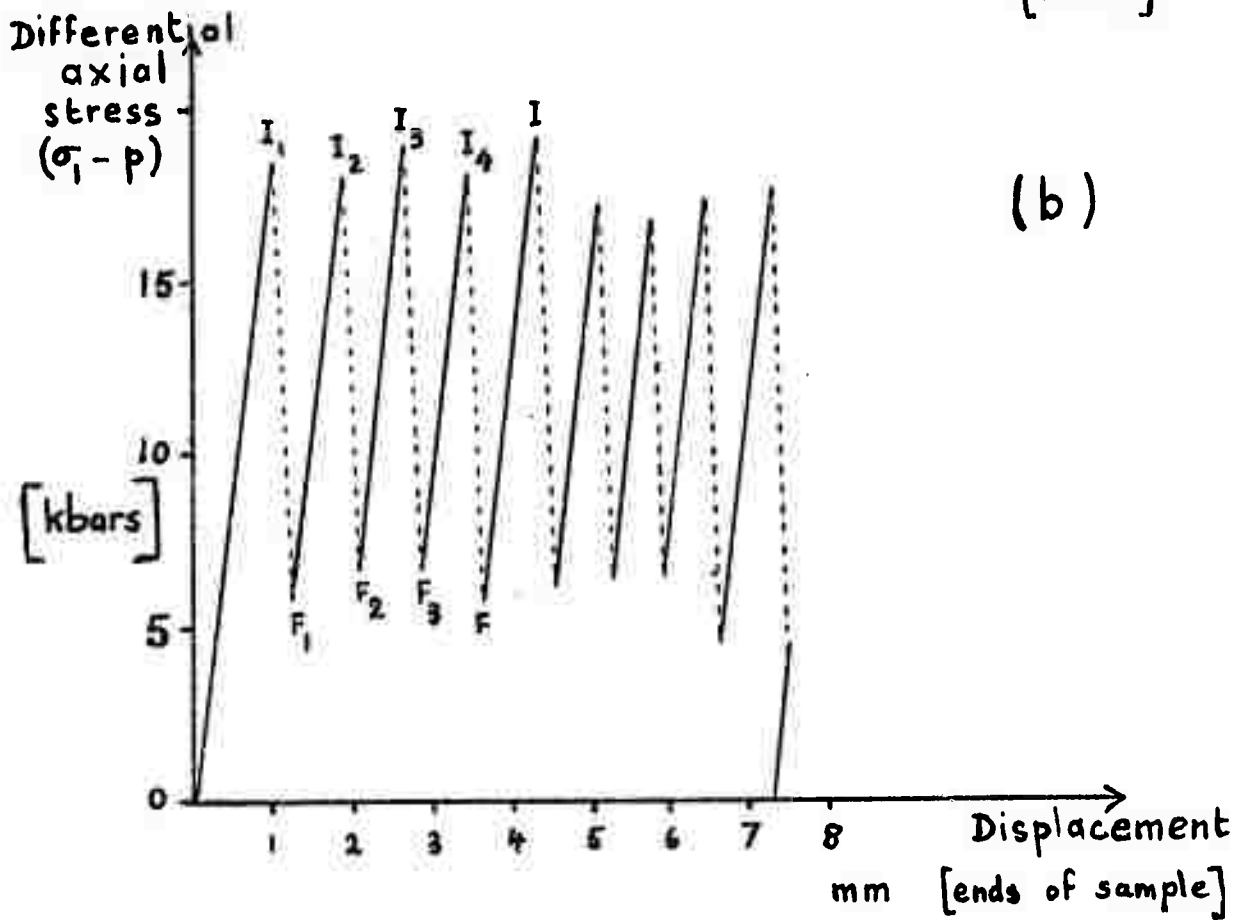
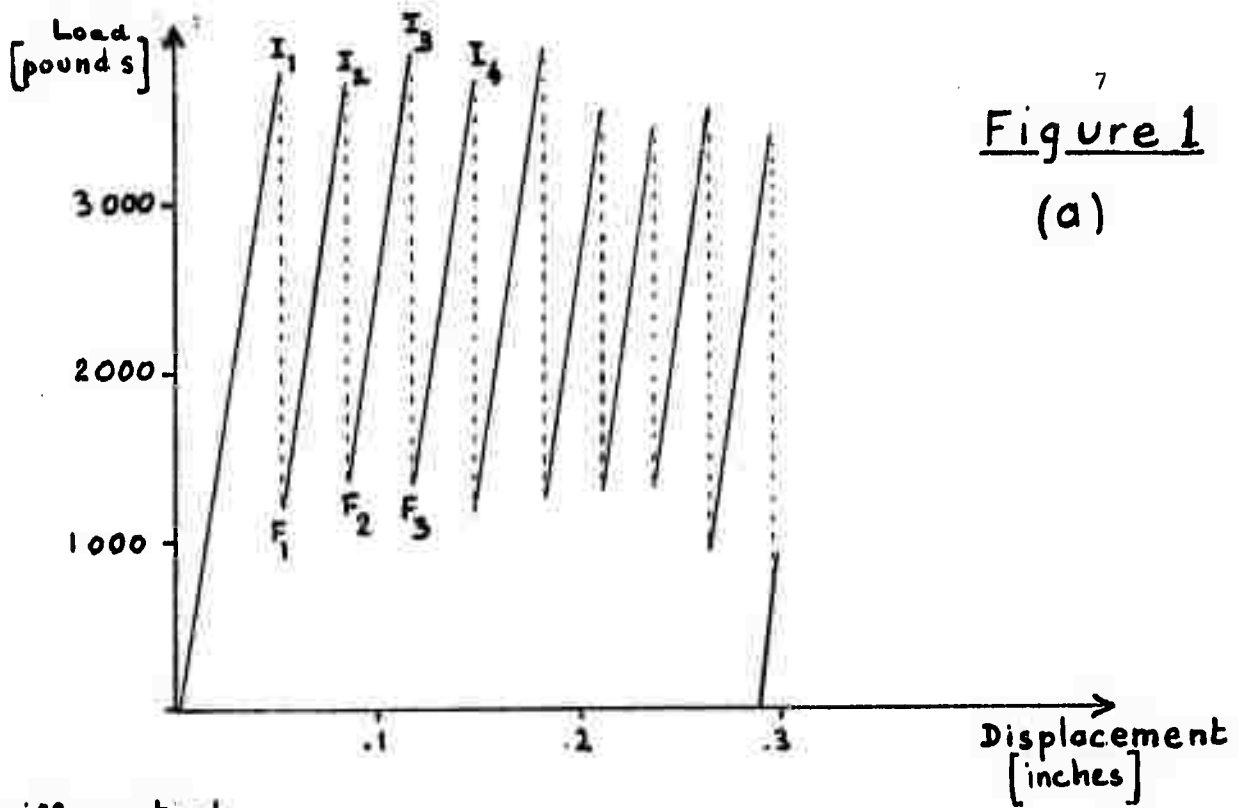
An understanding of this phenomenon is important to the geophysicist, because stick-slip is a possible mechanism for earthquakes (6, 9, 10). As Burridge and Knopoff (10) forcefully put it, "the nature of the friction during a shock determines the configuration of the system when it has finally come to rest. It is this final state that determines the conditions surrounding the next succeeding shock. Hence, if the demonstrations of the laboratory and numerical models are borne out in nature, it would seem likely that the nature of the friction on a fault surface determines the statistical properties of the earthquake shocks that are observed"

This paper analyses the dynamics of stick-slip for the experimental system which is most likely to provide data

pertinent to earthquake studies. The analysis shows how characteristics of friction may be obtained from experimental results. Available data (11) do not contradict the hypotheses proposed.

REPRESENTATION AND CHARACTERISTICS OF STICK-SLIP MOTION

In a typical experimental study of friction on rocks, a cylindrical specimen has a pre-existing cut at an angle with its axis. Jacketed, this specimen is submitted to a constant confining pressure p , and a load parallel to the axis of the cylinder is then applied. The displacement measured is the relative displacement, parallel to the axis, of two parts of the machine on either side of the specimen, usually sufficiently far from the actual cut to show no significant displacement during the stress drop. A typical record is shown on Figure 1(a). Such an experiment is often reported as Figure 1(b) (e.g. 6), obtained from Figure 1(a) by removing from the displacement the part which is due to the elastic compliance of the machine. Slopes of lines like F_1I_2 are the same as the slope corresponding to the elastic deformation of the whole specimen, except, perhaps, very close to I_2 . It is concluded that, in general, no significant sliding occurs along the cut when the stress increases from F_1 to I_2 . Hoskins et al (5), with an experimental system widely different from the one described here, and with a



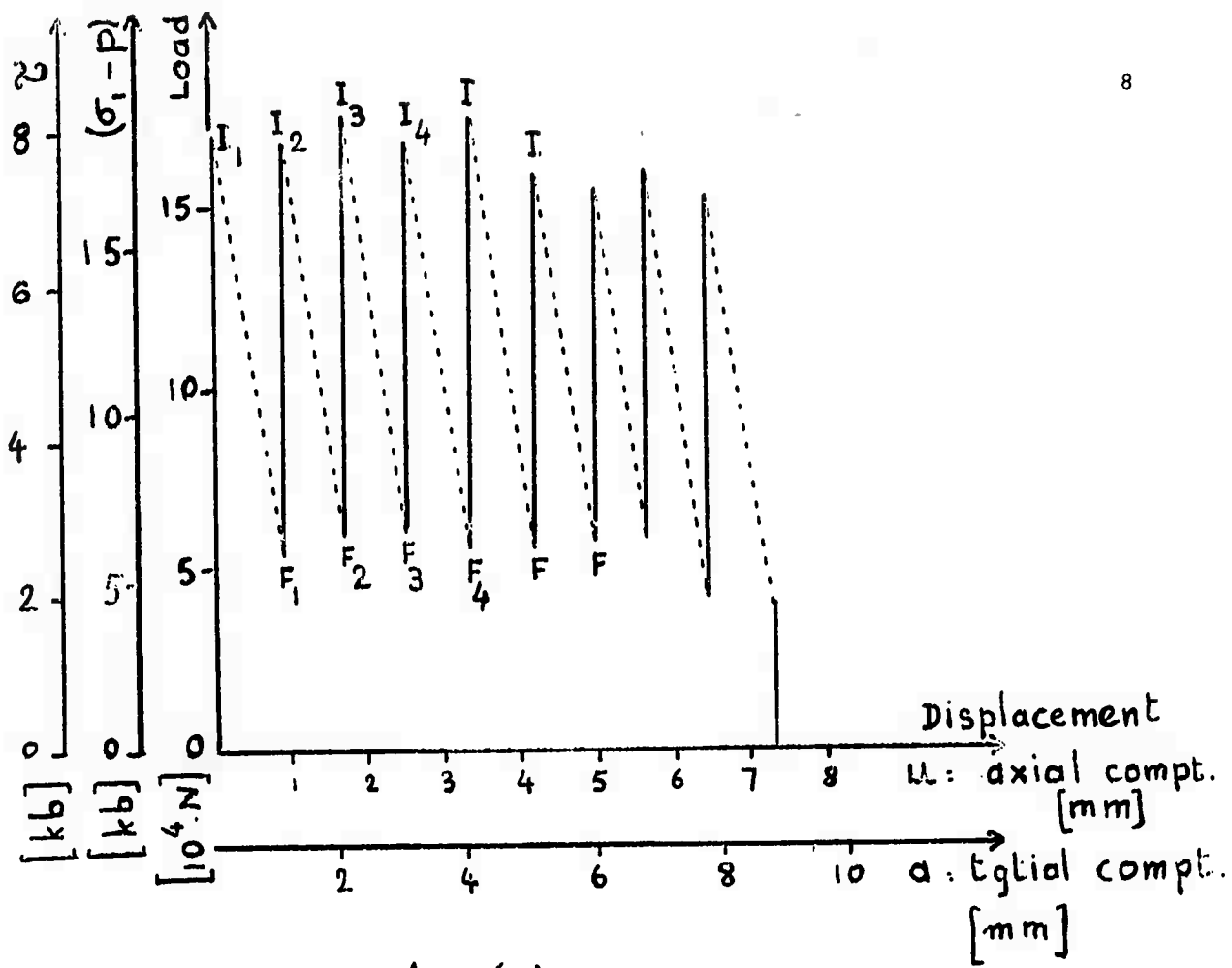


Figure 1 (c)

Various representations of a stick-slip experiment. Westerly Granite (sample diameter: 0.625 in; ground surface, at angle $\theta = 30^\circ$; confining pressure: 4.59 kb). After Byerlee (11).

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normal load never exceeding 70 bars, showed some movement along the surface, at constant value of stress, before the slip occurs. In general, however, we will assume that displacement only occurs during the stress drop.

If the angle of cut θ is defined as shown on Figure 4, differential stress $(\sigma_1 - p)$ and confining pressure p can be converted into normal and shear stresses by the following equations

$$\sigma_n = p + (\sigma_1 - p) \cdot \sin^2 \theta \quad (1)$$

$$\tau = (\sigma_1 - p) \cdot \sin \theta \cdot \cos \theta \quad (2)$$

Stick-slip experiments may then be reported as on Figure 1(c), where the displacement plotted is the relative displacement a parallel to the surface, or its axial equivalent u .

$$\Delta u = \Delta a \cdot \cos \theta \quad (3)$$

Figure 1(c) can be considered as transformed from Figure 1(a) by subtracting the displacement due to the compliance of the "machine", where "the machine" is now understood to include the length of the specimen. Because, indeed, for the surface in motion, it is, to this point, immaterial whether the compliance is provided by steel, granite or Teflon, this representation is preferable. It may be pointed out also that the affine transformation from 1(a)

to 1(c) can be performed geometrically, without having to measure separately the various compliances involved. The displacement of the driving mechanism during the time of a stress drop can be neglected, and the slope of lines like $I_1 F_1$ (in axial load vs. axial displacement coordinates) is therefore equal to the inverse of the compliance S of the "machine".

The shear stress at points like I_1 is the shear stress necessary to overcome friction. After a number of stress drops which depends on the confining pressure, some equilibrium is reached, and the stresses at points like I_3 , I_4 , etc. remain approximately constant, sometimes remarkably so (5, 6). Values of the stress drops are often quite regular; they are, typically, of the order of half the maximum stress.

THEORY

In this paragraph and the next, it is often easier to deal with differential axial load F and axial displacement u than with the shear stress τ and the displacement parallel to the friction surface a . As seen on Figure 1(c), the transformation involves only a change of scale along the axes, and the conversion factors are based entirely on the geometry of the system. In particular u (Eq. 3) designates the axial component of a , i.e. of the relative displacement

of two points immediately adjoining the cut and on either side of it. Also, the following quantities, having the dimension of a work, are equal:

$$F \cdot du = A \cdot \tau \cdot da$$

where A is the surface area of contact.

Clearly, stick-slip requires that the resistance to shear, immediately after initiation of motion, would be smaller than before motion. If this were not the case, as an infinitesimal motion, du , causes a decrease $dF = S \cdot du$ in the force applied by the machine, further motion would then be resisted by friction, until the driving mechanism raises F again. Sliding on the surface would then be stable. Before exploring the various possibilities, it is useful to study the energy transformations during stick-slip. The argument given here is similar to the one given by Rabinowicz (7), but includes the seismic energy in the system.

Let E_I be the initial elastic stored in the machine, before slip occurs. During the stress drop, neglecting the very small amount of energy given by the driving mechanism, this energy is transformed into several terms:

$$E_I = E_H + E_P + K_K + E_C \quad (4)$$

where E_H is the heat, or friction energy, generated on the surface;

E_P is the sum of the potential elastic energies of all parts of the system;

E_K is the sum of the kinetic energies of all parts of the system; E_K may include attenuation energy, i.e. heat generated, by vibrations, elsewhere than on the friction surface;

E_C is the work done against the confining pressure.

In general, when relative motion across the friction surface stops, not all parts of the system stop. The terms E_P and E_K of equation (4) can be redistributed into an elastic potential term for the final position E_F , and a seismic term E_S . E_S , like E_K , may include or transform into heat, generated elsewhere than on the friction surface. The energy equation becomes

$$E_I = E_H + E_F + E_S + E_C \quad (5)$$

Now, the origin of the axial displacement u can be taken at the position before motion, and u may be defined as positive as in Figure 1. The heat generated is then given by

$$E_H = \int_0^u F. dy \quad (6)$$

Because forces are taken as positive when corresponding to compressions, the compliance S of the machine is a negative quantity. It can be assumed constant over the range of the stress drop. Calling F_I the axial force on the surface at

equilibrium, before initiation of motion, the decrease in elastic energy is

$$E_I - E_F = \int_0^u (F_I + \frac{1}{S} y) dy + E_C \quad (7)$$

Substituting (6) and (7) into (5) gives:

$$\int_0^u (F_I + \frac{1}{S} y - F) dy = E_S \quad (8)$$

E_S , the energy dissipated seismically, is always positive. Therefore Equation (8) is expressed by the following inequality for the oriented surface areas of Figure 2:

$$A_1 + A_2 > 0 \quad (8')$$

The possibility, mentioned earlier, that stick-slip would result from random variations of the average friction coefficient across the interface can be represented as on Figure 3(a). Several features of Figure 3(a) distinguish it from Figure 1(c) and make this theory difficult to reconcile with the observed phenomenon without further modification.

After a stress drop, the shear stress across the surface increases without displacement, along branches like F_1G_1 , and this is similar to branches F_1I_1 in Figure 1(c). But stable sliding along branches like F_1I_1 would then occur, following the random friction curve. The stress levels at

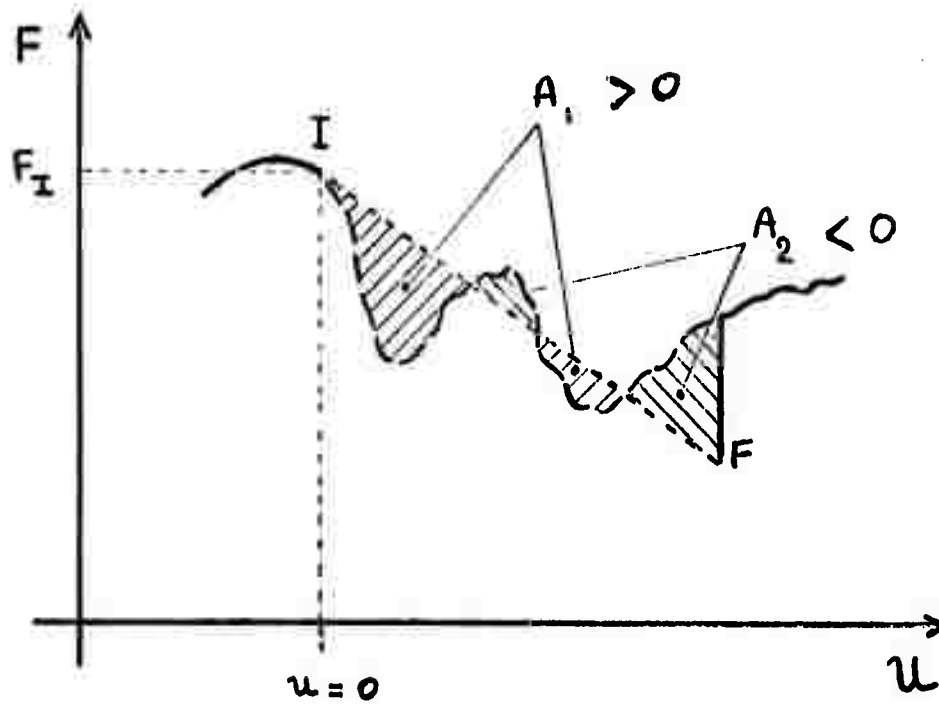


Figure 2

$$A_1 + A_2 > 0$$

Energy equation for stick-slip when friction varies with displacement.

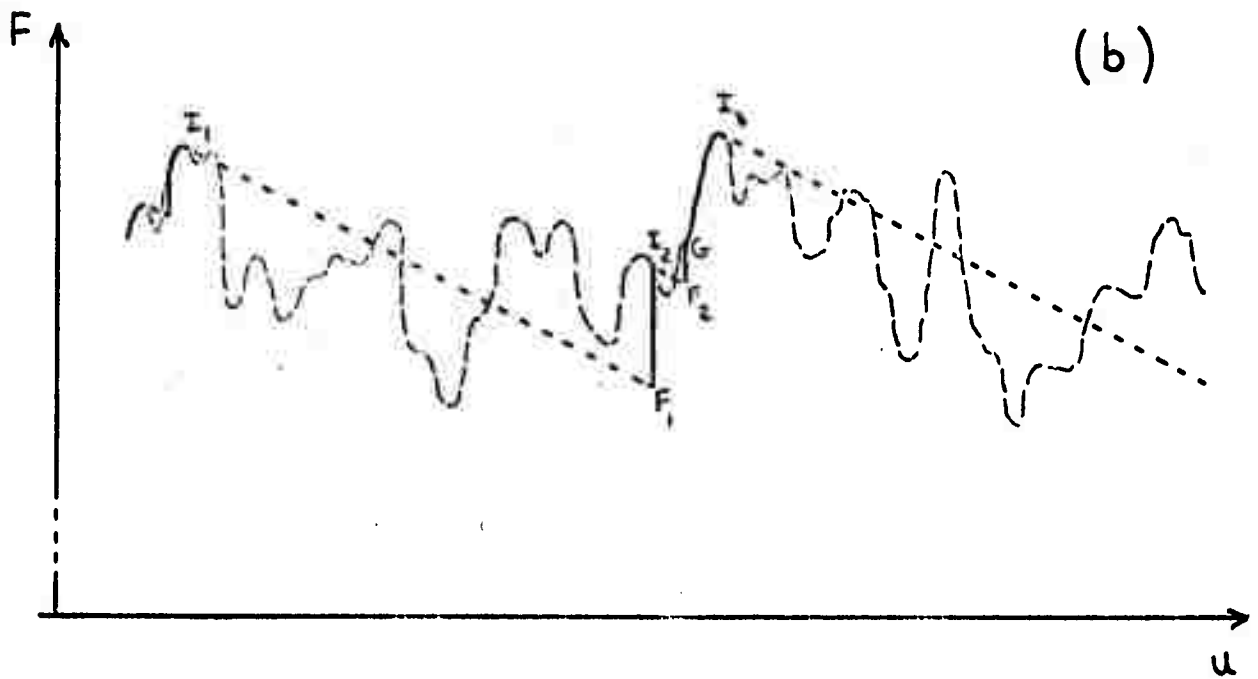
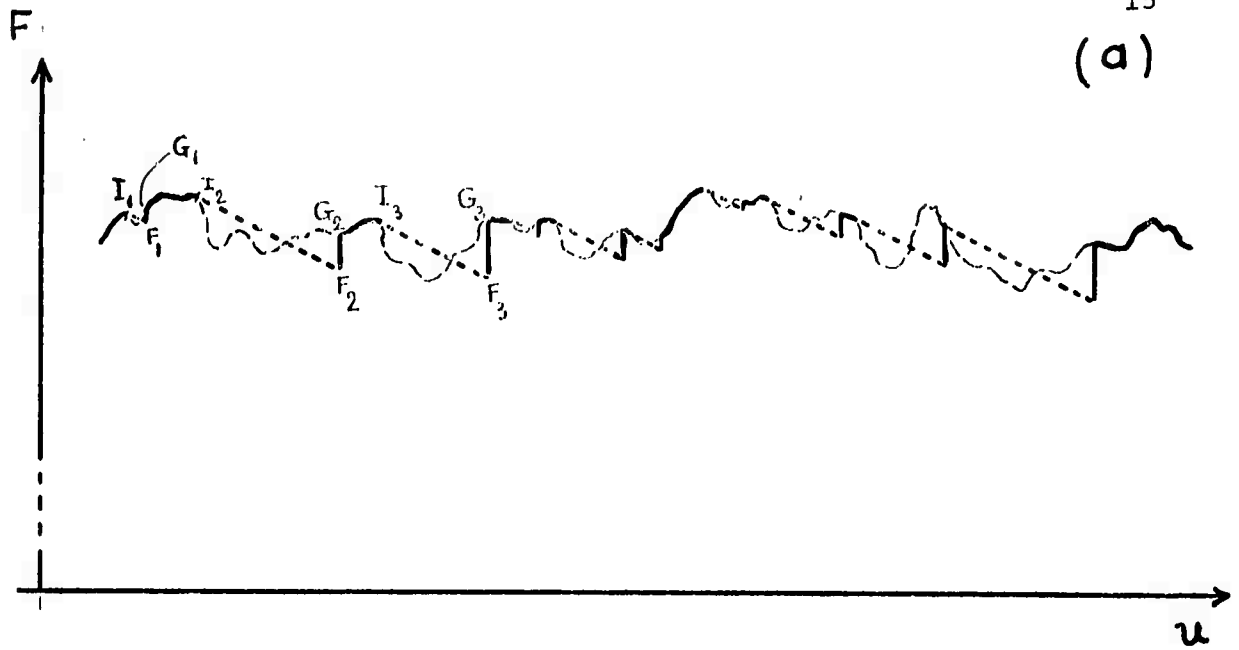


Figure 3

Irregular stick-slip, caused by variation of the resistance of friction with displacement.

point I or F would also be expected to show wider variations than the ones observed. Finally, a reduction of the compliance of the machine would be expected to cause stick-slip to disappear, and this is not found by experiments (6). This model can account, however, in a rough qualitative way, for the observed increase in the amplitude of the stress drop with an increase in confining pressure. Figure 3(b) is similar to Figure 3(a), drawn for the same hypothetical interface, under a higher normal stress. The compliance of the machine, however, is approximately unchanged. The stress drops can be seen to be statistically higher than in the case of Figure 3(a). In spite of this, and because of the reasons given previously, irregular variation with displacement of the average friction as an explanation of stick-slip (Rabinowicz's irregular stick-slip, 7) is tentatively rejected here. The other possibility, accepted for metals, is to consider the existence of a dynamic coefficient of friction, smaller than the static coefficient of friction, without at first trying to explain the physical nature of this difference. A priori, many factors may influence this dynamic coefficient of friction. As suggested by its very appearance, the dynamic coefficient may depend on the velocity of relative displacement during the stress drop itself; or it may also depend on the amount of relative displacement since the beginning of the individual stress drop. The dynamic coefficient may also depend on the

total amount of displacement since the beginning of the experiment. It may be a function of the normal stress across the sliding surface, or a function of the orientation of the stress quadric with respect to the surface.

Before developing the model, for reasons of simplicity, the following assumptions will be made:

- (1) The dynamic coefficient of friction is independent of the total amount of displacement since the beginning of the experiment. This may be justified by the fact that, after a few initial stress drops, stick-slip becomes a fairly stable phenomenon, as mentioned in Section II.
- (2) The dynamic coefficient, like the static (e.g. 4, 5, 12), depends only on the normal stress across the surface, and does not otherwise depend on the orientation of the stress quadric. The law of static friction for many rocks can be expressed by a relation of the form (4, 5, 6, 12)

$$\tau = S_s + \mu_s \cdot \sigma_n \quad (9)$$

where S_s and μ_s are constants. In the same way, dynamic friction is assumed to be of the form

$$\tau = S_d + \mu_d \cdot \sigma_n \quad (10)$$

- (3) μ_d is constant, i.e. independent of the amount of displacement during the individual stress drop,

or of the displacement velocity. It is not essential that μ_d reaches this constant value at the immediate initiation of motion, but it is assumed to have reached it during most of the motion. This assumption can only be justified, refined or discarded by the agreement or disagreement of predictions based on it with experimental results.

The development of the model is now a relatively simple matter.

DEVELOPMENT OF THE MODEL

A schematic diagram of the machine of the model is shown on Figure 4. The shear stress component on the surface is applied through a "column" of springs of varying characteristics (steel, rock, etc.). The surface area of friction, A , is assumed not to vary significantly during one single stress drop. Under the highest confining pressure, A may in fact vary by 3 or 4%. The confining pressure p is kept constant during the stress drop.

Immediately before initiation of motion the stress components near the surface are related by Equations (1) and (2); σ_n and τ are themselves related by Equation (9). Equations (1), (2) and (9) combine into

$$\sigma_{1,s} = p + \frac{S_s + \mu_s \cdot p}{\sin \theta (\cos \theta - \mu_s \sin \theta)} \quad (11)$$

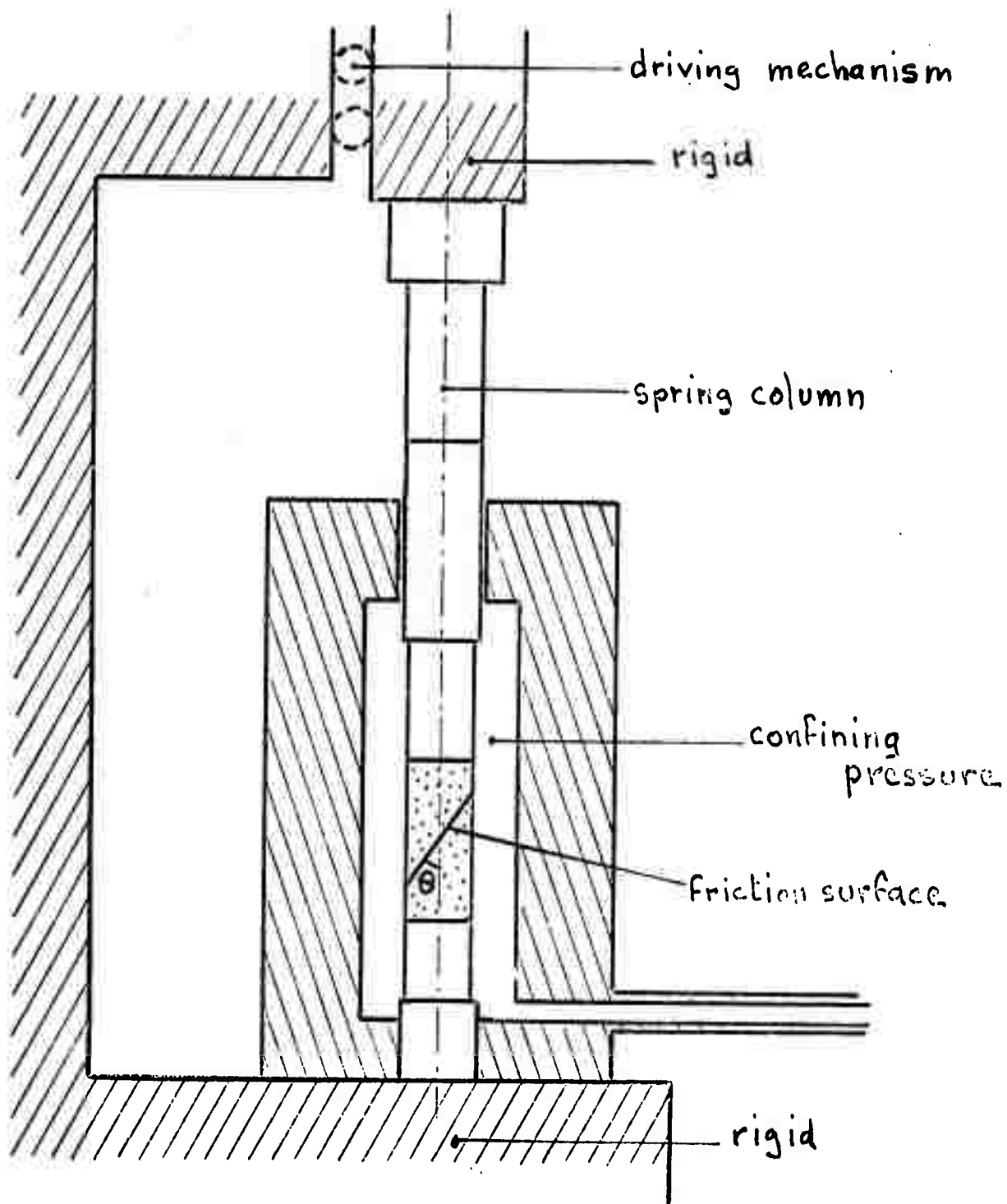


Figure 4

Sketch of a machine used to study stick-slip on rock surfaces with high normal pressures.

Consider now the state of stress during motion, in the immediate vicinity of the surface. The inertial forces due to lateral accelerations in the specimen are neglected. The minimum principal stresses are still $\sigma_1 = \sigma_2 = p$. The angle θ being unchanged, Equations (1) and (2) are still the transformation laws. When they are combined with Equation (10), the same algebra as in the static case leads to a similar equation:

$$\sigma_{1,d} = p + \frac{s_d + \mu_d \cdot p}{\sin \theta (\cos \theta - \mu_d \cdot \sin \theta)} \quad (12)$$

To $\sigma_{1,s}$ and $\sigma_{1,d}$ correspond axial forces F_s , F_d , by the geometric relation $F = A \sin \theta \cdot \sigma_1$. The problem can now be expressed in the following manner: a spring column, along which mass and compliance are distributed non-uniformly, is compressed, in equilibrium, by a force F_s . The force is suddenly reduced to a lower value F_d . What is the amplitude of the first uniform motion of the end of the spring?

Figure 5 is another sketch of the spring column. The coordinate along it is x . The column is fixed rigidly at $x = 0$. The displacement of a point, $\mu(x, t)$, is a function of time. The specific mass per unit length is a function of position, $m(x)$, and is always positive. The specific compliance is also a function of position, $s(x)$. Because of our convention that compressions are positive and that displacements corresponding to stress drops are also positive, $s(x)$ is

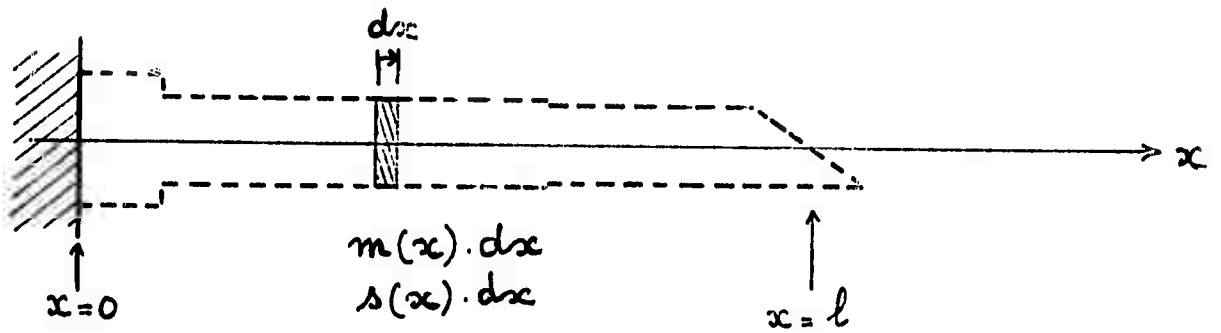


Figure 5

Diagram of the spring column.

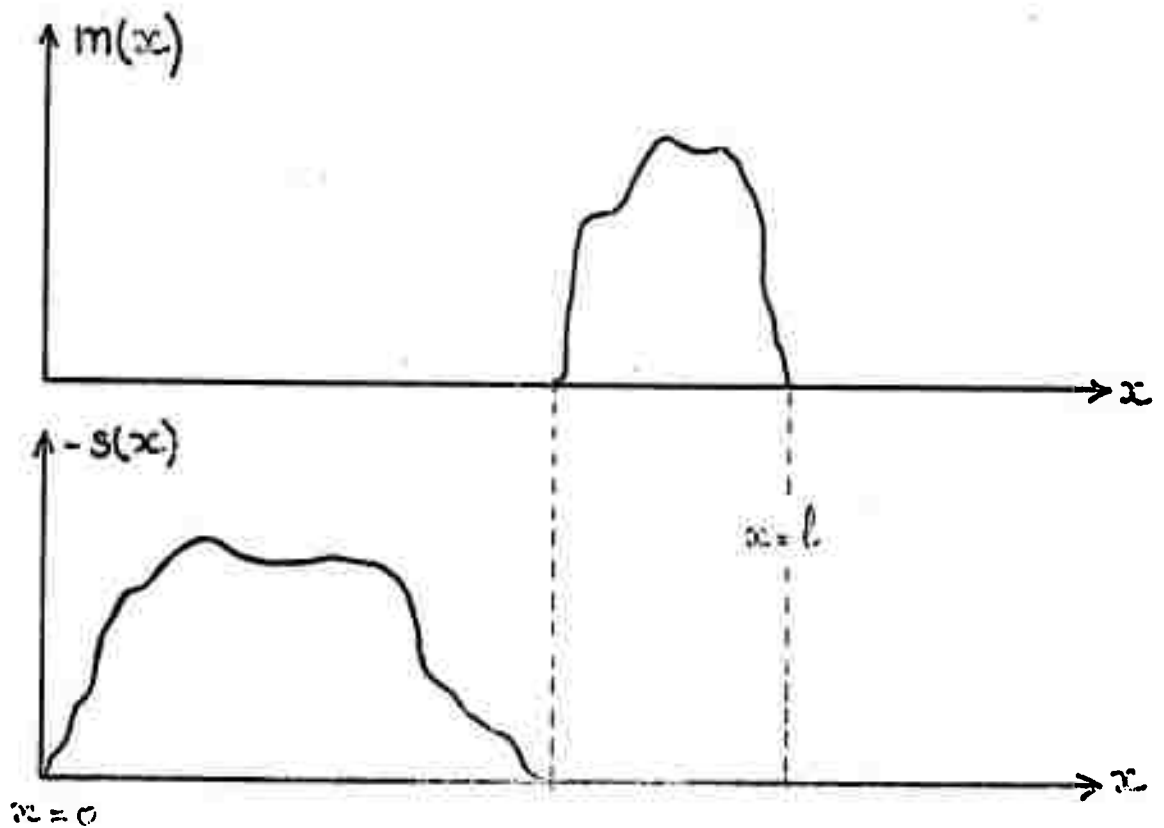


Figure 6

Distribution of mass and compliance. Case of a rigid mass at the end of a massless spring.

always negative; $s(x)$ can be zero (rigid section), but cannot be infinite. The total compliance of the machine is given by:

$$\int_0^1 s(x) \cdot dx = S, \text{ negative} \quad (13)$$

The origin of displacements $u(x, t)$ may be taken as the position of each section immediately before slip. It can be shown that the equation of motion is:

$$\frac{\partial^2 u}{\partial t^2} + \frac{1}{m(x)} \cdot \frac{\partial}{\partial x} \left(\frac{1}{s(x)} \cdot \frac{\partial u}{\partial x} \right) = 0 \quad (14)$$

The initial conditions are that

$$\begin{aligned} \text{at } t = 0 : \quad & u(0, t) = 0 \\ & \frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial t^2} = 0 \text{ for any } x \\ & \frac{1}{s(x)} \cdot \frac{\partial u}{\partial x} = 0 \text{ for any } x \end{aligned} \quad (15)$$

The boundary conditions, when $t > 0$, are

$$\begin{aligned} u(0, t) &= 0 \\ \frac{1}{s(1)} \cdot \frac{\partial u(1, t)}{\partial x} &= [F_d - F_s], \text{ for any } t \end{aligned} \quad (16)$$

Let T be the time at which the velocity of the end of the spring comes to 0. At this time, the coefficient of friction resumes its static value and relative displacement stops. The axial component of the relative displacement

for the stress drop is thus $u(1, T)$. In the general case, Equation (14) is not easy to solve and must be integrated numerically. However, if the mass and the compliance are distributed as in Figure 6, the problem becomes one of an inertial pendulum with a massless spring; Equation (14) may be solved directly (2, 7, 8). Instead it can also be noted that for such a distribution of mass and compliance no seismic energy remains in the system after the end of the motion. In such case, Equation (8) gives (see also Figure 7):

$$u(1, t) = 2[F_d - F_s].S \quad (17)$$

The argument leading to Equation (8) also indicates that this is the maximum value of $u(1, T)$ for a machine with a given total compliance S . In general

$$u(1, T) = K.S.[F_d - F_s] \quad (17')$$

where $0 < K < 2$

K is a constant coefficient characteristic of the machine, as can be shown easily. If u_1 is a solution of Equation (14) for a value $[F_d - F_s]$ in Boundary Condition (16), $u_2 = \alpha u_1$ is a solution for a boundary value $\alpha[F_d - F_s]$. In particular, if $u_1(1, T)$, equal to $K_1.S.[F_d - F_s]$, is the displacement in the first case, the displacement in the second case is:

$$u_2(1, T) = \alpha.u_1(1, T) = \alpha.K_1.[F_d - F_s] = K_2.S \alpha[F_d - F_s].$$

Therefore $K_2 = K_1 = K$.

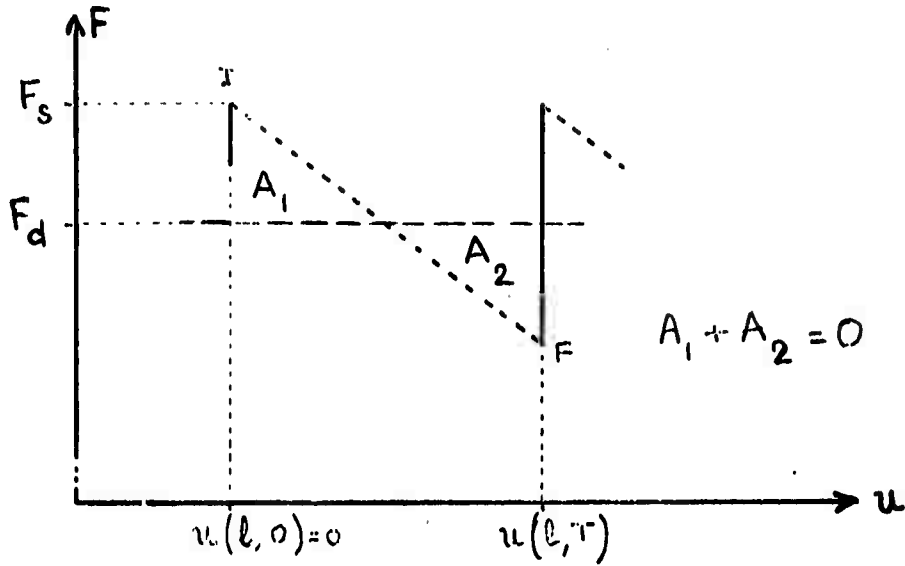


Figure 7

Stick-slip for a machine having a distribution of mass and compliance as in Figure 6.

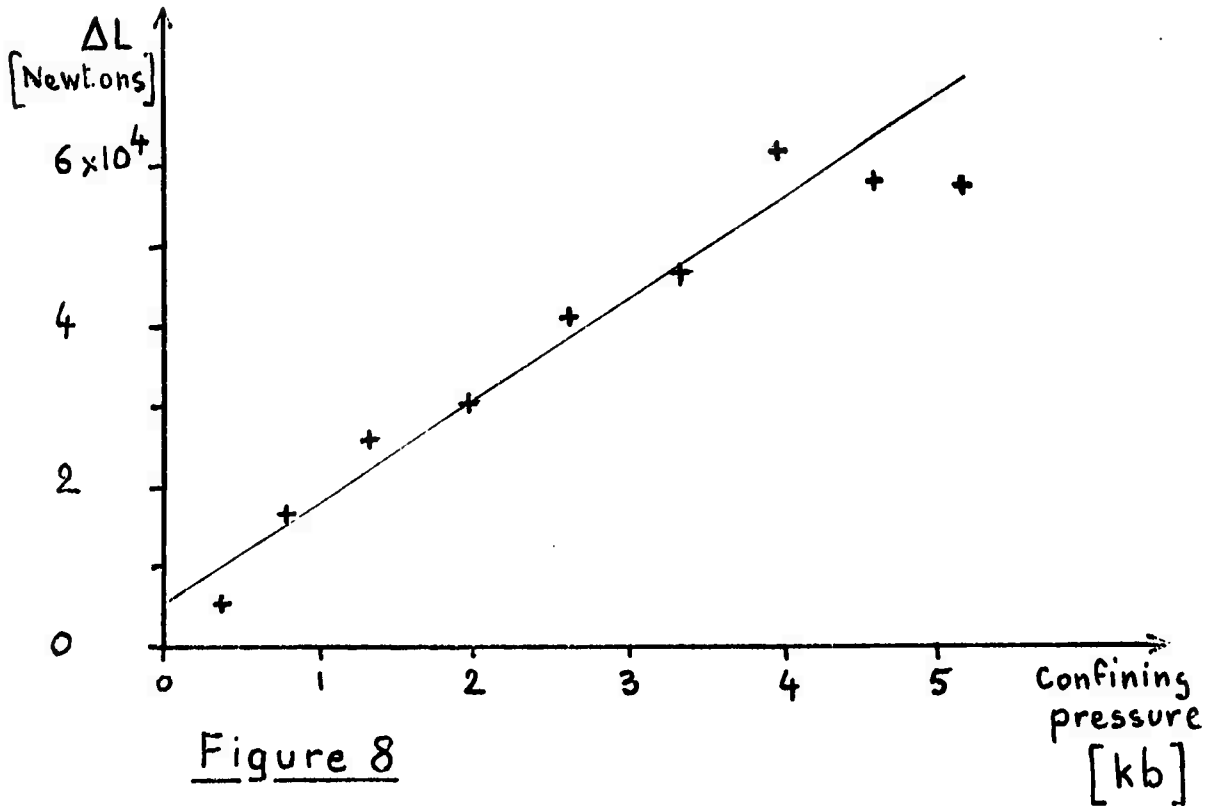


Figure 8

Increase of stress drop with confining pressure data from Byerlee (11). Corrected for the decrease in contact area.

The load drop is what is recorded directly in an experiment. In absolute value, it is equal to:

$$\Delta L = K[F_d - F_s]$$

Using Equations (11) and (12), it is:

$$\begin{aligned} \Delta L = K A \left[\frac{S_d}{\cos \theta - \mu_d \cdot \sin \theta} - \frac{S_s}{\cos \theta - \mu_s \cdot \sin \theta} \right. \\ \left. + p \left(\frac{\mu_d}{\cos \theta - \mu_d \cdot \sin \theta} - \frac{\mu_s}{\cos \theta - \mu_s \cdot \sin \theta} \right) \right] \end{aligned} \quad (18)$$

The load drop is thus found to be independent of the compliance S of the machine. This was found experimentally by Byerlee and Brace (6). Curves obtained by Byerlee (11) for friction of Westerly granite (with $\theta = 30^\circ$) show that ΔL does increase linearly with confining pressure as predicted by Equation (18).

The quantities S_s and S_d are readily obtained experimentally, and have been obtained in particular for Westerly granite (12). The only unknowns in Equation (18) are therefore K , S_d and μ_d . The slope r of the line in Figure 8 gives the following equation:

$$r = K A \left(\frac{\mu_d}{\cos \theta - \mu_d \cdot \sin \theta} - \frac{\mu_s}{\cos \theta - \mu_s \cdot \sin \theta} \right) \quad (19)$$

or, numerically:

$$1.28 (\text{cm}^2) = 7.92 K \left(\frac{\mu_d}{1.733 - \mu_d} - 0.53 \right) (\text{cm}^2) \quad (19')$$

Another series of experiments, with a different angle θ' , would give another equation similar to (19). The two equations would then be sufficient to determine K and μ_d . The intersection of the two lines (as in Figure 8) with the ordinate axis, $p = 0$, should both give the same value of S_d . There is, however, a large degree of uncertainty for these intersections.

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PART II

Stiffness in Faulting and in Friction Experiments

J.B. Walsh

ABSTRACT

Stiffness has been suggested as an important parameter in frictional behavior of rocks. Stiffness is calculated for a long, shallow, vertical surface fault of finite depth, which has slipped with a uniform stress drop over the surface. It is found that stiffness for typical source dimensions is several orders of magnitude lower than stiffness in typical laboratory high pressure experiments. As stick-slip is probably enhanced in softer systems, stick-slip observed in the laboratory will probably also be observed under geologic conditions, other factors being comparable.

THEORY

Stick-slip, or discontinuous relative motion between surfaces, has been observed in certain friction experiments on rock in the laboratory and has been suggested as a possible mechanism for shallow earthquakes [Brace and Byerlee, 1966]. Stick-slip traditionally is explained [Rabinowicz, 1965] by referring to the analogy of a block on a plane being pulled

along by an elastic spring. The block is motionless unless the force exerted by the spring exceeds the static friction force. The coefficient of dynamic friction is less than the coefficient of static friction, so the block jumps ahead. The block eventually comes to rest, the applied force is increased again, and the process repeats itself. The stiffness of the spring is important because stick-slip may be eliminated, at least in some experiments [Rabinowicz, 1965], by increasing the stiffness of the system.

In laboratory measurements of friction between rock surfaces, the testing machine corresponds to the spring in the analogue. The stiffness of these machines is known or can be measured. But what is the 'stiffness' of a fault in the earth and do laboratory conditions characterize those in situ?

Consider a long, shallow, vertical surface fault of depth d which has slipped accompanied by a stress drop $\Delta\tau$ uniform over the fault surface. The slip w at the trace of the fault on the surface is [Knopoff, 1958]

$$w = d\Delta\tau/\mu$$

where μ is the shear modulus. Stiffness, defined as $\Delta\tau/w$, is thus

$$\Delta\tau/w = \mu/d$$

The stiffness K of testing machines is usually defined as $\Delta F/\delta$, where δ is the displacement of the platens resulting from a change ΔF in the axial force on the specimen. In a typical friction experiment, the coefficient of friction is found by measuring the axial stress required to produce slip in a sample under confining pressure containing a fault oriented at some appropriate angle β to the vertical [see, for example, Byerlee and Brace, 1968]. Slip w and shear stress drop $\Delta\tau$ relative to the fault surface therefore are

$$w = \delta/\cos\beta \quad (3)$$

$$\Delta\tau = (F/A) \sin\beta \cos\beta$$

where A is the cross-sectional area of the specimen. The stiffness of the testing machine and specimen can be expressed as

$$\Delta\tau/w = (K/A) \sin\beta \cos^2\beta \quad (4)$$

for comparison with the in situ 'stiffness' given by (2).

Byerlee and Brace [1968] varied machine stiffness K in their experiments between 2×10^4 kg/cm and 20×10^4 kg/cm. The specimens had a cross-sectional area of about 2 cm², and in a typical experiment the fault angle β was 30°. We find from (4)

$$\Delta\tau/w \approx 0.4 \times 10^4 - 4 \times 10^4 \text{ kg/cm}^3 \quad (5)$$

In a large earthquake on a surface fault such as the San Andreas, slip occurs to depths of the order of 10 km. We find from (2), where rigidity μ is about 300 kb, that

$$\Delta\tau/w \approx 0.3 \text{ kg/cm}^3 \quad (6)$$

Thus, a large earthquake involves a system which is softer by four or five orders of magnitude than that modelled in the laboratory.

RESULTS

This result probably does not invalidate the suggestion that earthquakes may involve stick-slip. Byerlee and Brace [1967] found that stick-slip occurred for all values of machine stiffness in the range they employed. And, in experimental studies of the friction between metal surfaces, stick-slip was enhanced in softer systems [Rabinowicz, 1965]. However, the comparison above suggests that the experimental range should be increased to include even lower stiffnesses if observations in the laboratory are to be applied directly to large earthquakes.

The analysis leading to (5) and (6) is not strictly accurate because the edges of the fault in an experiment are free to slide whereas one edge of a surface fault is constrained. This defect is not likely to be serious in an approximate calculation. For example, consider another case, slip with

uniform stress drop on a circular patch of radius a at depth. One can show [Keer, 1966] for this case that

$$\Delta\tau/w \approx \mu/a, \quad (7)$$

that is, the stiffness is about the same formally as for the case of the vertical, strike-slip fault given by (2). From (7) and (4), we find that experiments in the laboratory model slip on faults in situ which are only 10 cm to 1 m in radius.

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PART III

Experimental studies of high temperature friction

W.F. Brace and D.K. Riley

ABSTRACT

Frictional sliding on sawcuts and faults in laboratory samples of various silicate rocks is markedly temperature-dependent. At pressures from 1 to 5 kb, stick-slip gave way to stable sliding as temperature was increased 200° to 500°C. The particular temperature of transition to stable sliding varied with rock type.

EXPERIMENTAL METHOD

Several field and laboratory observations suggest that earthquakes result from a large-scale form of stick-slip (5). For one thing, unstable (stick-slip and earthquake-producing) and stable (fault creep and stable sliding) motion have been found both in the field and in laboratory experiments on rocks under high pressure. For another, the same mineralogic controls on stability have been noted in field and laboratory. For example, minute amounts of serpentine in a dunite produced stable sliding (6); fault creep in California seems restricted to areas where the San

Andreas fault system cuts serpentine-bearing rocks of the Franciscan series (7).

How can the disappearance of earthquakes at shallow depths be explained on the basis of laboratory studies? Three possibilities are apparent: a mineralogic change with depth, existence at depth of certain pore pressure conditions known to stabilize sliding in rocks (8), and temperature increase. The last is the least understood. Stable sliding at high temperature is suggested by a few observations of stable faulting at high temperature (9) and by somewhat ambiguous results with powders deformed between rotating anvils (10).

There are relatively few laboratory studies of rock fracture at high temperature and pressure (11) and practically none of frictional sliding. The biggest experimental difficulty, particularly for sliding, is jacket design. The jacket, required in a triaxial experiment to exclude the gas pressure medium from the rock sample, is typically metal foil. The foil ruptures easily at any strain discontinuity such as a fault. Our procedure was to retain the thin foil, but to add a sleeve of graphite between rock sample and foil (Figure 1). The sharp offset at the fault is smeared out in the soft graphite, and appreciable motion on the fault is tolerated before the foil ruptures. This simple modification in jacket design enabled us to use otherwise standard experimental procedure

for high temperature deformation study, to obtain the first detailed picture of the effects of temperature on friction of rock.

The rock sample was a precisely ground cylinder 16 mm in diameter by 35 mm long. Sawcut, if present, was located midway between the ends and made an angle of 30° to the cylinder axis. Graphite sleeve was 1.3 mm thick, the annealed seamless copper foil, 0.32 mm thick.

An extensive series of experiments was conducted at room temperature to determine any possible stabilizing effect of the graphite-copper jacket. The results (Figure 2) revealed that a stabilizing effect on sliding existed only below 2 kb pressure. This took the form of lowering the amplitude of stick-slip to nearly zero. The shearing stress to cause frictional sliding increased about 10 percent compared with an experiment at the same pressure, using a 3 mm thick polyurethane jacket. Because of these effects, most experiments here were conducted at or above 2 kb pressure where room temperature experiments using copper-graphite were nearly identical with those using polyurethane. In any event, stabilizing effects present at room temperature probably would not be important at high temperature because of increased ductility of the copper.

Our apparatus resembled in a general way that described on page 46 of Reference 9. It was internally heated, with low friction O-ring seals. Stiffness of the loading system was

about 10^5 kg/cm. Pressure was known to 1 percent, temperature to about 10° . Strain rate was calculated from the rate of advance of the screw-driven piston.

Frictional sliding was studied in triaxial experiments in which the cylindrical sample contained a fault or sawcut (12). The fault was formed by loading an initially intact sample to failure; the sawcut was made in the sample at an angle (30°) close to that of typical faults ($26-32^\circ$).

Of our two types of experiment, with sawcut and with fault, presumably the latter more nearly resembles actual faults. Sawcuts are flat and have a finely ground surface; faults have abundant gouge and the surface irregularity one normally associates with actual faults. Unfortunately a 'fault' experiment is more difficult and the results often more ambiguous than a 'sawcut' experiment. For example, each laboratory fault differs in detail; sawcuts are nearly identical; as a result, data from faulted samples shows greater scatter than that from sawcuts. For exploratory work, results from sawcuts are probably valid; Byerlee (13) found for granite only minor differences in friction between sawcuts and faults once some motion had occurred. Most of the results reported here are for sawcuts.

We studied frictional sliding in Westerly granite and San Marcos gabbro (14) at pressures to 5 kb, temperatures to 525°C , strain rates from 10^{-4} to 10^{-6}sec^{-1} . The samples were vented to the atmosphere through a hollow piston, so that presumably pore pressure was nearly zero.

RESULTS

The results for both rocks are shown in Table 1. In the first column, W refers to the granite and SM refers to gabbro. The displacement in the fourth column is displacement at pressure and temperature on the fault. In all runs the sample was heated at temperature for one hour, and the strain rate was 10^{-5} per second unless otherwise noted.

Results are shown in Figure 2 for sawcuts in granite. Apparently high temperature had a strong stabilizing effect on stick-slip; large amplitude stick-slip at low temperature (the 22° curve in Figure 3) gave way to stable sliding as temperature is increased (the 306° curve in Figure 3). Results at higher pressure were similar. No change in character of the sliding was evident over the 3 mm or so of sliding motion, which was the limit imposed by the apparatus. Neither strain rate nor heating procedure appeared to affect behavior such as shown in Figure 3. Samples were run at 10^{-4} to 10^{-6} sec $^{-1}$ strain rate, were heated at pressure for 1 to 25 hours, with and without vacuum (10^{-2} Torr), and were heated and then run at room temperature.

Results for faults in gabbro are shown in Figure 4; these are also typical for granite. The faults were formed in the samples at 0.5 to 1 kb pressure and room temperature. Pressure and temperature were then raised to the conditions of the friction experiment. The marked effect of high

TABLE 1

High Temperature Friction

Sample	Motion	P kb	T °C	D kb	Displ. mm	Comments
WG-1-S	STA	1.00	303	3.2	2.1	$\dot{\epsilon} = 10^{-4}$ and 10^{-6}
WG-2-S	STK	1.91	140	4.6	1.0	
WG-3-F	STA	1.92	527	6.5	1.3	
WG-4-S	STA	1.99	191	5.5	1.2	
WG-5-S	STA	1.99	302	5.3	1.4	
WG-6-S	STA	2.08	468	2.7	2.8	$\dot{\epsilon} = 10^{-4}$
WG-7-5	STA	2.09	306	4.6	2.4	
WG-8-F	STA	2.84	407	7.0	1.4	
PC-9-F	STA	2.94	253	11.8	1.3	
WG-10-F	STA	2.99	407	7.9	2.0	
RQ-11-F	STK	3.00	22	13.9	1.4	
SM-12-F	TRAN	3.00	103	7.9	2.4	
WG-14-F	STA	3.00	354	7.8	1.7	
WG-15-F	STA	3.00	508	5.4	1.8	
PC-16-F	STA	3.00	528	9.5	1.0	
RQ-17-F	STA	3.00	640	9.9	1.0	
PC-18-F	STK	3.04	102	11.7	1.7	
RQ-19-F	STK	3.04	440	11.9	1.4	
WG-20-S	STA	3.05	305	7.9	0.8	
SM-21-F	STA	3.50	356	8.3	2.6	
SA-22-F	STA	3.50	508	9.5	1.9	
WG-23-F	TRAN	3.52	205	11.3	2.2	
MA-24-F	STA	3.97	150	10.9	1.8	
SA-25-F	STK	4.00	22	13.4	2.7	$\dot{\epsilon} = 10^{-4}$
SM-26-F	STK	4.00	140	11.0	2.7	
WG-27-S	STK	4.00	197	9.1	1.0	
MA-28-F	STA	4.00	213	9.7	1.4	
SA-29-F	STA	4.00	256	11.9	1.6	
WG-30-F	STK	4.00	260	11.7	3.7	$\dot{\epsilon} = 10^{-4}$
WG-31-S	STK	4.00	293	>8.5	1.5	
SA-32-F	STA	4.00	352	11.1	1.7	
SM-33-F	STA	4.00	398	11.0	1.5	
WG-34-S	STA	4.02	440	4.8	1.4	
SM-35-F	STA	4.04	512	9.3	2.8	
WG-36-F	STA	4.05	304	11.3	1.5	
SM-37-F	STK	4.13	100	11.5	2.0	
SM-38-F	STA	4.50	304	9.6	1.7	
WG-39-F	STA	4.95	302	14.4	1.3	
SM-40-F	STK	5.00	197	11.5	4.3	$\dot{\epsilon} = 10^{-4}$
WG-41-F	STK	5.02	354	13.4	2.0	
WG-42-F	STA	5.02	507	13.1	2.0	
WG-43-F	STA	5.05	403	14.4	3.2	
WG-44-F	STK	5.50	204	14.2	2.0	
WG-45-F	STA	5.50	298	14.0	0.8	
WG-46-F	STA	6.00	252	12.6	0.6	
WG-47-F	STA	6.11	405	14.9	1.6	

STA refers to stable sliding; STK to stick slip; S in sample number to sawcut; F to fault

temperature is again evident, although the transition between stick-slip and stable sliding appears less sharp than for sawcuts. In other words, there appears a significant range of temperature over which stick-slip was preceded by some stable sliding. It is not certain that even at the highest temperature stick-slip would not have occurred had there been additional displacement.

Results for both sawcuts and faults are shown in Figure 5, in which stick-slip (open figure) or stable sliding (closed figure) is indicated. Where appreciable stable sliding preceded the stick-slip, this is designated by a half-closed figure.

Several features are evident in Figure 5. First, sliding on granite sawcuts has a well-defined field of stability; thus, the sliding was stable at high temperature and low pressure, and unstable at high pressure and low temperature. Second, the field boundary for the sawcuts is very sharp; within about 100°C large amplitude stick-slip gave way to stable sliding. Third, the results for the faults in granite, although very limited in number, are at least consistent with results for the sawcuts; the transition from unstable to stable may be more gradual for faults than sawcuts at the pressures of these tests. Finally, the field boundary may be different for gabbro and granite with stick-slip disappearing at lower temperature for gabbro.

At present no physical explanation can be offered for this pronounced effect of temperature on stick-slip. Our understanding of the stick-slip process is still rather incomplete. Byerlee's studies (15) suggest that brittle fracture plays an important role in the frictional behavior of rocks; perhaps an explanation would be apparent if more were known about effect of temperature on brittle fracture of rock-forming minerals. A significant observation from the present work is that frictional strength is lowered by temperature by about the same amount as fracture strength, relative to room temperature values. This suggests that the behavior on a small scale is the same in both cases. The details of this behavior are still obscure.

Before we apply present results to real faults, we need to consider differences which still exist between the laboratory experiment and the field, other than the obvious one of scale. Our experiments will need to be repeated with pore water pressure, for presumably natural rocks are wet. Probably the effective stress law will be followed as it is at room temperature (16). Additional, chemical effects may be present, though, to judge from the water-weakening observed in certain silicate minerals (17). Presumably these will have a further stabilizing influence and shift the field boundary of Figure 3 to the left, to lower temperatures. Slower strain rate than used here need

also be considered; at high temperature some welding or sintering may be expected at very slow strain rates, and this could lead to stick-slip. Further study is needed here, as well. Finally, the effects of displacement will have to be examined more fully. To judge from our observations with faults in gabbro and granite, the nature of the sliding motion changes somewhat with displacement (the middle curve of Figure 4). Some way of obtaining much larger displacements in our laboratory samples is needed.

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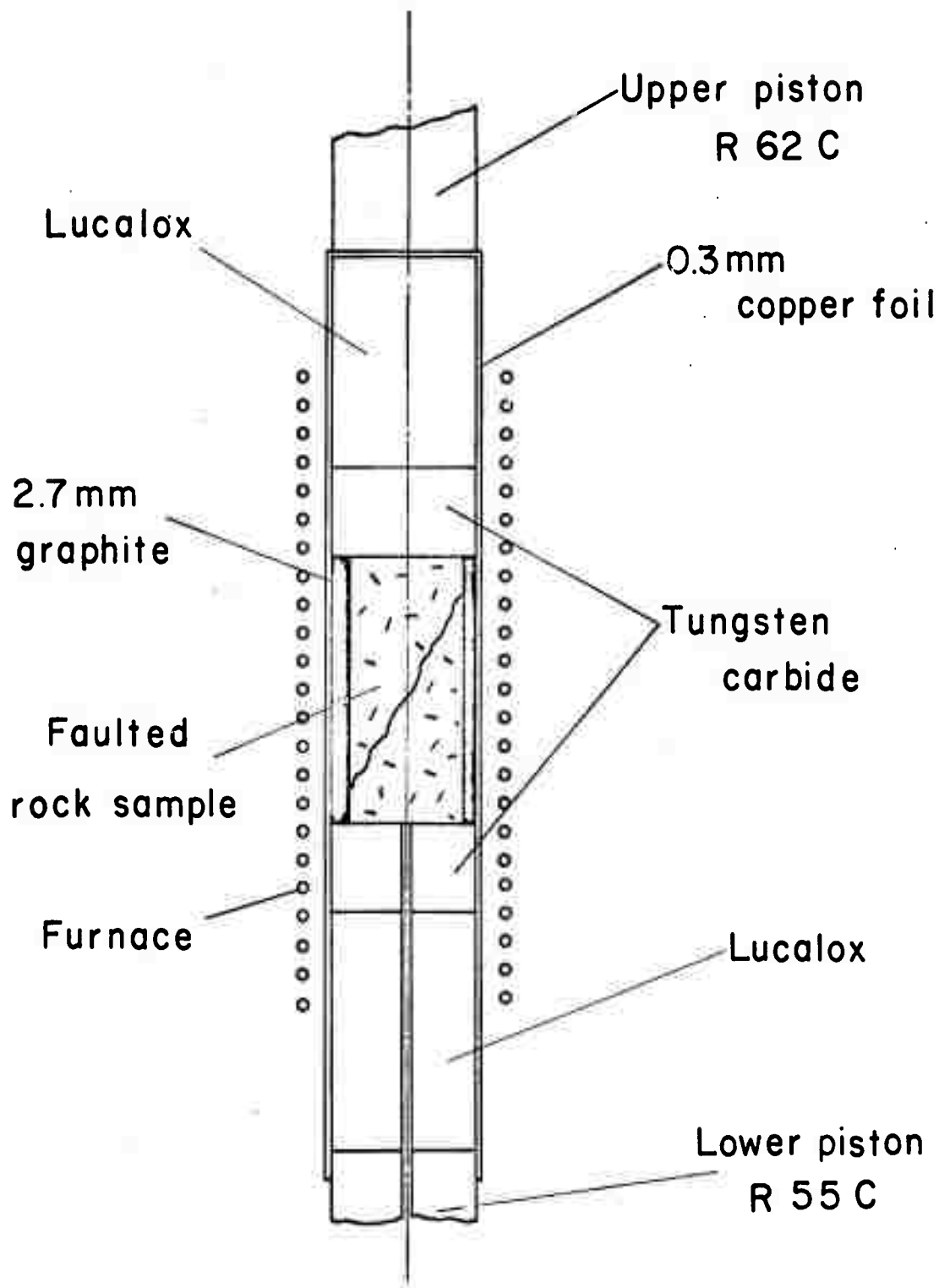


FIG. 1

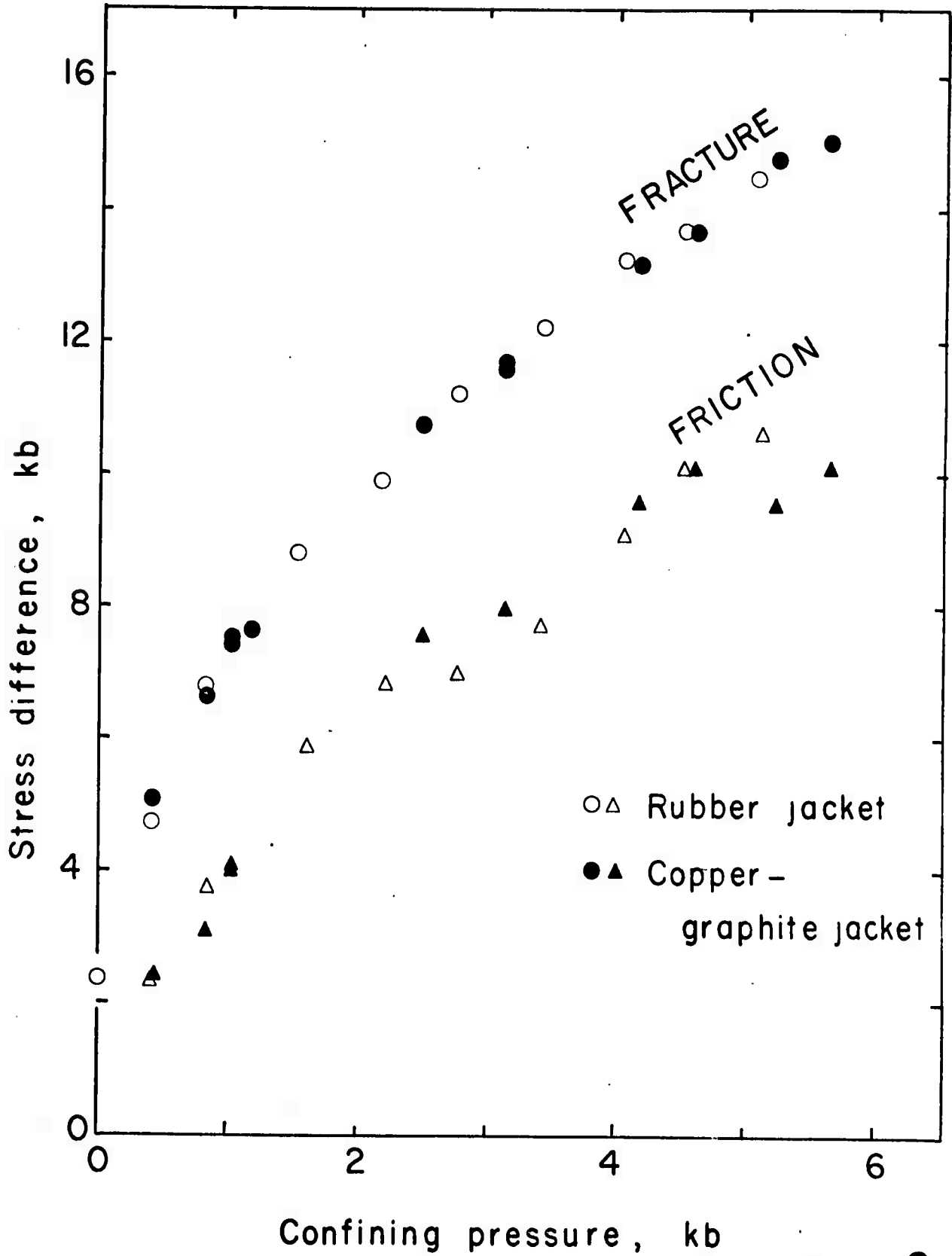


FIG. 2

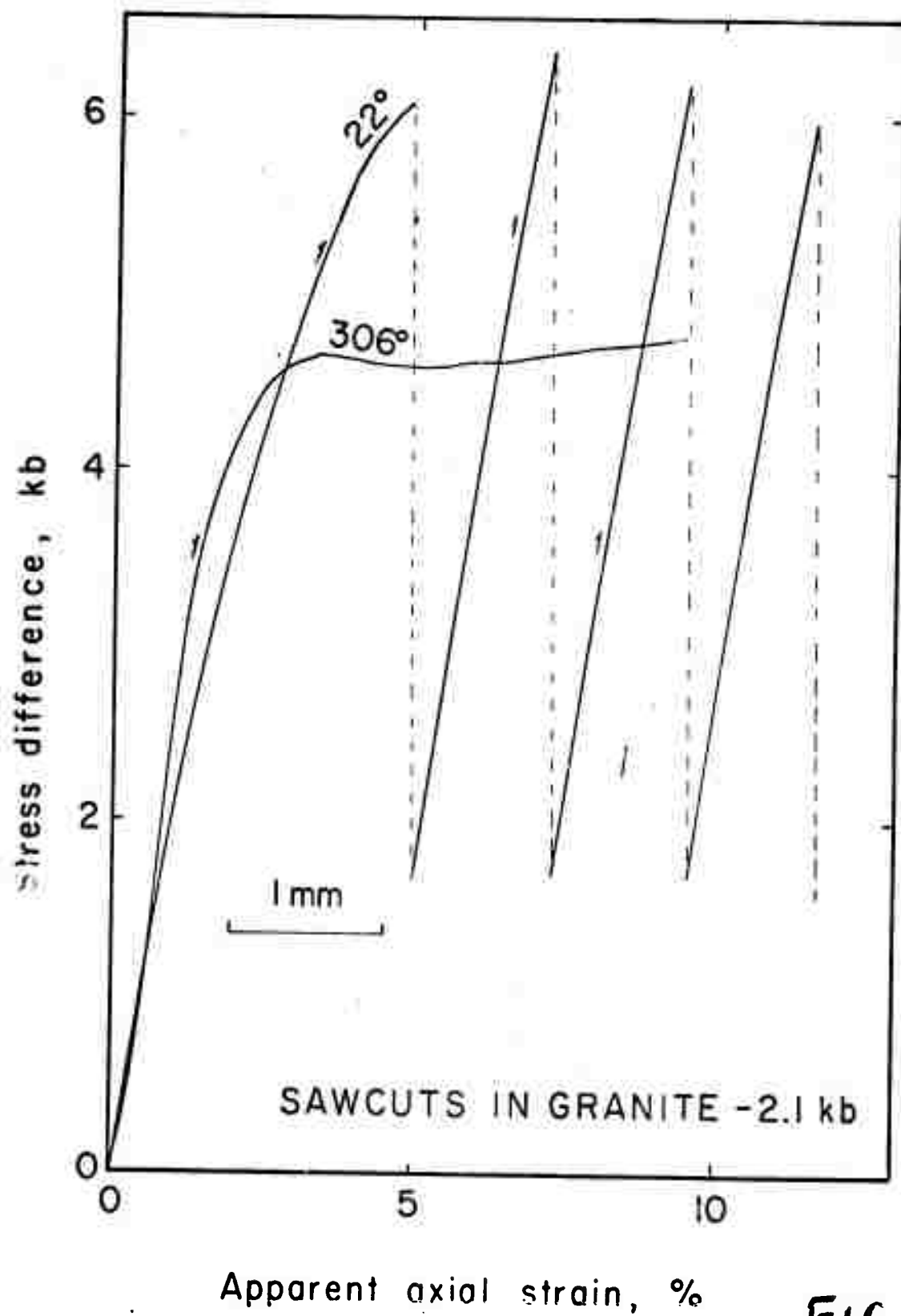


FIG. 3

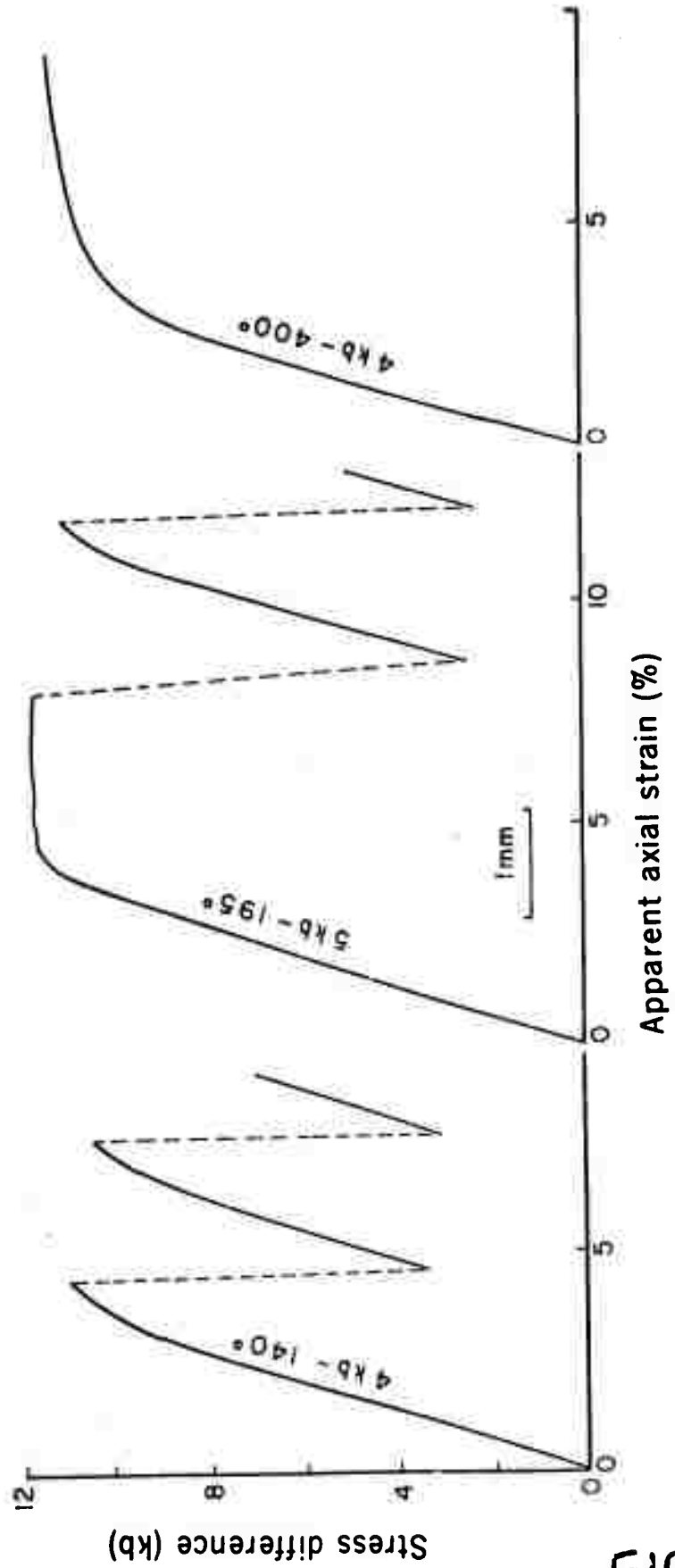


FIG. 4

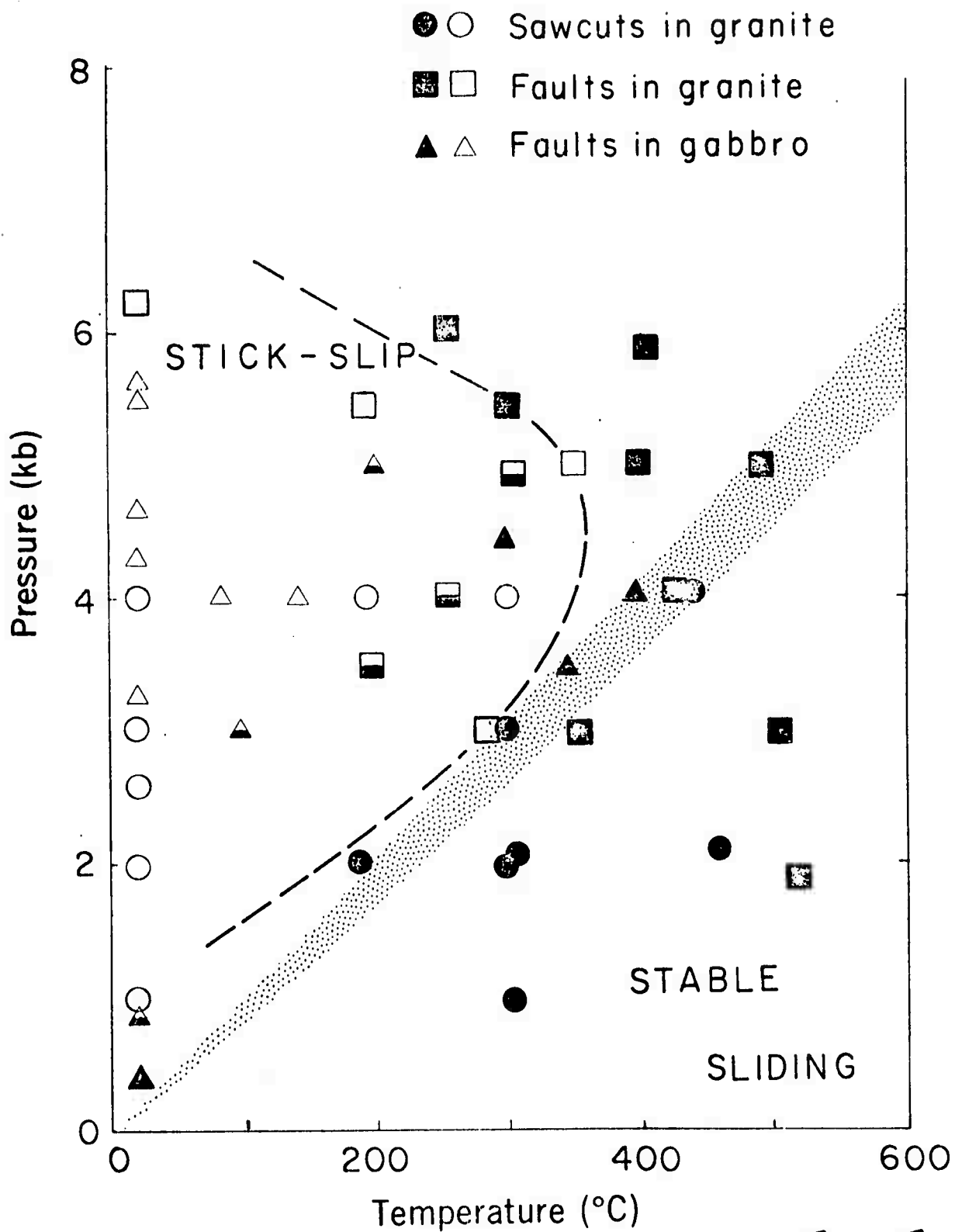


FIG. 5

PART IV

Laboratory studies of stick-slip and
their application to earthquakes

W.F. Brace

ABSTRACT

Stick-slip on pre-existing faults has been suggested as one source of crustal earthquakes. We review current laboratory studies of stick-slip to note factors which determine whether sliding is stable or unstable in laboratory samples, point out ways in which the laboratory experiment may not model the situation in the earth, and emphasize areas in which further laboratory study is needed.

The most important factors which determine whether sliding will be unstable (stick-slip and earthquake-producing) or stable (stable sliding or fault creep) include mineralogy, porosity, effective confining pressure, temperature and thickness of fault gouge. In general, stable sliding is enhanced by high temperature, low effective pressure, high porosity, thick gouge, and the presence of even small quantities of minerals like serpentine and calcite.

It is still not clear just how well the laboratory experiment models a seismic region in the earth. This is in part because both the detailed geometry of natural seismic

faults and factors like gouge thickness are not well-known. Also, it has not yet been possible in the laboratory to study the characteristics of a fault in which slip is limited to part of the surface, as is the case in a typical seismic area. The laboratory experiment also does not correctly model the real situation in which normal stress, temperature, and effective pressure may vary along the fault surface.

In addition to design of experiments in which the above features are included, work should be done both on the theory of stick-slip and on a better understanding of the physical characteristics of rocks responsible for observed differences in sliding behavior.

INTRODUCTION

From a purely mechanical point of view, an earthquake must be produced by a sudden instability. A number of different instabilities have been suggested as a source of earthquakes, including fracture (Reid, 1911), stick-slip sliding (Brace and Byerlee, 1966a), shear melting (Griggs, 1954; Griggs and Baker, 1969), and creep instability (Orowan, 1960). Of these, stick-slip has received considerable recent attention in the laboratory, and in this paper, we summarize current results. Although considerable progress

has been made since this subject was last reviewed (Brace, 1968; Rikitake, 1968), it is evident that much remains to be done and we point out areas which seem particularly worthy of further study. Because stick-slip is only one of many possible instabilities likely to be of interest for earthquake studies, we first review the concept of instability, particularly in its application to seismology.

Mechanical Instability

Mechanical instabilities are commonplace in solids (Bridgman, 1952; McClintock and Argon, 1966) and include buckling of long columns, tensile failure of glass and Lüders bands in mild steel under tension. An instability occurs during deformation when the resistance of a material begins to decrease with further deformation. Typically, the instability is due to a localization of deformation at a Lüders band or a tension crack. For geologic problems, instabilities in compression are of special interest; for seismology, instabilities which occur suddenly may be considered possible sources of earthquakes (Griggs and Handin, 1960). At a sudden instability, stress drops very rapidly and elastic energy is radiated from the site of the instability.

For the purpose of earthquake studies, it is of interest to list all possible sudden instabilities which might occur in

deeply buried rocks in the earth. So far, a number of phenomena have been suggested which might lead to sudden mechanical instability, but for one reason or another only one or two of these have actually been observed under laboratory conditions. For example, shear melting (Griggs and Baker, 1969) and creep instability (Orowan, 1960) both satisfy the definition given above, and yet largely because of experimental difficulties have, to our knowledge, never been observed unambiguously. Clearly though, this is an area which deserves a great deal of attention, particularly because of possible application to deep-focus earthquakes. Phase changes are thought to be responsible for earthquakes (Bridgman, 1945; Benioff, 1964; Griggs and Handin, 1960), for certain transitions would seem to provide the basis for mechanical instability. For example, in a transformation to a more dense phase, volume changes might lead to development of local stresses in excess of those which could be supported at the conditions of the transformation (Benioff, 1964). Or, transformation of a strong to a weak material might again lead to a situation in which material is subjected to stress in excess of its strength. However, for seismological applications one has to ask, are the instabilities so produced likely to occur suddenly enough to produce elastic waves? Elastic shocks during phase changes are rarely observed. Shocks were observed during the martensitic transition of iron alloys (Livshitz et al., 1969; Owen et al., 1970; Magee, 1970),

and at the polymorphic transition of NH_4F (Kasahara et al., 1971). An elastic shock accompanied the brittle faulting of serpentine near its upper limit of stability at 5 kb, 700° (C.B. Raleigh, personal communication, 1971; Raleigh and Paterson, 1965). Apart from these rare occurrences, phase changes do not cause shocks, as apparently reaction rates are too sluggish. In addition, it is difficult to visualize how an instability could form over a large region within the short period of time that would be required to produce a strong seismic signal. This would seem to require extremely uniform pressure and temperature over a large volume of rock. This may well be the case deep in the earth but seems unlikely for the crust and upper mantle.

The collapse of cavities might be viewed as a seismic source and it is of interest to consider the observations that have been made by experimentalists of this phenomenon. Cavities occasionally do collapse under high external pressure in non-metallic materials like glass, single-crystal oxides and brittle rocks. This collapse is typically gradual. Bridgman (1918, 1952) studied the collapse of cylindrical holes in glass, single crystals and rocks, and we observed the collapse of cylindrical cavities in a wide range of rocks and ceramics. In no case did collapse occur rapidly enough to produce audible elastic shocks. Failure occurred by a gradual inward spalling of the cavity wall.

Failure of brittle material when one or more of the principal stresses is tensile is typically unstable, and occurs sufficiently rapidly to be considered a seismic source mechanism. However, tensile stress is unlikely below very shallow depths in the earth (Hubbert, 1951) except on a very local scale. Brittle tensile failure, therefore, probably has little significance here. And it should not be assumed that brittle failure in compression and tension are comparable. Although the detailed mechanism in both cases is still obscure, failure of rock in the two cases seems to be fundamentally different (Brace and Byerlee, 1966b).

The two remaining instabilities of interest here are brittle failure in compression and sliding accompanied by stick-slip. Considerable effort in recent years has been devoted to study of these two processes. Although the two may be closely connected on actual faults, it is convenient to separate them, the distinction being that for failure in compression, one starts with intact material, whereas for stick-slip, material contains a fault or other planar discontinuity. For shallow focus earthquakes, many observations suggest that stick-slip may well be the more significant phenomenon, inasmuch as such earthquakes seem to be closely related to existing faults (Eaton et al., 1970). Some material may in fact be fractured locally during sliding, but the key feature is the pre-existing surface or zone of discontinuity.

STICK-SLIP SLIDING

In common with other mechanical instabilities, material properties alone do not completely determine instability during sliding. To some extent stability depends on the dynamic characteristics of the system applying loads to the rock in question. In the laboratory, this system is a loading machine; in the earth it is the rock surrounding the fault. Stiffness is one of these characteristics, and the exact role of stiffness of the loading system is still not clear. Experience from metals suggests that high stiffness suppresses stick-slip (Rabinowicz, 1965), whereas observations on rocks are somewhat conflicting. Byerlee and Brace (1968) found no stiffness effect, whereas Jaeger and Cook (1971) reported a decrease in stick-slip amplitude at high stiffness. Whatever result is correct, Walsh (1971) has recently shown that stiffness in the case of a natural fault is probably much less than that of typical loading machines. On that basis, stick-slip observed on real faults will probably be at least as severe as that observed under laboratory conditions.

Based on laboratory studies, the most significant parameters affecting stick-slip appear to be mineralogy, porosity, gouge thickness, effective pressure, temperature and presence of water (Byerlee, 1970a). In what follows we will examine the effect of these different parameters, emphasizing their role in stability.

Mineralogy

In general, rocks containing weak minerals cause stable

sliding rather than stick-slip, other conditions being equal (Byerlee and Brace, 1968; Logan et al., 1970). Weak minerals include calcite, dolomite and platy silicates such as talc or serpentine. Apparently even small quantities of minerals like serpentine are significant. In Fig. 1 the behavior of two dunites is contrasted. One, the Twin Sisters dunite, is serpentine-free. The other, the Spruce Pine dunite, contains about 3 percent serpentine localized in grain boundaries. As shown, both faulting and sliding are stable for the serpentine-bearing rock. Similar characteristics have been observed for other ultramafic rocks, for rocks containing appreciable quantities of carbonate minerals, and for multilithogic specimens when one member is limestone or dolomite. As we note below, transition from unstable to stable sliding as a function of temperature also depends on mineralogy.

Porosity

Porosity also tends to cause stable rather than unstable sliding (Byerlee, 1970a, Byerlee and Brace, 1969). This is observed when one compares faults in quartzose sandstone (porosity 15 percent) with quartzite (porosity less than 1 percent), or rhyolite tuff (porosity of 40 percent) with rhyolite felsite (porosity less than 1 percent). Typically, both fracture and sliding of the low porosity species are unstable, whereas stick-slip of the porous varieties is only observed at extremely high pressure and large strain. Compacted granite sand illustrates the behavior of very porous material. As shown in Fig. 2, 7.8 kb pressure and nearly 20 percent axial strain were required to produce instability.

Porosity also plays a role through the thickness of fault gouge (Byerlee, 1970a). Gouge in laboratory-produced faults is typically ground-up rock with a wide range of grain size. The factors which determine gouge thickness are not well understood. However, two contrasting situations suggest the important role of gouge thickness in sliding behavior. When sliding is observed on sawcuts, stick-slip occurs at lower pressure than with sliding on a pre-existing fault; with the sawcut, gouge thickness is close to zero, whereas on the fault it may be appreciable. An extreme case of gouge thickness is the granite sand which, in a sense, is all gouge and, as noted above, deforms stably throughout a large pressure range in which sawcuts and faults would be unstable.

Pressure

Increase in effective confining pressure generally favors stick-slip rather than stable sliding (Byerlee and Brace, 1968, 1969, 1971). A typical result for unaltered gabbro is shown in Fig. 3 where it can be seen that amplitude of stress drop increases with pressure. The importance of pressure differs somewhat with rock type and porosity. For example, the serpentine-bearing dunite, Fig. 1, eventually became unstable at around 8 kb, as did sandstone (porosity of 15 percent). So far no stick-slip has been observed for the carbonate rocks at pressures of this order. Perhaps this might occur at still higher pressures.

Water

Water plays a complex role in sliding phenomena with at least two different functions. First, water may act as a fluid under pressure and reduce effective confining pressure (Byerlee and Brace, 1970). In that role it could be replaced by a wide range of nonreactive fluids. This mechanical role of water is illustrated in Fig. 4 for a number of sliding experiments which were done for granite at different combinations of pore pressure and total pressure (Byerlee, 1966). The data follow a single curve when replotted in terms of effective stress, suggesting that it is this stress which determines frictional resistance. In general, dependence on effective pressure is observed for sliding on faults both in the stable and unstable regimes, and is of course the basis of the earthquake mechanism which has been suggested for Denver (Healy et al., 1968) and Rangely (Raleigh, 1971). In the laboratory, most departures from this simple dependence are connected with effects similar to those reported in Brace and Martin (1968). For example, if experiments involving pore pressure are done at rates too rapid to maintain constant fluid pressure throughout the rock, then frictional resistance may increase anomalously or stick-slip may be forestalled for periods of time up to tens of hours. However, these effects are transient, and given sufficient time they disappear.

A second role of water is chemical interaction with the silicate minerals in a rock. Recent work by Martin (1971) and Scholz (1971) has shown that crack growth in and fracture of quartz depend on presence of water and suggest that static fatigue, a process well-known for glass and certain ceramics, may be significant for rocks. If true, increase in partial pressure of water should lead to stable sliding if one assumes that crack growth or fracture is important on a small scale during sliding. This effect would be somewhat comparable to the "water weakening" of Griggs et al. (1966) reported for quartz single crystals. This would be consistent with the role which mineralogy plays, as noted above, in that the weaker minerals tend to favor stable rather than unstable sliding. A strong mineral such as quartz or feldspar might be sufficiently weakened by water to alter frictional characteristics of importance here.

Temperature

High temperature tends to stabilize both faulting and sliding (Brace and Byerlee, 1970). In Fig. 5, the effect of temperature is shown for faults in gabbro. Stick-slip at 140°C was replaced by stable sliding at 400°C, with transitional behavior at 195°C. This sort of behavior has also been observed for two granites, quartzite, anorthosite and dunite, although the temperature of transition varied from rock to rock. For example, at 3 kb pressure, transition for

quartzite occurred between 425° and 625°, whereas for anorthosite it occurred between 150° and 250°. Results for two rocks are shown in Fig. 5 (Part III), where it can be seen that a stable-unstable boundary can be defined. Stick-slip occurs at high pressure-low temperature, whereas stable sliding dominates at high temperature-low pressure. The boundary varied somewhat for the two rocks and also with the abundance of gouge as contrasted by fault and sawcut.

To sum up the role of these different parameters, in general, low effective pressure, high porosity, weak minerals, thick gouge, high temperature and high partial pressure of water, favor stability. Nearly all of these parameters interact with one another, as sketched above, and not all rocks exhibit both stable and unstable sliding behavior within the range of conditions which have been studied.

It is worth noting factors which have little or no effect on stick-slip. Principal among these is strain rate. Byerlee and Brace (1968), Wolters (1970), and Coulson (1970) found no effect, whereas Scholz and Dieterich (personal communication, 1971) report a slight increase in amplitude at slow strain rates. The range of strain rates investigated is still rather small to bring out certain effects, such as static fatigue or melting caused by sliding (Griggs and Handin, 1960), and this range clearly needs to be extended. Byerlee (1966, 1970a) found that initial surface roughness had little effect on maximum frictional resistance at pressures of geologic interest. At low pressure, roughness is important; amplitude of stick slip and frictional resistance increase markedly with surface roughness (Handin, personal

communication, 1971). Apparently, frictional resistance is almost independent of mineralogy (Byerlee, 1970a; Brace, 1971) at room temperature, but as we noted above, mineralogy becomes of increasing significance for sliding stability at high pressure and temperature.

DIFFICULTIES WITH APPLICATION TO THE EARTH

There are two problem areas in the application of laboratory studies to earthquakes on real faults. First, a number of details of natural faults are as yet poorly understood, at least in terms of the factors noted above which seemed important in determining sliding behavior. For example, for a seismic fault one would like to have details of gouge thickness and to know the pore pressure. In addition, the mineralogy of the rocks on both sides of the fault is important, at least over the areas where slip occurs. The temperature profile is also significant, as noted above. Recent detailed maps of micro-earthquake activity on the San Andreas in California (Eaton et al., 1970) show areas in the fault with more or less activity. On the basis of our present results, an area of fault creep and of relatively low seismic activity might be a region in which rocks are relatively wet, or pore pressure is relatively high, or temperature is relatively high. Or the explanation may be found in the local mineralogy of the rocks, in gouge characteristics, or irregularities in the fault surface. Obviously it would be of great interest both for an understanding of earthquake mechanics and for possible prediction schemes to

know which of these many possibilities is most nearly correct. Detailed exploration along the faults, of the sort needed to pinpoint factors such as gouge thickness and temperature, will probably be costly, and in highly seismic areas will have to be done with the danger of triggering a major earthquake in mind. However, both the costs and the risks may be well worth it.

A secondary uncertainty in application of present laboratory studies to the earth lies in important differences between the laboratory sample on the one hand and the seismic fault on the other. Slip in the laboratory example occurs over the entire fault. Stress, effective pressure and temperature are all nominally uniform over the fault. The rock on either side of the fault is the same and uniform. In contrast, slip on the real fault is a local phenomenon in that the region of slip only occurs over a portion of the surface; in other words, the fault is bounded. On the real fault, stress, effective pressure and temperature all vary at least vertically, and in general rocks both across and along the fault probably vary in composition.

On this basis, the laboratory experiment is as yet a poor model of a seismic fault, even apart from the difficulties involved in the difference of scale of the two phenomena. It is still not clear, for example, how one should scale stress drop. Some progress in this direction has been made by Dieterich (1971), who may have come much closer to the real situation with a computer model. He finds that stress drop for a bounded fault

would be a small fraction of that observed for the unbounded laboratory fault. Owing to the difficulties involved in doing much more elaborate high pressure-high temperature experiments on sliding friction, the use of computer models may be the more profitable approach.

A final area in which effort could be profitably expended is toward a better understanding of the theory of stick-slip. Some progress in this direction has been made by Byerlee (1966, 1970a,b), Jaeger and Cook (1971) and Robin (personal communication, 1971). However, none of these explains many of the laboratory observations. It is still not clear why, for example, temperature and effective pressure play such an important role in stability. Because of the detailed way in which mineralogy enters this dependence, a theory will have to take into account physical characteristics of rock-forming minerals and include factors such as surface geometry. A complete theory should also include the role played by stiffness of the loading system, so that this rather important difference between field and laboratory (Walsh, 1971) can be taken into account with greater confidence.

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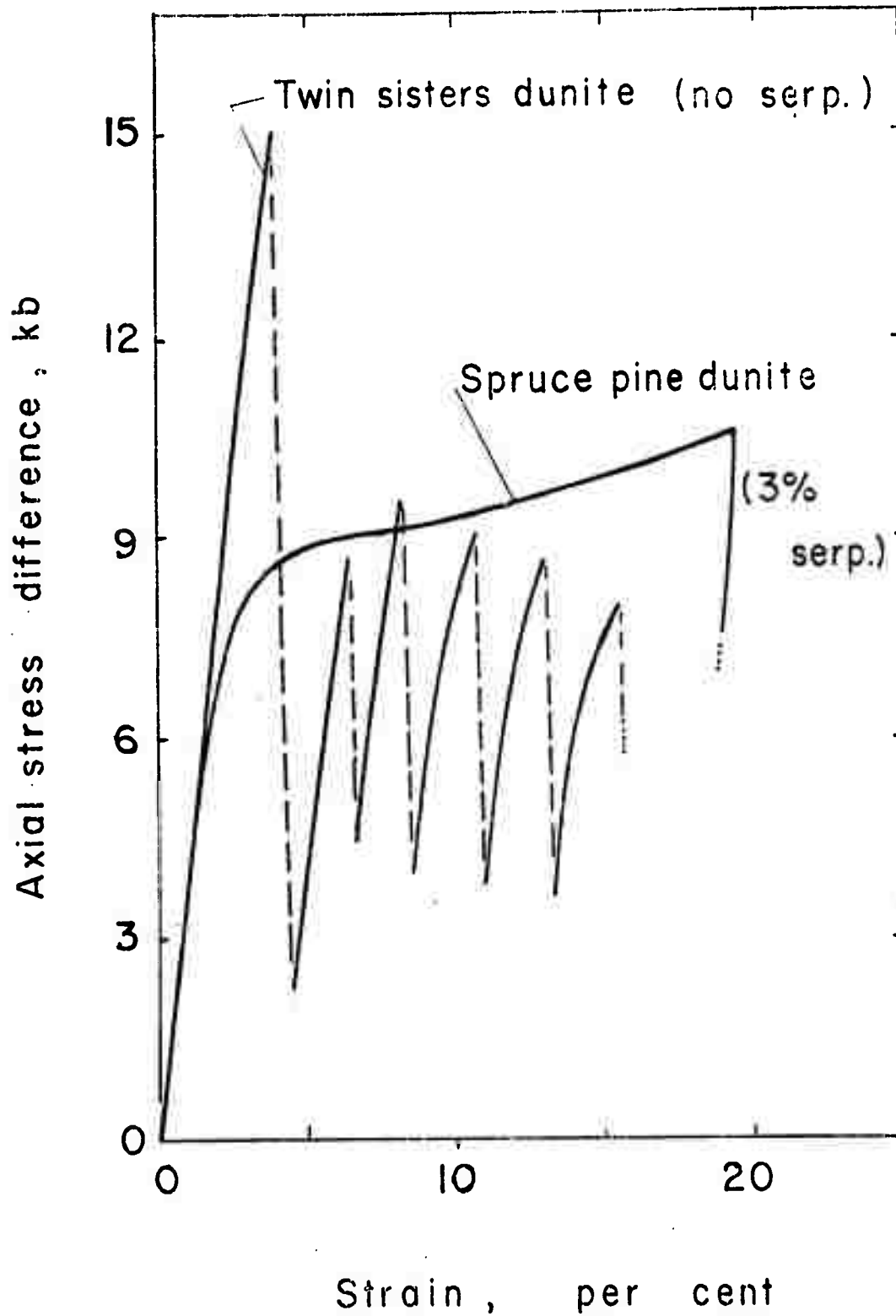


Figure 1 Stress-strain behavior of two dunites at 3 kb showing the effect of small amounts of serpentine.

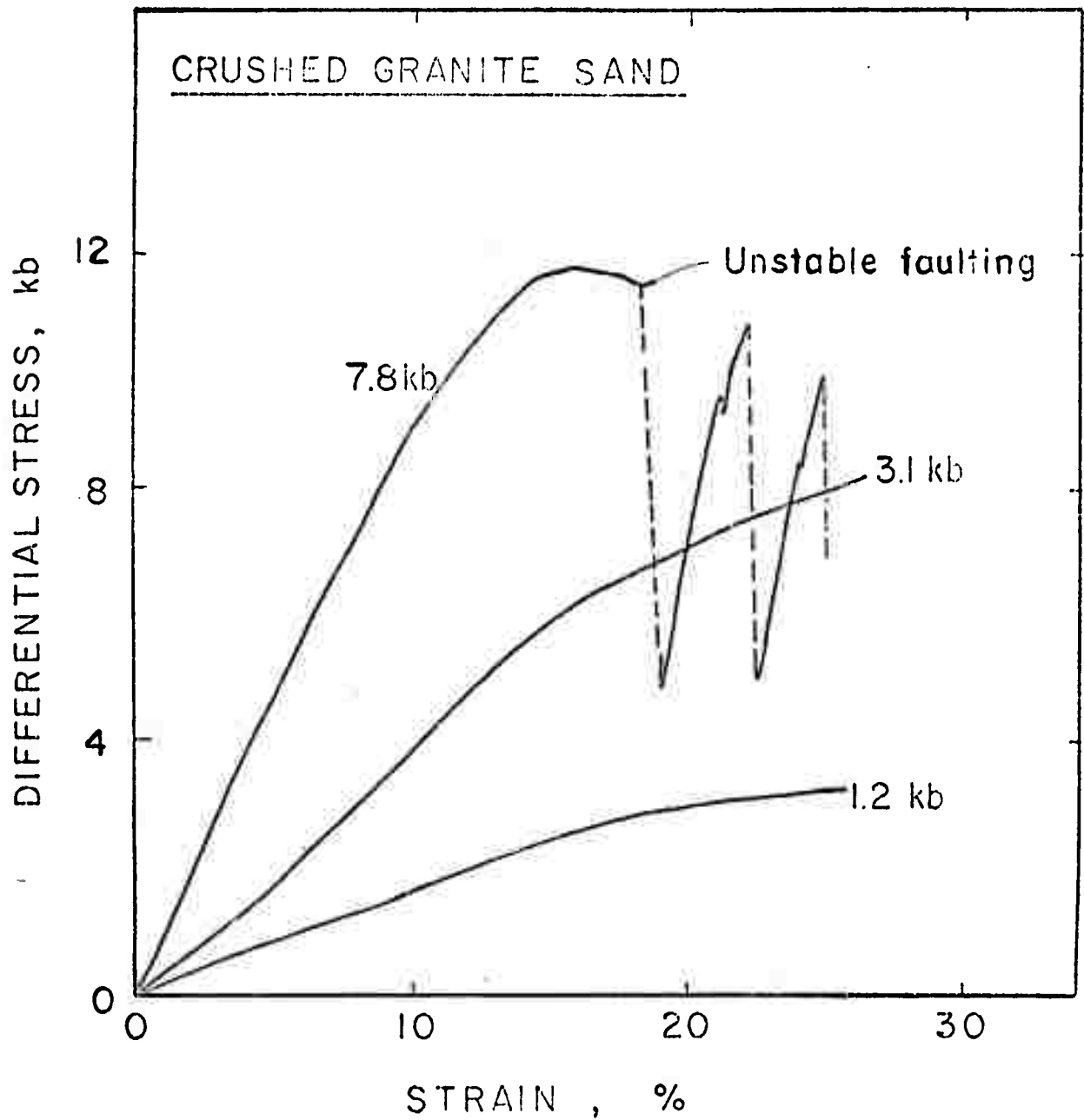


Figure 2 Stress-strain behavior of compacted granite sand at three different confining pressures.

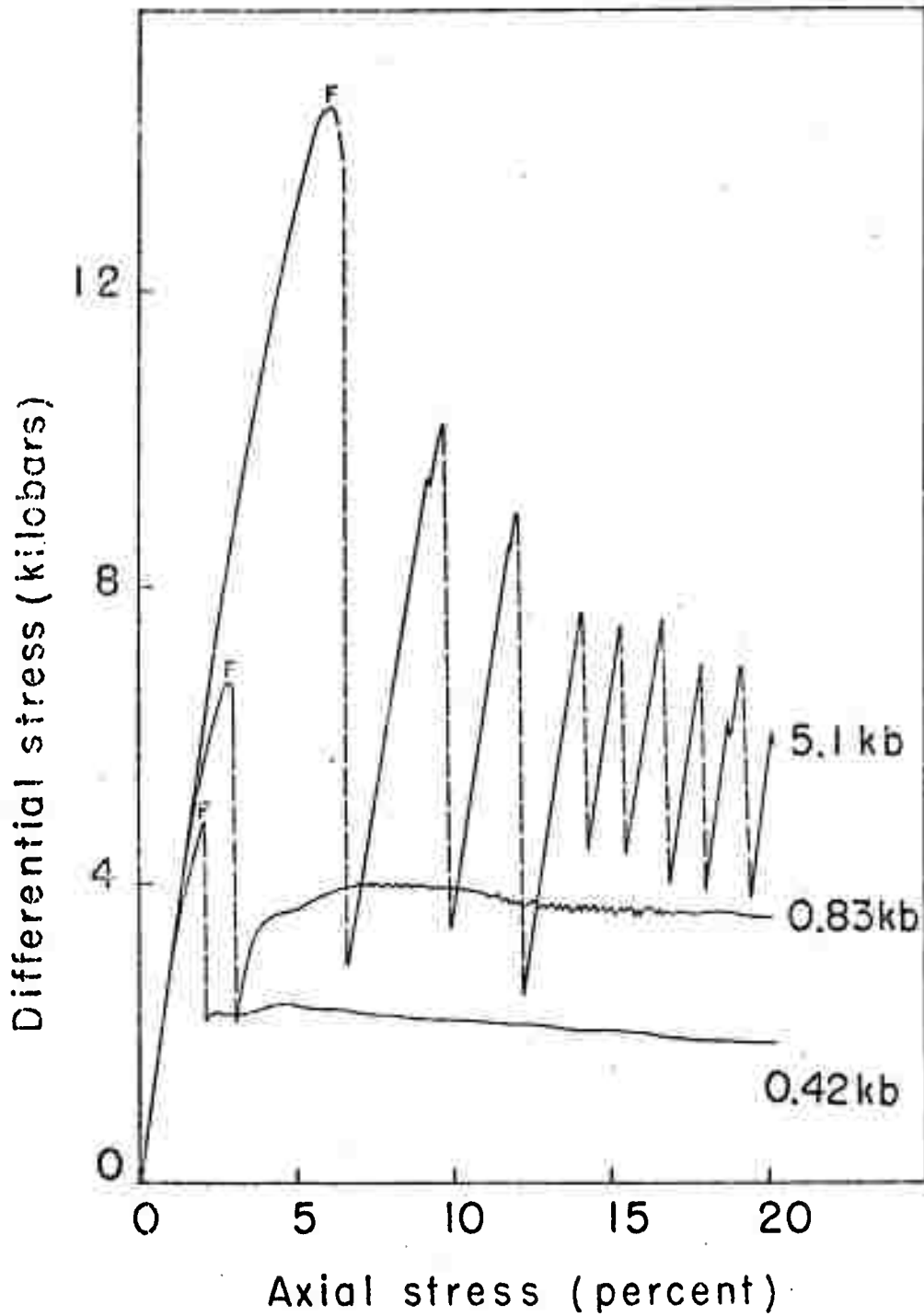


Figure 3 Stress-strain behavior of gabbro at three confining pressures. Faulting occurred at F.

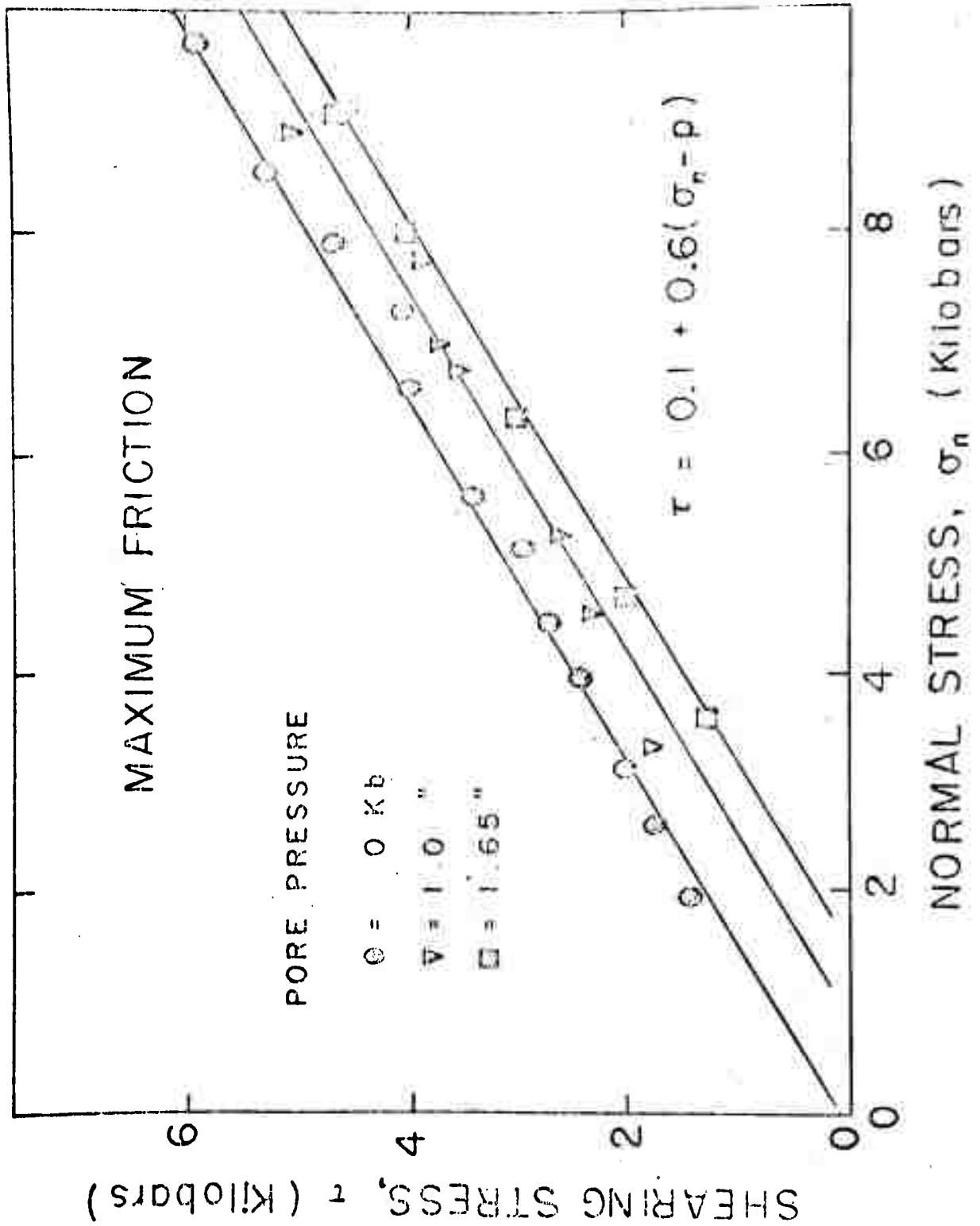


Figure 4 Frictional sliding on granite sawcuts at different pore pressures.

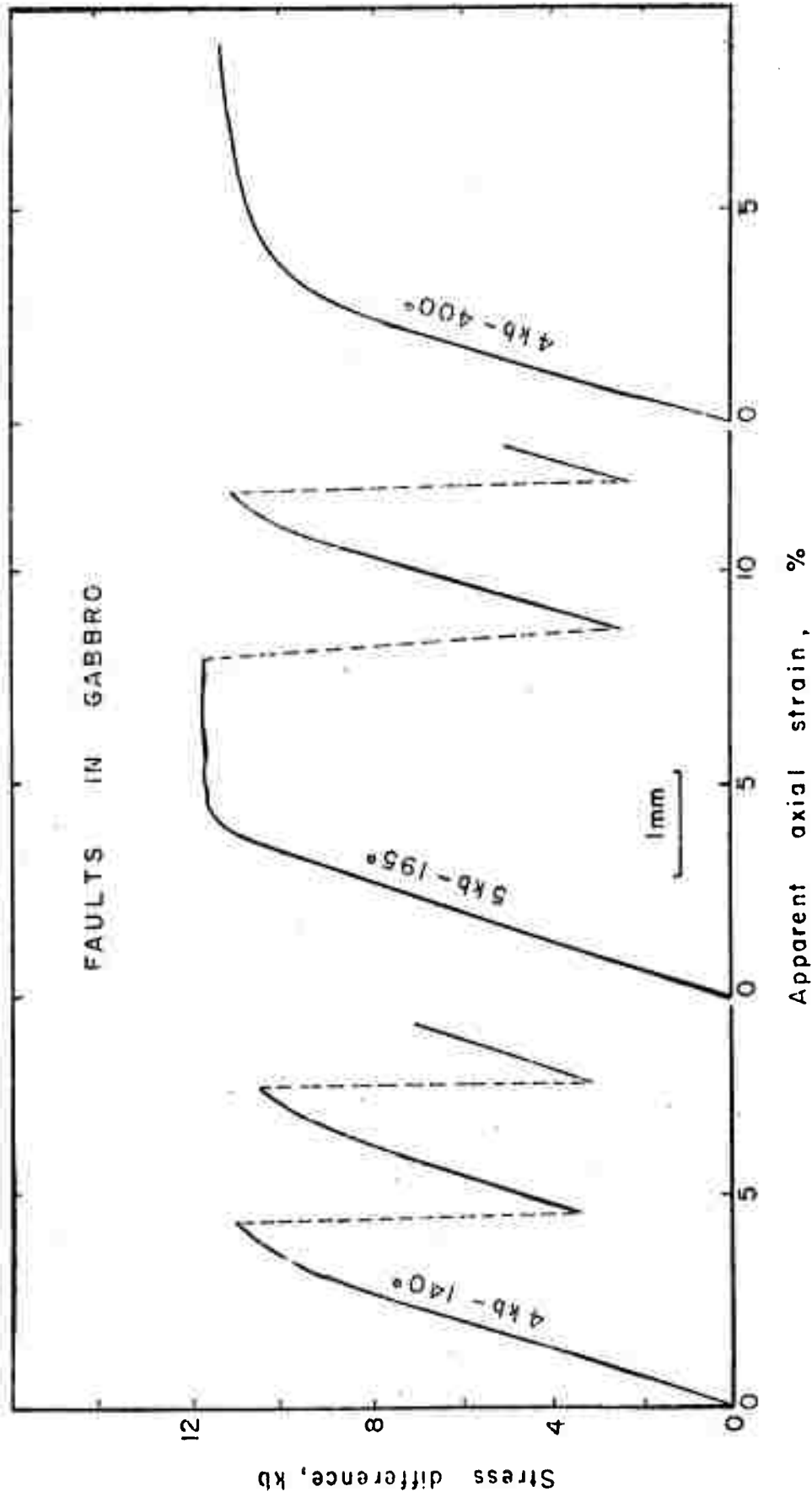


Figure 5 Stress-strain behavior of gabbro faults as a function of temperature. Dotted portions indicate sudden stress drops.



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Under this contract, MIT is studying the temperature and mineralogical dependence of stick-slip and the possibility of conversion of stick-slip to sliding by introducing lubricants and chemically active substances along saw cuts or faults in samples. Theoretical studies on the mechanics of stick-slip, fault propagation, and volume changes associated with fracture and sliding are being conducted. Several other parametric studies involving fault motion and its importance to earthquake generation will also be conducted. For additional information, contact either James J. Olson, Twin Cities Mining Research Center (612-725-4557) or Dr. William F. Brace, MIT (617-876-3391).

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13. ABSTRACT A theory of stick-slip, based on the concept of a static and dynamic coefficient of friction, predicts that the stress drop during stick-slip is independent of machine stiffness. The displacement during stick-slip is by contrast directly proportional to the machine compliance. Stiffness has been suggested as an important parameter in frictional behavior of rocks. Stiffness is calculated for a long, shallow, vertical surface fault of finite depth, which has slipped with a uniform stress drop over the surface. It is found that stiffness for typical source dimensions is several orders of magnitude lower than stiffness in typical laboratory high pressure experiments. Frictional sliding on sawcuts and faults in laboratory samples of various silicate rocks is markedly temperature-dependent. At pressures from 1 to 5 kb, stick-slip gave way to stable sliding as temperature was increased 200° to 500°C. The particular temperature of transition to stable sliding varied with rock type.		

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