Stick Slip, Stable Sliding, and Earthquakes—Effect of Rock Type, Pressure, Strain Rate, and Stiffness

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The magnitude of the stress drops that occur during frictional sliding on ground surfaces and on faults has been studied at confining pressures of as much as 5 kb. It was found that the stiffness of the loading system and the rate at which the load was applied had no effect on the magnitude of the sudden stress drops. Confining pressure and rock type were found to be the most important parameters. For example, sliding on fault surfaces in unaltered silicate rocks at confining pressure below 1 to 2 kb was stable; that is, stick slip was absent. At higher pressures, motion occurred by stick slip, and the magnitude of the stress drop during slip increased with pressure. Stick slip was absent at all pressures in gabbro, in dunite where the minerals are altered to serpentine, and in limestone and porous tuff. These results suggest that, if stick slip on a fault in the earth produces earthquakes, the earthquakes should become more abundant and increasingly severe with depth. Also, if a fault traverses various rock types, then over part of the fault elastic buildup of stress prior to sudden movement may occur at the same time as stable creeping motion elsewhere on the fault.

INTRODUCTION

Byerlee [1966, 1967] showed that, when two surfaces of granite slide on one another under high confining pressure, the motion occurs through stick slip. That is, the surfaces momentarily lock together, then suddenly release and slide forward, and then lock again. As they slide, shearing stress is released and an elastic shock is produced. Typically, the amplitude of the stress drop in one cycle of stick slip amounts to a fraction of the shearing stress required to cause the sliding.

Brace and Byerlee [1966] suggested that stick slip on pre-existing faults might be a source of shallow earthquakes. The idea was attractive for two reasons. First, stick slip could explain why the stress drop calculated for even large earthquakes is small relative to the stress that most crustal rocks can probably support. Second, stick slip provides a mechanism for energy release in material (such as rock in seismic areas) which may already contain many fractures. Although the stick-slip hypothesis is thus attractive, its relevance as a crustal process remains open to question. It is certainly valid to ask whether stick slip observed in small laboratory samples will also occur during the sliding of large rock masses under natural conditions. To answer this we need to consider how natural conditions differ from those of the laboratory experiment. Certainly the scale will be very different; this factor cannot, unfortunately, be easily assessed. Other natural factors include elevated temperature, slow strain rate, and variation in rock type. Temperature is known to affect stick slip markedly: *Griggs et al.* [1960] detected no stick slip in granite or dunite at 5-kb pressure and 500°C. Rock type, too, seems to be important: stick slip was absent in serpentinite even at room temperature [*Raleigh and Paterson*, 1965]. There are still other factors. The amplitude and other characteristics of stick slip may depend on the elasticity of the surrounding material through which load is applied. Thus, for certain metals the stress drop during stick slip is high if the loading system is very elastic, whereas it drops to zero if the loading system is very stiff [*Rabinowicz*, 1965]. Finally, water under high pore pressure produces some puzzling effects: *Brace and Martin* [1968] showed that violent stress drops disappear under high pore pressure at slow strain rates.

In the earth, many of these factors must be considered. Most rock will contain water, will be at elevated temperatures, will be loaded slowly, and will vary widely in composition and texture. The stiffness of the natural loading system can only be surmised, but it is probably safe to assume that it will be different from the stiffness of a laboratory press.

This paper is the first of several in which these and other factors will be systematically studied with the over-all objective of testing the stick-slip hypotheses. Here we will consider the effect on stick slip of strain rate, loading machine stiffness, and rock type. Experiments done at various confining pressures revealed that pressure itself had an interesting and unexpected effect on stick slip; these observations are included as well. Although final appraisal of the stick-slip hypothesis must wait study of the remaining factors, the results presented here have some interesting implications for earthquake studies. Although tentative, these results are discussed briefly following a review of our observations.

Experimental Methods

Frictional sliding was studied by using the methods described by *Byerlee* [1966, 1967]. In essence, this consisted of observing the motion on a more or less plane surface which passed through a slender cylindrical specimen of rock. The surface was inclined at 20° to 40° to the axis of the cylinder. The cylindrical specimen was first loaded radially by fluid pressure through an impervious jacket and then axially until sliding by a steel piston of the same diameter occurred. Stresses and displacements for the sliding surface were obtained by the resolution of axial and radial stresses or displacements.

Sliding on two types of surface was studied: the ground surface (abbreviated G) cut and ground at 30° to the axis, and the fault surface (abbreviated F), which was produced by stressing the sample to fracture. The rocks selected for study had a wide range of characteristics (Table 1) and included rocks likely to be abundant in the crust. A wide range of porosity, grain size, and degree of alteration was present in this group.

All specimens were 3.8 cm long and 1.58 cm in diameter and were enclosed in a copper jacket 0.13 mm thick. A 3-mm thick gum-rubber tube went over the copper jacket and was clamped to hardened steel end plugs. The purpose of the copper jacket was to support the two halves of the G sample during assembly and during grinding of the end surfaces. The purpose of the rubber jacket was to exclude the pressure medium after the copper jacket ruptured.

The pressure vessel used in the experiments was described by *Brace* [1964]. Axial force was applied to the piston with a ball screw driven by an electric motor through a reduction gear box. The force was measured by a load cell outside the pressure vessel. The strain rate was maintained constant during each experiment. Axial displacement of the piston was measured by a Sanborn DCDT 500 transducer attached to the piston. Confining pressure was maintained constant throughout an experiment with an automatic pressure regulator described by *Byerlee* [1968]. Confining pressure was measured by a manganin coil inside the pressure vessel. Differential force on the specimen was found simply by subtracting the force required to advance the piston against the confining pressure medium from the total force recorded. Differential force could be measured with an accuracy of $\pm 1\%$, and axial displacement could be measured to better than 0.1 mm. Confining pressure was maintained constant to within ± 5 bars during each experiment.

The effect of loading-machine stiffness on stick slip was of interest. The term stiffness as used in this paper is defined as the axial force divided by the axial displacement produced by this force. To obtain variable stiffness, we employed a 'stiffness reducer.' This reducer was, in essence, a column of fluid of variable length. As shown in Figure 1, this reducer was a separate pressure vessel in which pistons of various lengths could be inserted. The axial displacement at any load depends on the length, diameter, and compressibility of each component. The stiffest system was obtained by replacing the stiffness reducer, situated at the lower end of the main pressure vessel, with a solid steel nut. The most elastic system was obtained by using the longest possible column of fluid. The actual magnitude of stiffness for any one com-

TABLE 1. Description of Rocks

Rock, Source	ρ, g/cm³	d, mm	n	Type	Modal Analysis
Rhyolite tuff, Castle Rock, Colo.	2.45	0.5	0.40	2	33 gl, 20 qu, 40 ks, 4 an_{10}, 2 ox
Granite, Westerly, R. I.	2.646	0.75	0.009	1(1.2 kb)	27.5 qu, 35.4 ks, 31.4 an_{17}, 4.9 bi
Granodiorite, Dedham, Mass.	2.66	1.2	<0.01	1(2.1 kb)	40 qu, 30 an_{35}, 24 ks, 2 ep, 2 mus, 1 chl, 1 ox
Limestone, Solenhofen, Germany	2.663	0.01	0.048	2	99 ca (?)
White marble, Source unknown	2.715	0.20	0.003	2	99 ca
Limestone, Oak Hall, Pa.	2.766	0.10	0.003	2	99 ca-do
Gabbro, San Marcos, Calif.	2.819	2.0	0.002	1(0.83 kb)	70 an_{42}, 12 bi, 8 pyr, 7 am, 3 ox
Gabbro, Duluth, Minn.	2.94	4.0	0.004	1(0.84 kb)	62 an_{53}, 22 pyr, 7 mus, 7 chl, 1 bi, 1 ox
Gabbro, Nahant, Mass.	3.084	5.0	0.001	2*	40 pyr, 20 serp, 15 ol, 10 an_{70}, 10 bi, 3 ox
Dunite, Spruce Pine, N. C.	3.262	0.50	0.002	2	96 ol, 3 serp, 1 ox
Dunite, Twin Sisters Mt., Wash.	3.315	10	0.001	1(0.76 kb)	99 ol, 1 ox

Notes:
The column headed 'type' refers to the frictional sliding characteristics described in the text; ρ is density, *n* is porosity, and *d* is average grain diameter.

Abbreviations:

qu, quartz,
ks, orthoclase, microcline.
an_{10}, plagioclase with anorthite content.
pyr, pyroxene.
am, amphibole.
ol, olivine.
mus, sericite, muscovite.
serp, serpentine.
bi, biotite.
chl, chlorite.
ca, calcite.
do, dolomite.
ox, oxides.
ep, epidote.
gl, glass.

* At confining pressure greater than 4 kb, a single violent stress drop occurred at about 10% axial strain. Before and after this stress drop, sliding was stable.

bination was obtained by measuring the displacement under known loads. Stiffness ranged from 2 to 20 × 10^4 kg/cm.

In all our experiments, the temperature was close to 25°C and the pore pressure was zero. The rock samples were nominally dry; that is, they had been air dried in the laboratory at about 40% relative humidity. Actually, some moisture was undoubtedly held in pore spaces.

Observations

As previously noted, frictional sliding is influenced by many factors, and, even if we limit our study to the effect of four of these, many experiments would be required to define all the possible interrelated effects. If, for example, amplitude of stick slip is independent of strain rate in a stiff machine at low confining pressure, will the amplitude also be independent of strain rate in an elastic machine at high confining pressure? For purely practical reasons, we assumed that there was no coupling of effects; after spot checks, this assumption seemed justified. Accordingly, we explored the effect of each factor (e.g., strain rate and stiffness) separately.

Byerlee [1967] compared in some detail sliding on F and G specimens in granite. In a very general way, they had the same characteristics. Here the procedure has been to use a G specimen unless it had been established that F and

G specimens respond differently to the variable in question; in that case, an F specimen was used. The reason is that the F specimen is probably more nearly like the natural counterpart. A practical advantage in using the G specimen, however, is that a sample can be reused. This is impossible with an F specimen.

Strain rate. The effect of strain rate on frictional sliding of G specimens of granite is shown in Figure 2. Confining pressure was held constant (4.25 kb) both at the different strain rates and during an individual experiment. To check reproducibility, three duplicate runs were made at each strain rate; the three were almost identical, and only one is shown at each strain rate in Figure 2.

Stiffness. Machine stiffness was varied for a series of G samples of granite which were held at a constant confining pressure (1.85 kb) and loaded at a constant strain rate (2.4×10^{-4} sec^{-1}). One point from the stress-strain curve for each experiment was selected for comparison. In Figure 2 this point would be the second maximum on the stress-strain curves. This was the point representing maximum friction. *Byerlee* [1967] found that at this point intimate contact is first established between sliding surfaces in a G specimen. The value of the friction here is also close to the initial value in an F specimen.

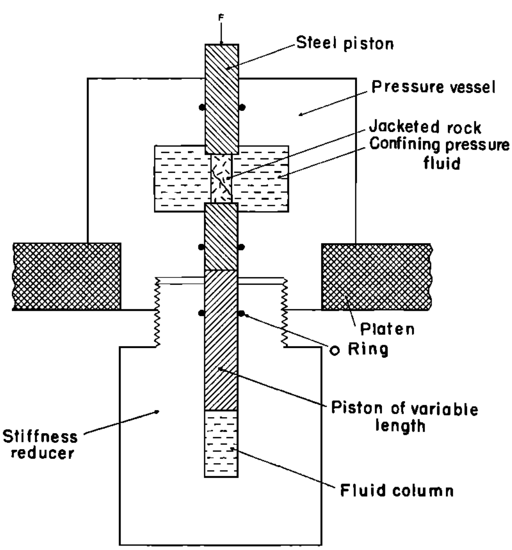

Fig. 1. Schematic diagram of pressure vessel and stiffness reducer.

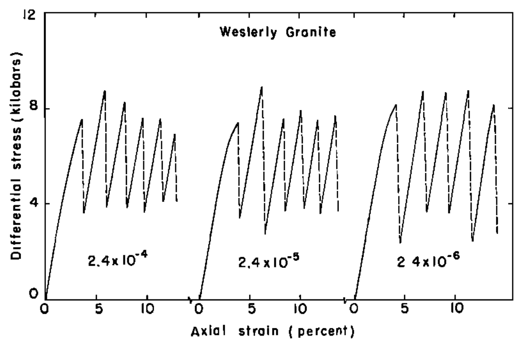

Fig. 2. Differential stress versus axial strain for ground surfaces of Westerly granite at a confining pressure of 4.25 kb. Numbers below each curve are the strain rates per second.

At the point of maximum friction and at the point when sliding ceased, shear stress on the saw cut was calculated from the known axial and radial stresses. A correction was applied for the changes in area that occurred as the two halves of the specimen slid past one another, starting with the first cycle of stick slip. The difference between the shear stress at the maximum friction and at the time when sliding ceased gave the shear-stress drop during slip. The results are shown in Figure 3.

Confining pressure and rock type. Frictional sliding on F specimens was studied at one strain rate (2.4×10^{-4} sec^{-1}) at confining pressures from a few hundred bars to nearly 6 kb. Behavior among the rocks could be clearly grouped into one of two categories. In what we have called type 1, stick slip was very pronounced at high pressure (2 to 6 kb), weak but distinct at intermediate pressure (0.8 to 2 kb), and absent at low pressure. Typical behavior in these three ranges is shown in Figure 4 for a gabbro. On each curve, the rock fractured at the point marked *F*.

For a rock classed as type 2, stick slip was absent at all pressures (Figure 5). Although stress may drop at fracture (note the lower curves in Figure 5), this was not accompanied by an elastic shock. Sliding on the fault produced no audible effects.

Type 1 behavior characterized Westerly granite, Dedham granodiorite, San Marcos gabbro, gabbro of the Duluth complex, and dunite from Twin Sisters Mt. Type 2 included Solenhofen limestone, limestone (Oak Hall),

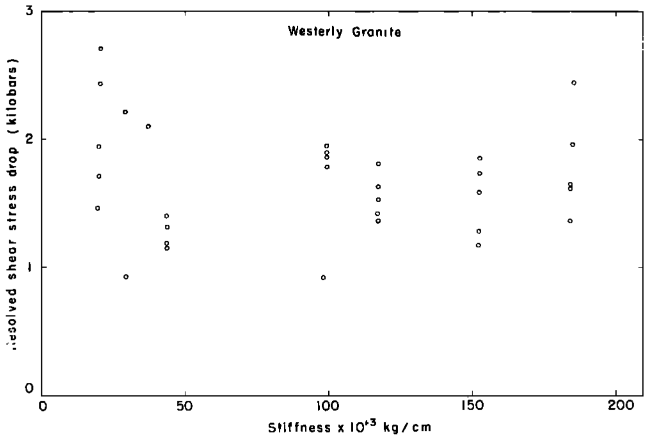

Fig. 3. Shear stress drop versus stiffness of the loading system for ground surfaces of Westerly granite at a confining pressure of 1.85 kb.

marble, rhyolite tuff, gabbro (Nahant), and dunite (Spruce Pine). From work reported elsewhere, type 2 also includes an altered granite [*Paterson,* 1964] and a serpentinite [*Raleigh and Paterson,* 1965]. Sandstone [*Handin and Hager,* 1957] may also belong in this category. *Mogi* [1965] gave stress-strain curves of the ductile type resembling those of our tuff; his rocks, which included andesite, trachyte, and tuff, had a porosity of 5% or more. The characteristics for the rocks studied here are summarized in Table 1, in which the category (type 1 or type 2) is given, as well as the pressure for type 1 above which distinct stick slip occurs.

Discussion

To judge from our results (Figures 2 and 3), neither loading-machine stiffness or strain rate has much effect on the amplitude of the stress drop in stick slip. This is not entirely as might have been predicted. *Rabinowicz'* [1965] observations for certain metals suggested that stick slip might be reduced in amplitude or even eliminated in a very stiff machine. There is no such trend in our data. There may be several explanations for this trend, but we believe that it is due to differences in the detailed mechanics of sliding of ductile metals and rocks. *Byerlee* [1967] suggested that sliding in rocks involves brittle fracture of asperities. Presumably this takes place by brittle crack growth with little or no true plastic flow. Brittle crack growth is usually an unstable process, particularly in the presence of tensile stress. Failure of asperities, in Byerlee's theory, arises because of local tensile stress.

It is difficult to say whether the stiffness attained in our present loading system is comparable with the stiffness of material surrounding stressed crustal rock. Perhaps in the earth this stiffness will be approximately that of the stressed rock itself. In our experiments, stiffness of the unfractured sample is about 2×10^4 kg/cm, so that the stiffness of sample and loading machine are about the same at one end of

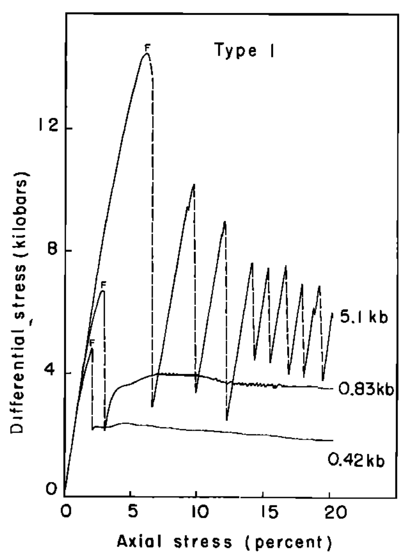

Fig. 4. Differential stress versus axial strain for San Marcos gabbro. The value at the end of each curve gives the confining pressure in kilobars.

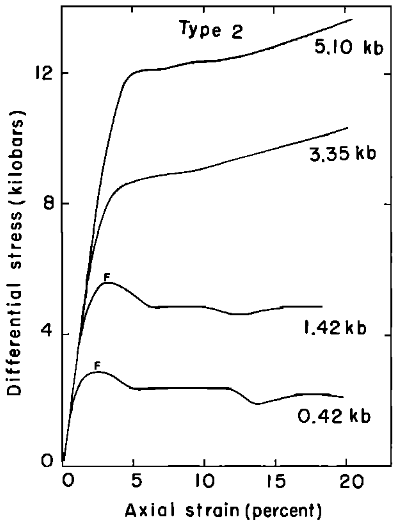

Fig. 5. Differential stress versus axial strain for Spruce Pine dunite. The value at the end of each curve gives the confining pressure in kilobars.

our range of stiffness. Here, and to the extent that this truly duplicates the natural situation, stick slip seems to be independent of the elastic properties of the surrounding media. There is a large scatter in the results, but Figure 3 shows no trend toward a reduction in the stress drop as the stiffness of the leading system is increased.

It is convenient to distinguish between stick slip and stable sliding. Stable sliding lacks audible stress drops and is smooth rather than jerky. Stable sliding is in fact accompanied by very low amplitude elastic shocks [*Scholz,* 1967], but these are only detectable ultrasonically at high amplification. This activity is apparently many orders of magnitude weaker than the elastic shocks due to stick slip.

Type 1 rocks showed stable sliding on fault surfaces at low pressure and stick slip at intermediate and high pressure. The amplitude of the stress drop increased with pressure. Type 2 rocks showed stable sliding up to the highest pressures at which motion on a fault took place. Above this pressure, deformation of the sample was more homogeneously distributed, but no elastic shocks were produced.

What determines the category to which a rock will belong? To judge from Table 1, the controlling factors are mineral type and porosity. Stick slip apparently does not occur in rocks with high porosity like the tuff. Just how much porosity is necessary to produce this effect is not known. Stick slip also is absent for rocks that contain calcite and serpentine. It is interesting that only 3% of serpentine content completely changes the frictional characteristics of the two dunites. It is also interesting that large amounts of minerals such as chlorite and the micas have relatively little effect. Grain size also is of little influence; Solenhofen limestone and marble are both type 2, although grain size differs greatly. The role of alteration is somewhat uncertain. One granite, reported to contain micaceous alteration products [*Paterson,* 1964], is apparently of type 2. On the other hand, Dedham granodiorite and gabbro of the Duluth gabbro complex, which contain a great deal of finely disseminated sericite and chlorite, are type 1. However, alteration of minerals to serpentine seems to give type 2 behavior consistently.

Although the underlying causes of type 1 and type 2 behavior are still unclear, our results suggest some interesting implications for earthquake studies. Let us assume for the moment that we are dealing with earthquakes produced by frictional sliding. Then, apparently, sliding on a fault may or may not be accompanied by sudden stress drops, depending on the rock type traversed by the fault and on the pressure in the vicinity of the fault.

For rocks of type 1, the effect of pressure or depth may be as follows. At the surface and to a depth of a few kilometers, stable sliding predominates, so that stress is relieved without producing earthquakes. Below a certain depth (3 to 5 km is suggested by the data of Table 1) earthquakes would be produced because of stick slip. Earthquakes would be more abundant and increasingly severe with increasing depth. Nothing in this study would place a limit on this depth, but work by *Griggs et al.* [1960] suggests that sliding again becomes stable at temperatures of about 500°C. This may correspond to the lower crust. Thus, there would be a zone within the crust to which earthquakes due to stick slip will be limited. The rocks we have studied (Table 1) would not be out of place in the zone.

The effect of rock type is particularly significant if we imagine rocks of types 1 and 2 adjacent to one another and traversed by an active fault. In rocks of type 2, stress would be relieved by stable sliding. This might be evident at the surface as a slow creeping motion. Along the fault in the type 1 rocks, however, no motion would occur until the stress reached a critical value, and then slip would take place suddenly.

Although this picture is speculative, it is of interest to carry it a step further and consider the prediction of an earthquake that could result from the motion of such a fault. Clearly, elastic energy will be stored preferentially in the places where the fault is locked and where stress is building up to a sudden stress drop. In these places, which should be seismically very quiet, surface strains and tilts should be larger and therefore more easily measurable than in adjacent regions of stable sliding.

It seems likely that, when the stress reaches the critical value for slip to occur in a region of type 1 rocks, motion could take place suddenly along the entire fault. Steady creeping motion on the fault in one region would therefore be no assurance that the fault would not be the site of a severe earthquake.

In recent work in California [for example, *Cisternes,* 1964], it has become increasingly clear that earthquakes associated with the San Andreas fault system emanate from shallow depths, from just below the surface to perhaps 15 to 20 km. The mechanics of this fault system become hard to explain if this depth is also the actual lower limit of the horizontal shearing displacements. One possibility is that these displacements do continue to greater depth but are not accompanied by earthquakes. In other words, the shearing motion on the fault above 20 km is by stick slip or growth of brittle fractures, whereas below 20 km it is by creep or stable sliding. If the shearing motion is by sliding, this would imply the existence of predominantly type 2 rocks below 20 km, perhaps partly serpentinized mafic rocks, and predominantly type 1 rocks above this depth. Of course, other factors than rock type may be responsible for this supposed change in character of the shearing motion. Among these, temperature certainly needs to be considered, although this would require, for the California situation, that the change in the motion be affected by a rather modest temperature increase, perhaps a few hundred degrees. Some results of *Griggs et al.* [1960] support this possibility; they observed stable sliding in granite and dunite at 5 kb and 500°C.

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