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STICK-SLIP OF LIGHTLY LOADED LIMESTONE

PROGRESS REPORT

C. B. Drennon and R. L. Handy

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ABSTRACT

The phenomenon of stick-slip of a limestone tested in direct shear at a constant rate of strain under normal loads of 0.75 to 20.00 kg/cm^2 and temperatures from 30 to 200 $^{\circ}$C was investigated. Stick-slip was found to depend upon the temperature, normal load, and previous frictional history of the rock. Stick-slip could always be induced from smooth slip by raising the temperature. Temperatures above that required to induce stick-slip result in larger slips, longer sticks, and higher shear load relaxations. At normal loads above 3.00 kg/cm^2, stick-slip began at 30 $^{\circ}$C. Accumulation of debris has the same effects as lightening normal load, allowing smooth slip below 100 $^{\circ}$C. Smooth slip below this temperature is attributed to adsorbed water. The dependence of stick-slip upon temperature and reaction to the creation or introduction of debris led to the conclusion that stick-slip of limestone is a result of asperity to asperity bonding.

CONTENTS

Introduction

Stick-slip is a phenomena observed in most studies of sliding friction, particularly at light normal loads. Stick-slip is the movement of a sliding element in abrupt jerks. The tangential force required to cause movement builds up to a critical value, then suddenly reduces as the element slides forward. The sliding element then sticks again (stops moving) and the cycle begins anew. The variation of frictional force with time is shown in Fig. 1. The velocity of the sliding element fluctuates greatly during movement, and the coefficient of friction varies between the limits prescribed by values τ_1 and τ_2 in Fig. 1.

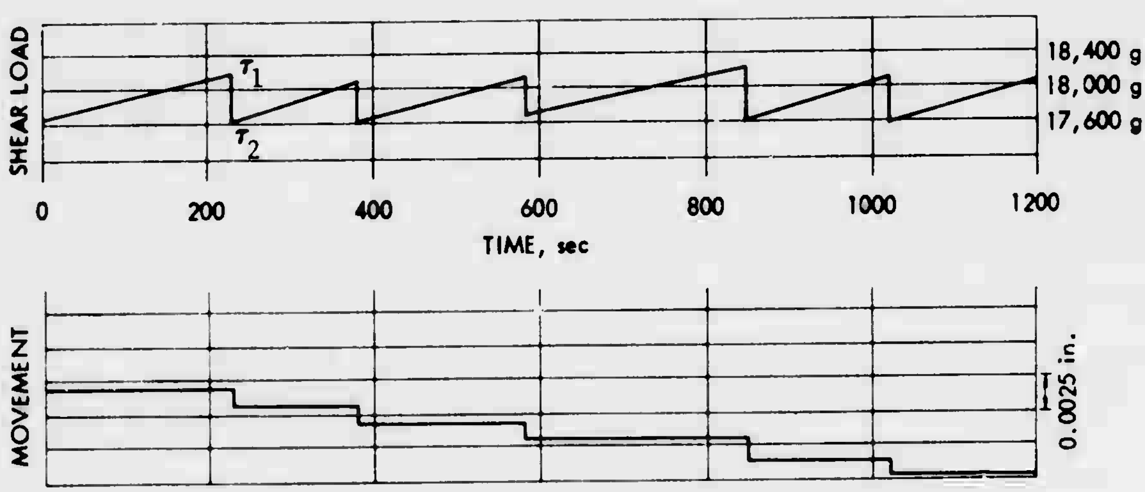

Fig. 1. Typical stick-slip pattern. Test 97C, temperature 125°C, $\sigma_n = 3.00$ kg/cm^2.

A very common audible manifestation of stick-slip is a squeak, a layman's indication that the surfaces involved need oil. Audible stick-slip appears to be involved in shearing under foot of of the famous "barking" sands near Polihale Beach, Hawaii, and an audible repetitive stick-slip has been heard by one of the authors during in-situ shear testing of dry, friable loess silt soil using the bore-hole shear device[1].

One may conjecture that stick-slip could be involved in subaudible rock "noises" produced during the initial creep stage of landslides. Stick-slip also is commonly believed to be at the seat of shallow focus earthquakes[2].

Most of the research on stick-slip has been with metals, where stick-slip at high velocity of slider movement is a troublesome phenomenon in the machine-tool industry[3]. Much of this work has been of a mathematical nature, attempting to use the equations of motion to describe the typical stick-slip curve[4-6]. Less work has been done on attempting to define mechanisms of stick-slip. The principal investigation in this direction is by Rabinowicz[7]. He states that sll stick-slip processes are caused by the fact that the junction force does not remain constant as a function of some other variable.

Bowden and Tabor[8] describe the cause of stick-slip as the increase of the static coefficient of friction. Rabinowicz[7], following the initial suggestion of Ishlinski, proposed that the static coefficient of friction varies with the time of contact between sliding elements, building up within a short time of contact to be higher than kinetic friction. This assumption has been supported by the research of Kosterin and Kragelsky[9] and Brockley and Davis[3] but not by Simkins[10] who claims there is no basic difference between static and kinetic coefficients of friction.

Relatively little previous work has been done on stick-slip as applied to rocks. Jaeger, in his pioneering study of frictional properties of rocks[11], did encounter stick-slip in an artificial plaster joint. More recently[12], he mentioned stick-slip in an overview of frictional properties or rock. Horn and Deere[13] in their study on friction of pure mineral specimens, encountered stick-slip in many of their tests on quartz, where the phenomenon was a nuisance in attempts to obtain friction coefficients. The most work on stick-slip in rocks has been done by Byerlee[2] who concentrated on stick-slip which can occur at very high pressure deep in the earth because of the possible relation to shallow focus earthquakes. Byerlee's investigations led him to propose a theory of stick-slip of rock which is dependent on the mechanisms of brittle fracture.

The investigation which most closely resembles this one is that of Hoskins, Jaeger, and Rosengren in Australia[14]. These investigators studied large-scale rock speciemns in a type of direct shear apparatus. Though stick-slip was not the purpose of the investigation, the phenomenon did occur and received much comment in the paper. However, no temperature effects were investigated in that study. Brace and Byerlee[15] investigated effects of temperature, but at normal loads exceeding 50 kg/cm^2.

The objective of the present study was to ascertain the effects of temperature on the phenomenon of stick-slip of lightly loaded rock.

Apparatus

A temperature-controlled, constant-rate-of-strain direct shear device was used to conduct the stick-slip tests (Fig. 2). The shear apparatus consists of a larger, stationary rectangular specimen holder with a smaller, movable holder placed on top, allowing about 2.5 cm of travel with no change in gross contact area. Normal load is transferred to the upper holder by a ball and socket, which allows a hanging load to travel with the moving block.

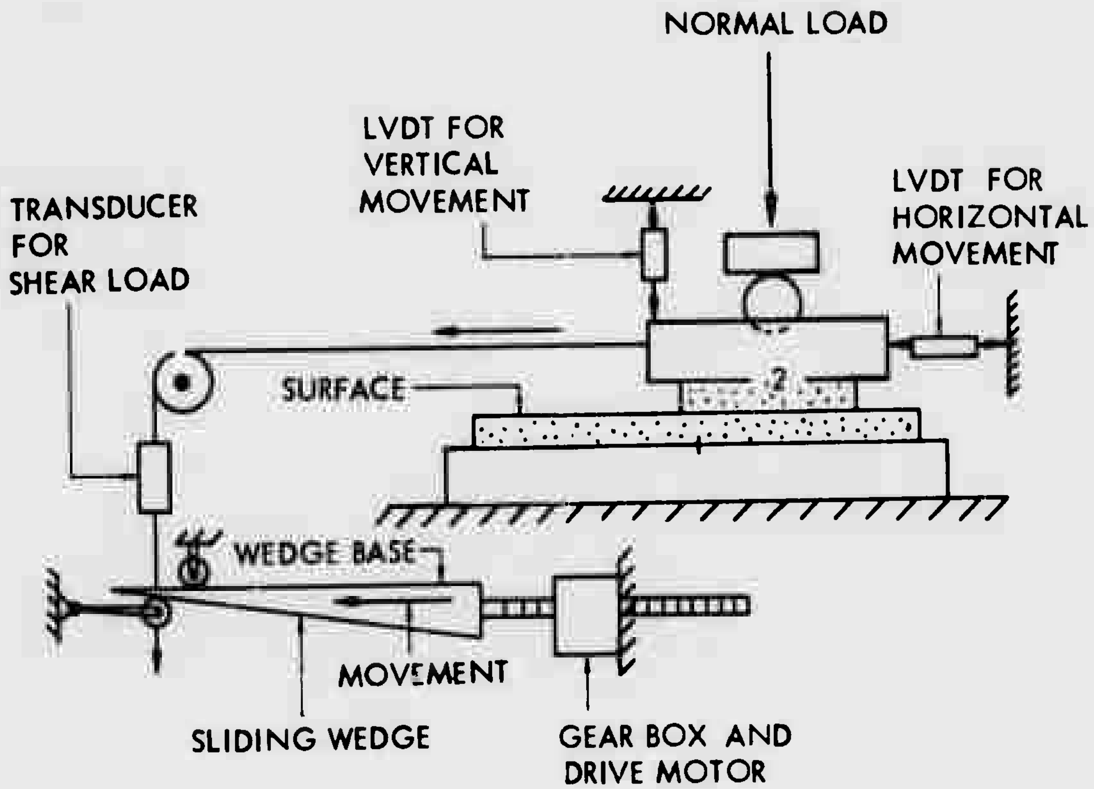

Fig. 2. Schematic of shear apparatus: (1) stationary block and holder; (2) sliding block and holder.

The upper block and holder are pulled at a constant rate by a screw and wedge mechanism drive by an electric motor. The screw drives the wedge at a very slow rate, and a pulley impinging on the wedge then pulls the upper block by an attached wire. The strain rate is adjustable by changing the wedge base angle. A nominal strain rate of 1.4×10^{-3} cm/min was used in the stick-slip tests.

The shear load required to move the block is measured by a strain gauge direct-tension load transducer consisting of two arms of a Wheatstone bridge mounted on a thin piece of metal. The transducers used in the lighter-load tests were accurate to within $\pm$ 300 g; that used in the higher-load tests is accurate to within $\pm$ 100 g.

Horizontal movement of the upper block is measured by a linear variable differential transformer (LVDT) accurate to ± 0.0002 cm. A second LVDT was arranged to measure vertical movement of the upper block. Though this is accurate to within ± 0.0001 cm, the blocks were ground too smooth for any vertical movement to be recorded.

The information gathered was recorded on an ink-writing oscillograph. Times and movements were taken from the oscillograph record.

Specimens

The principal rock tested was the well-known building limestone from the vicinity of Bedford, Indiana, the Salem limestone. This bioclastic limestone is about 98% calcite, the remainder being quartz. Unconfined compressive strength was evaluated as 400 kg/cm^2.

Each block was sawed to the appropriate size, then ground "smooth" with a number 45 grit aluminum oxide grinding wheel. This degree of smoothness is much rougher than the "rough" quartz block of Horn and Deere[13], which was ground to 240 grit, but smoother than the "rough" blocks of Hoskins et al.[14]. The blocks as ground are much idealized compared to natural joints and fractures, but not so smooth as to be in the realm of purely academic interest. They are rough enough that water does not act as an antilubricant[13]. The grinding was believed necessary to minimize dilatancy (interlocking) and to give some degree of uniformity so that tests run on different blocks could be compared.

After grinding, the blocks were carefully washed in clean water to remove all debris. The blocks were then oven dried at 110 °C, removed from the oven and allowed to cool and air-equilibrate at room temperature. For second runs on the same block, the blocks were again carefully washed, oven dried, and equilibrated except where otherwise noted.

One test was run for comparison on a metamorphic rock, a biotite-rich schist. The preparation of the metamorphic rock was the same as that of the limestone.

Tests

Twelve test series were conducted, eleven on limestone with gross normal stresses of 0.75, 1.52, 1.95, 3, 5, 10 and 20 kg/cm^2 and one on the metamorphic rock with a gross normal stress of 3 kg/cm^2.

Movement of the blocks was begun at between 30 and 35 $^{\circ}C$. The mode of the movement was usually smooth, i.e., without stick-slips at these temperatures. The temperature was then raised in increments of about 10 $^{\circ}C$ until stick-slip began, and further raised to show the effect of higher temperatures up to 200 $^{\circ}C$. Observations were made at each temperature for time between slips (i.e., time of stick), amount of slip, and load relaxation during slip. The character of the slip was also observed. The temperature was then gradually reduced, and movement during cooling was observed. In particular the temperature of cessation of stick-slip was noted.

Results

Initiation of Stick-Slip

The initiation of stick-slip was found to depend upon three factors which interact: (1) the temperature, (2) the normal load, and (3) the previous frictional history of the specimen. Increasing the temperature caused a change from smooth to stick-slip, Table I shows the initiation temperature at various normal loads. The effect of increasing normal load is to decrease the temperature at which stick-slip initiates. For example, at the lightest normal load of 0.75 kg/cm^2, the minimum temperature of initiation of stick-slip was 100 ^oC and the average of 13 tests was 160 ^oC, whereas at normal loads exceeding 3.0 gk/cm^2 most blocks began stick-slip at room temperature. On only one test, 99A at 10 kg/cm^2, did smooth slip occur at the initial room temperature, and then only after a short interval of stick-slip.

The previous frictional history of the specimen is critical in the initiation of stick-slip. Blocks tested for the first time or blocks which had been removed, washed, and retested all show low temperatures of initiation of stick-slip at all loads. This is illustrated by test 91A, which used the same blocks as test 90, but with the surface carefully recleaned before use.

Continuous Runs at Constant Temperature

Most of the tests were allowed to run for considerable period of time at each temperature. Groups of 10 successive slips were then averaged and studied to determine if any trends occurred with time.

The most extensive test at the lowest normal load of 0.75 kg/cm^2 was test 88G, which gave a pattern of time between slips shown in Fig. 3. The time between slips shows a fairly constant increase with time. This was also observed in several other tests at the same normal load at other temperature.

In tests with normal loads from 1.95 kg/cm^2 and higher, the above trend was sharply reversed, as shown in Fig. 4. Note in Fig. 4 that the

Table I. Temperature at Initiation of Stick-slip.

Test	Normal stress, kg/cm^2	Temperature, °C	Test	Normal stress, kg/cm^2	Temperature, °C
88A	0.75	160 (fresh)	96A	3.00	30 IT
B	"	160	B	"	30 IT
C	"	192	C	"	30 IT
C2	"	190	D	"	125 IT
D	"	190	E (d)	"	125 IT
E	"	145			
E2	"	171	97A	3.00	125 IT
F	"	150 IT	B (d)	"	125 IT
					149
89A	0.75	128	B2	"	125 IT
A2	"	127 IT			75
C	"	100	C	"	125 IT
C2	"	200			88
D	"	155			
			98A	5.00	30 IT
90A	1.52	30 IT	A2	"	125 IT
A3	"	125			150
B	"	150 IT	B (d)	"	125 IT
					125
91A	1.52	35 IT (clean)	B2	"	125 IT
B	"	150	C	"	125 IT
C	"	100			
D	"	175	99A	10.00	30 IT (became smooth)
					125
94B	1.95	190 (clean)	A2	"	125 IT
D	"	200 IT	B	"	125 IT
F	"	250			200
G	"	270	C (d)	"	125 IT
			D	"	125 IT
95E	1.95	35 IT			200
			100A	20.00	30 IT
			A2	"	125 IT
			B	"	125 IT
			C	"	125 IT

IT - Initial temperature of test
(d) - debris test

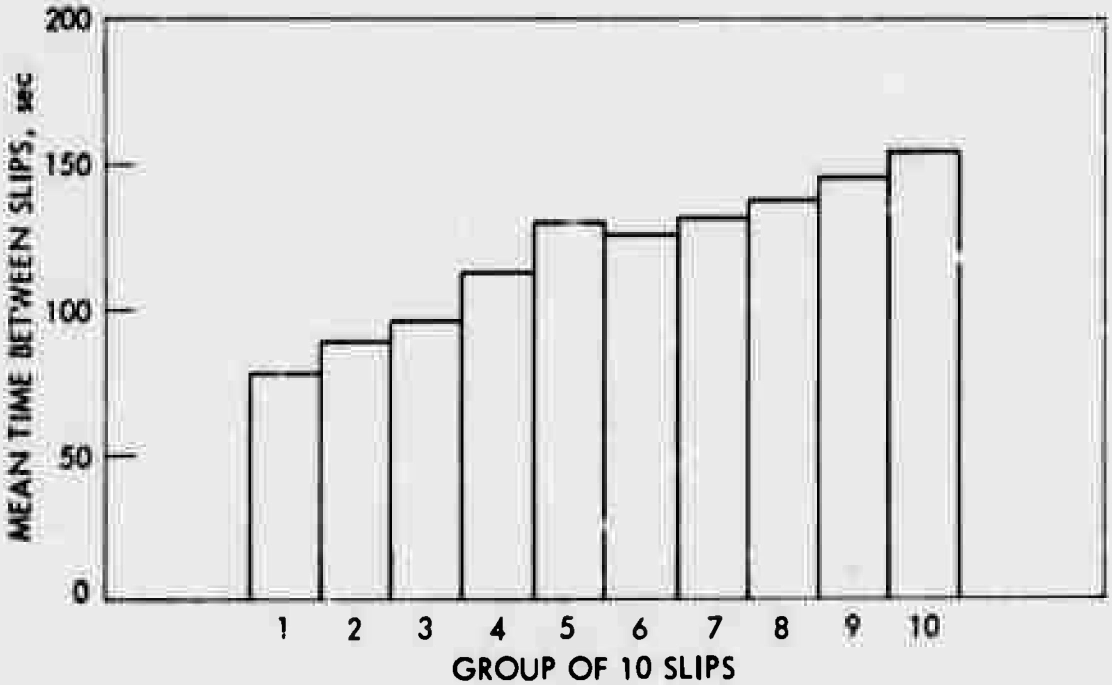

Fig. 3. Variation of mean time between slip of successive groups of ten slips. Test 88G, $\sigma_n = 0.75$ kg/cm^2, at 190^{o}C.

stick time appears to be approaching a constant value of 170 sec, which corresponds to a distance of about 0.004 cm per slip. This slip value also was approached in other tests and was found to depend on temperature and materials, and most probably elastic rebound properties of the test apparatus. Tests which were stopped and restarted at the same temperature gave the same average slip value as had been attained before stopping.

In several tests upon raising the temperature to 200 ^{o}C, the mean slip increased to a maximum in the second or third group of ten slips before beginning its decrease. It is believed that this simply reflects the fact that air temperature in the enclosure rather than rock temperature is measured, and that the rock had not yet attained the higher temperature.

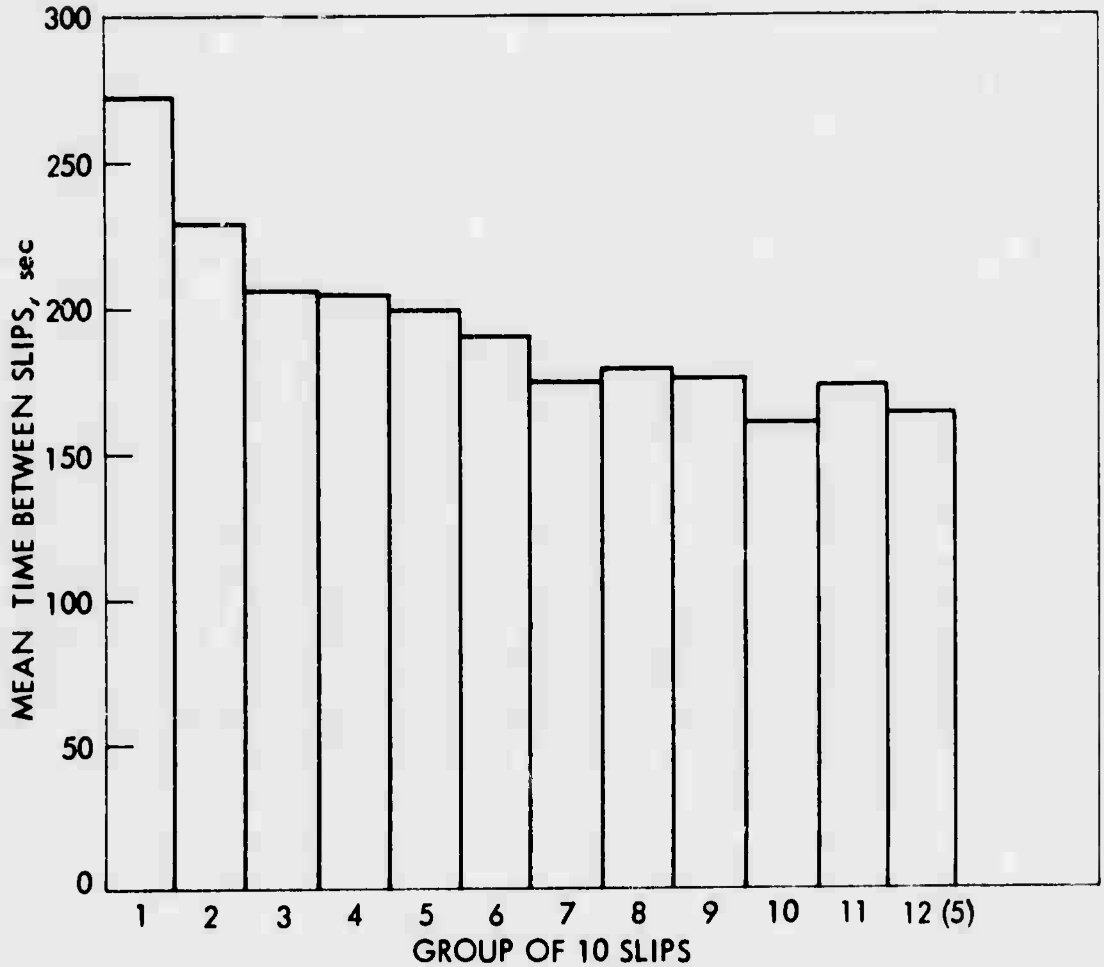

Fig. 4. Variation of mean time between slips of successive groups of ten slips. Test 96D, σ_n = 3.00 kg/cm^2, at 125°C.

<u>Effect of Debris</u>

The above-mentioned results of decreasing amount of slip with time led to the suspicion, shared with Hoskins et al.[14], that debris caused by sliding in some way reduces the tendency for stick-slip to occur. Byerlee[2], though not concurring that debris reduces stick-slip, indicates that debris is an important factor when he suggests that stick-slip in rocks is caused by brittle fracture. Examination of blocks after testing showed very little damage to lightly loaded blocks, but the more heavily loaded blocks used in tests at 10 and 20 kg/cm^2 showed extensive rock flour. Upon washing these blocks, however, striae were not visible with the naked eye or with the binocular microscope. Examinations of a chip fractured from the upper block in test 100 C under a scanning electron microscope showed that the natural debris was concentrated on the high rather than the low parts of the clock. The debris was composed of small crystals of calcite, the particles appearing to have been plucked from the edges of the calcite cleavage steps (Fig. 5).

Fig. 5. Scanning electron micrograph of surface after completion of sliding. Note debris. Test 100C, $\sigma_n = 20\ kg/cm^2$, 300X.

The amount of debris seldom amounted to more than 0.01 g. Several tests were run with artificially added debris to study the effect of debris on stick-slip. Test 95B was conducted with 0.02 g of powdered debris added, and results did not vary from those of the control tests having no debris. In subsequent debris tests 96E, 97B, 98B, and 99C, 0.05 g of debris was added. This amount had a significant effect on the nature of the stick-slip, especially at the initiation of movement, even though the debris added was coarser than that created by sliding, ranging up to 0.5 mm in diameter.

The effect of adding debris was to remove the initial high slip values shown in Fig. 4. Typical of debris tests was a low initial mean slip followed by a slight increase of slip up to a constant value. Thus the behavior of the blocks with debris added became the same as that of a block with no debris added, but within a much shorter distance of movement. In the case of Test 97, 0.0333 cm slip for the debris test gave the same plateau as was attained in 0.2825 cm by the block which started clean.

Effects of Temperature of Stick Time

In all cases, increasing the temperature of the rock while it was undergoing stick slip tended to cause an increase in stick time, a corresponding increase in the length of the individual slips, and an increase in the amount of relaxation of the shearing load upon slip (Fig. 6). An apparent debris effect occurred when the temperature was increased to 150 °C after a large distance of sliding. As temperature was gradually decreased at the end of the test, the amount of stick, slip and load relaxation decreased (though nonlinearly) until smooth slip finally became evident. Actually, though the displacement transducer indicated that smooth slip was occurring, the load transducer showed the shear load to be oscillating between about 500 and 600 g.

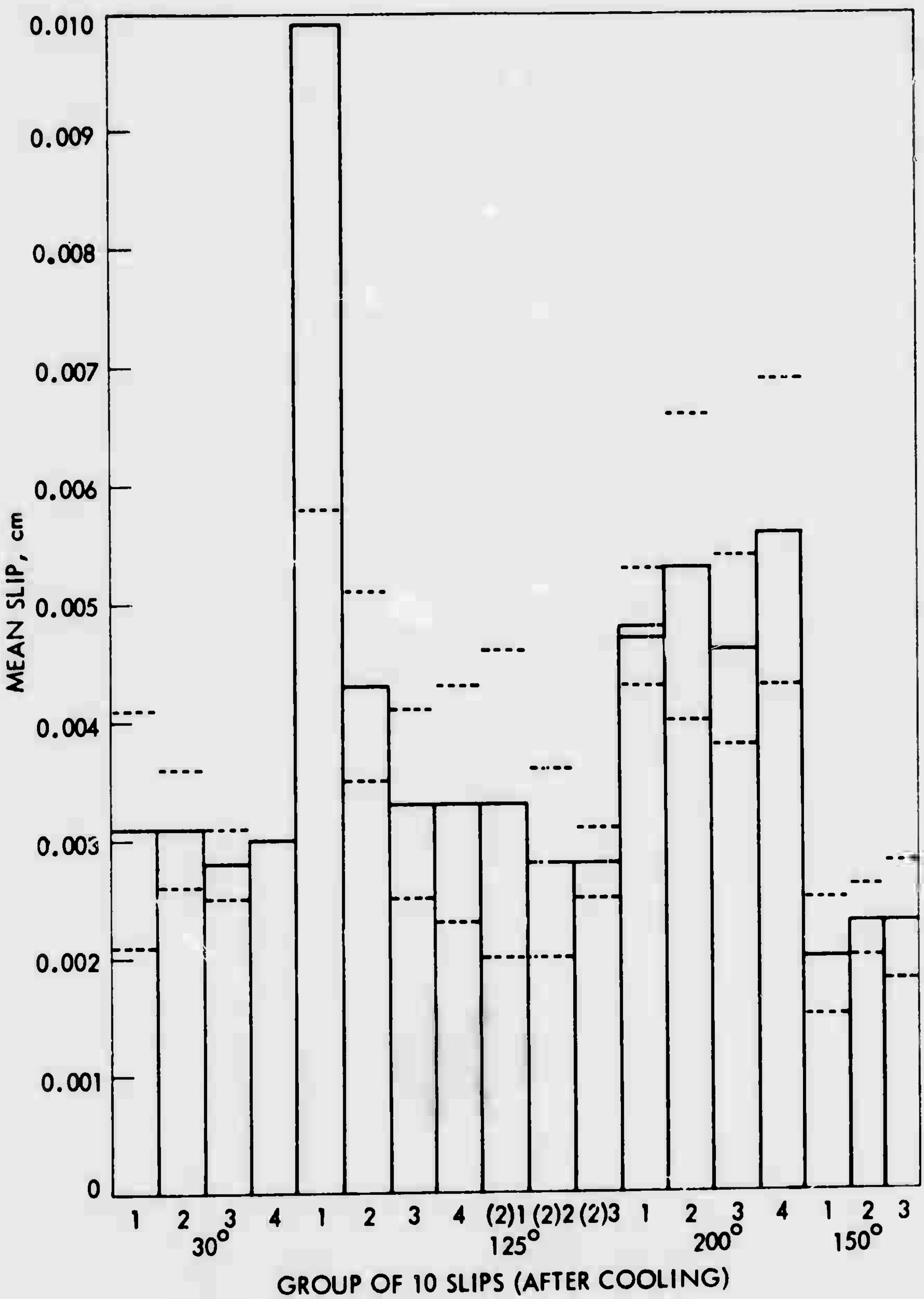

Fig. 6. Increase of mean slip upon increase of temperature. Test 98A1 and A2, $\sigma_n = 5.00\ kg/cm^2$.

Elimination of Stick-Slip

Stick-slip could be induced in every case in the experiments, either initially or by raising the temperature. Conversely, stick-slip could in most cases be eliminated by decreasing the temperature. Even in tests where stick-slip began at a low temperature, the phenomenon could usually be made to disappear after the temperature was first raised and then reduced to below 100 °C. In only two tests could stick-slip not be stopped, and even in these tests it became quite irregular with small slips taking long time intervals for completing.

The temperature of cessation of stick-slip varied from test to test, but was lower than that of initiation of stick-slip in all cases where some temperature rise was required to induce stick-slip. The temperature of cessation of stick-slip varied from 42 to 105 °C, except in one case where it ceased at 200 °C after a considerable period of running. The temperature of cessation varied according to Table II.

Table II. Temperature of Cessation of Stick-slip.

Temperature of cessation, °C	Number of Tests
40-50	7
51-60	3
61-70	1
71-80	4
81-90	2
91-100	9
over 100	2

Generally the temperature of cessation varied with load, with most of the lower temperatures representing tests with higher normal stress. Four of the low temperature (40-60 ^{o}C) cessations, however, occurred in Test 89. Though this was a very light normal stress test (0.75 kg/cm^2), the block displayed the most surface damage of any test below 10 kg/cm^2. It is believed that all cases of continuation of stick-slip at temperatures below about 80 ^{o}C may have been affected by asperity interlock.

Surface Damage

Damage to the sliding blocks of limestone was minimal until normal pressure reached 5 kg/cm^2. Some tests, like Test 89 at 0.75 kg/cm^2, showed some "stringers" of ground-up limestone. These could be washed off with water, with no evidence of surface damage visible under a biocular microscope.

At 5 kg/cm^2 a major "dust striation" and a small chip at the rear of the moving block showed that the surface damage was increasing with load. The tests at heavier normal stress, 10 and 20 kg/cm^2, showed considerably more damage. As shown in Fig. 7, the rear edge of the top block broke off at an angle of about 45 degrees to the horizontal, first at the two corners and then in the middle. Considerable ground-up, striated rock debris existed both in front of and behind the chips. The faces of the fractured chips also showed some rock debris which demonstrates, as does the position of the chips of the lower block, that they had moved some distance before fracturing. The record of this test shows three major anomalous stick-slips and three major drops in the coefficient of friction, believed to reflect the three brittle fractures.

Fig. 7. Debris in place on lower, stationary block. Test 100C, σ_n = 20 kg/cm^2.

It can be noted that the fractures were deep in the rock along the weakest plane, not along the surface; that the fragments were left in place exactly as they broke; and that the large fragments thus did not contribute gouge to the shear zone. Apparently, the force holding the upper block to the lower block was greater than that holding the crystals of the lower block to each other and, since the fracture was deep in the upper moving block, interlocking of asperities had little bearing on this bonding.

Coefficient of Friction

The static coefficient of friction of the limestone was calculated in smooth slip and in both the load and unload modes of stick-slip.

Numerically, the initial loading static coefficient of friction of fresh blocks ranged from 0.198 to 0.533, being highest at high and at low normal stress (Fig. 8). Omitting one anomalous test, unload coefficients of friction were lower, varying from 0.203 to 0.535 for tests with a normal stress of 10 kg/cm^2 or less.

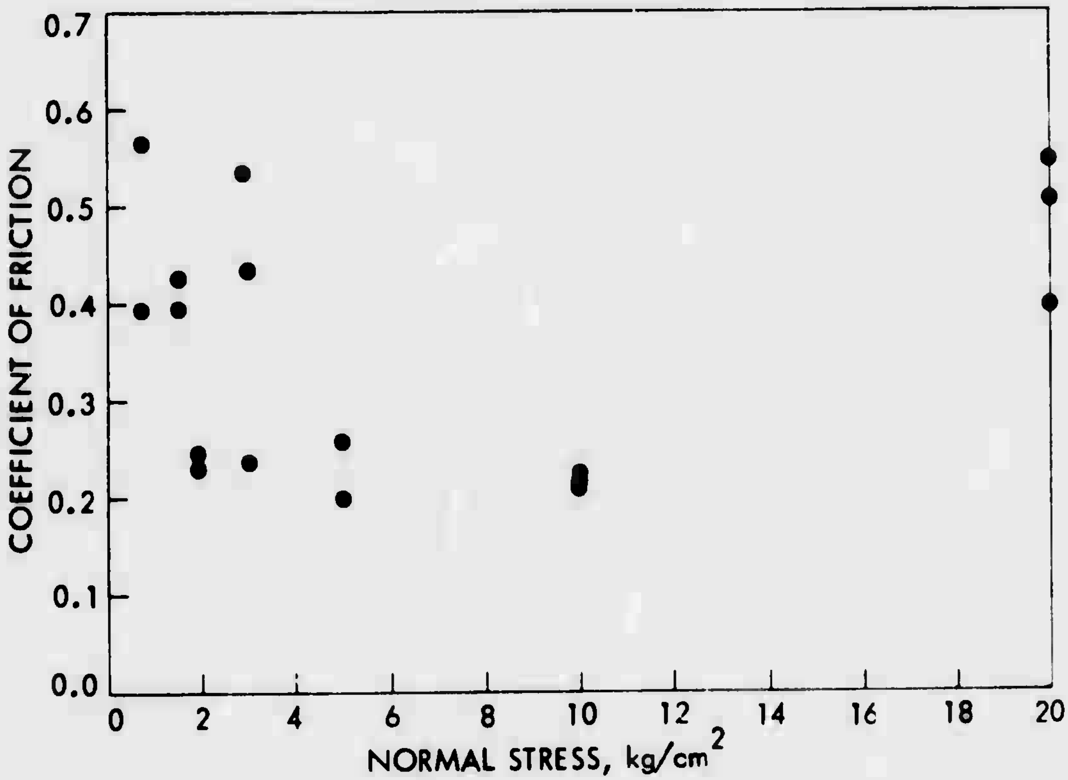

Fig. 8. Variation of initial coefficient of static friction with normal stress.

The behavior of the static coefficient of friction varied considerably according to the past frictional history of the specimen. For all tests on clean blocks with normal loads of 10 kg/cm^2 and under, the coefficient of static friction tended to remain stable or slowly rise so long as temperature was not changed.

Tests run with debris introduced as explained above gave very different results. The initial static coefficient of friction of debris tests ranged from 0.406 to 0.551 and climbed rapidly to values much above those reached on tests with clean blocks, reaching in one case a value of 1.002 (Fig. 9). Unload values were similarly high.

Tests conducted at a normal load of 20 kg/cm^2 behaved similarly to debris tests, the initial coefficients on clean blocks ranging from 0.396 to 0.544. In all cases a rapid climb of friction coefficient occurred with occasional sharp decreases indicative of brittle fracture of the rear edge of the upper block.

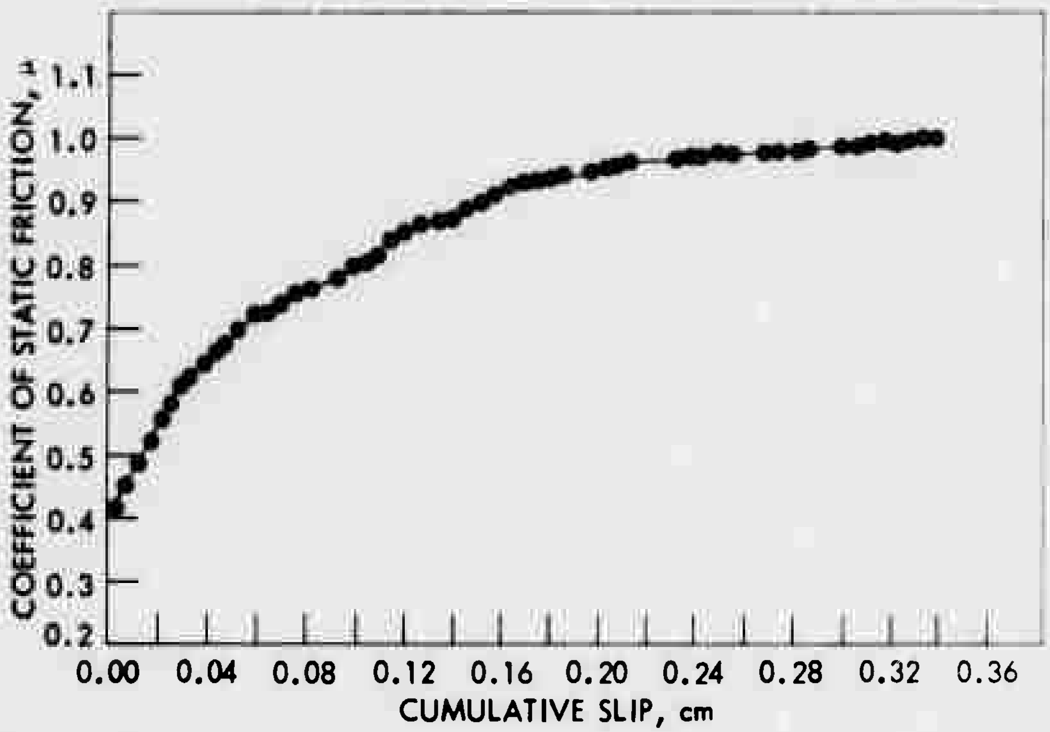

Fig. 9. Increase of coefficient of static friction with slip. Test 99C, 10 kg/cm^2, at 125°C, debris test.

<u>Metamorphic Rock</u>

One test series was conducted on a sample of metamorphic rock, a hornblende biotite schist prepared in the same manner as the limestone. The normal stress used was 3 kg/cm^2, and the direction of sliding was approximately parallel to orientation of the rock grains. The rock behaved in almost all ways similar to the limestone tested at the same normal load except that more surface damage was displayed by the metamorphic rock, the damage consisting of striations parallel to the direction of movement. The striations were regularly spaced about 2 mm apart and believed to be related to the mineralogy and structure of the rock.

The second test on the metamorphic rock, conducted on the same blocks cleaned with water, resulted in smooth slip at 30 ^{o}C. Stick-slip was induced by raising the temperature to 125 ^{o}C, consistent with previous experience with limestone.

Interpretation

The sensitivity of smooth slip to temperature and normal load suggests it may be caused by a film of adsorbed water. On the majority of low-normal-stress tests, stick slip did not commence until the temperature was raised above 100 ^{o}C. Higher normal stresses tended to initiate stick-slip at room temperature; but after a period of stick slip at a higher temperature cooling nearly always resulted in smooth slip, also suggesting an essential role of adsorbed water. For re-initiation of stick-slip, the temperature then usually had to be raised above 100 ^{o}C. A similar relationship of friction to adsorbed water was found by Peterson and Murray[16] for ceramic materials.

Further reinforcement to the concept of smooth sliding on a boundary layer of adsorbed water is given by activation energies. In an earlier phase of the experiments, the measurement of activation energy required to initiate and maintain creep was attempted. Though success was not complete, sufficient results were obtained to have a bearing on the current problem. The activation energies obtained were found to be temperature dependent. For all creeps begun below 100 ^{o}C, activation energies ranged from - 5.12 to - 10.73 kcal/mole, averaging - 7.78 kcal/mole. This value compared favorably to the value for the activation energy of water determined by Glasstone, Laidler and Eyring of - 4 to - 5 kcal/mole (reported in Mitchell, Singh, and Campanella[17]). Further, activation energies determined at higher temperatures show a definite increase with temperature, with an average value of - 23.9 kcal/mole for temperatures between 140 and 200 ^{o}C. This value is similar to that determined for dry sand, about - 25 kcal/mole, by Mitchell, Singh, and Campanella[17]. According to Horn and Deere[13], the oven dried, air-equilibrated static coefficients of friction of calcite and quartz are almost identical. Thus it is believed that most adsorbed water is being driven off above 100 ^{o}C, and that limestone asperity-to-asperity contact is taking effect. The fact that the average value of the activation energy below 100 ^{o}C is above that of water may be due to occasional asperity-to-asperity contact. This can be regarded as part of the structure factor of Noble and Demirel[18].

Above 100 ^{o}C, as the effect of adsorbed water is eliminated, contact of asperities may result in actual bonding as described by Bowden and Tabor[19]. These asperities must not be considered as sharp mountain peaks, but, as seen by scanning electron microscope examination, as small areas of flat cleavage face which are slightly higher than the adjoining areas and thus can come into contact with the opposing very small areas of flat cleavage face Increased temperature could allow further plastic deformation of these asperities, and larger areas of contact. This requires longer time to build up the required shearing force to break the bonds developed. Following Rabinowicz' theory[7], this in turn leads to a larger slip.

The tests which started stick-slip below 100 ^{o}C were for the most part clean or fresh blocks. The absence of debris may permit major asperities to come into direct contact, penetrating the intervening film of adsorbed water, and thus initiating stick-slip at low temperature. Once initiated, stick-slip might continue as the asperities destroyed the film of adsorbed water.

The above model differs from the brittle fracture theory of Byerlee[2], primarily in recognition of the influence of plastic deformation of asperities as a primary cause of stick-slip. Brittle fracture is seen only as a contributor to modification of structure. Heard[20] shows that the brittle shear strength of a limestone similar to that tested here is not affected within the temperature and the nominal normal loads used in this experiment. Nevertheless, brittle fracture was indeed present in our experiments; debris does accumulate and has a great effect on the magnitude of stick-slip even though brittle fracture of asperities does not appear to be the cause of stick-slip at these relatively low normal stresses. Large brittle fracture such as the breaking off of the rear edge of the upper block causes larger than normal slip, but this is caused by the sudden reduction of the bonding area. As soon as the block sticks again the increase of true normal stress takes effect, stick-slip magnitudes become the same as those in effect before the fracture occurred. Such brittle fracture of large natural irregularities along faults may indeed contribute to earthquakes, but they are not the usual stick-slip, but anomalies.

The effect of debris in reducing the magnitude of initial stick-slip and making smooth slip easier to induce seems to be related to contact area and to particle orientation. The added debris was larger in size than that created by sliding. Initially, then, fewer points of contact were available between the lower block, intervening debris particles, and the upper block. As the particle size of the debris was reduced by crushing, the contact area increased until a stable point was reached with a cover of debris between the upper and lower block. A net increase of contact area occurs because filling of former lows with debris allows more block-debris-block contact. Though individual bonds are probably weaker, higher coefficients of static friction result from increased overall bonding.

In a clean block, good bonding occurred because of proper orientation of the flat calcite cleavage faces for good bonding. As debris particles were created by plucking from the sides of the relatively flat highs, the contact area was actually reduced as some of the particles fell into the extensive area between asperities. The particles which rode up onto the asperities eventually formed a scattering of small particles on the reduced-sized asperities. These particles are not as suitably aligned for bonding as the original calcite faces. The coefficient of friction rose slightly, however, there are more total points of contact and total bonds. Slip decreases, as distance between good bonding positions and strength of individual bonds is less. The increased total surface area in both cases creates a greater area for adsorption of water and allows adsorbed water to create smooth slip below 100 ^{o}C.

Conclusions

1. Stick-slip is not limited to quartz-rich rocks as indicated by Coulson[21] but also occurs in limestone and in schist, neither of which contain significant amounts of quartz.

2. Stick-slip of lightly loaded limestone blocks pulled at a constant strain rate is temperature-sensitive and appears to be the result of asperity-to-asperity bonding.

3. When smooth slip does occur it is at temperatures below 100 °C, indicative that smooth slip is due to a boundary layer of adsorbed water. As the system is heated such that adsorbed water is driven off, stick-slip is induced.

4. Temperatures above those required to induce stick-slip result in larger slips, longer sticks, and higher shear load relaxations. This is consistent with the concept of bonding as the cause of stick-slip.

5. Higher normal loads in the range 3 to 20 kg/cm^2 on a gross area basis often cause stick-slip to be initiated below 100 °C, apparently by perforating or otherwise disturbing the adsorbed water layer.

6. Accumulation of debris has the same effect as lightening the normal load, allowing smooth slip below 100 °C.

7. Tests conducted on limestone at a normal load of 20 kg/cm^2 behaved similar to debris tests, reaching equilibrium quickly and giving a moderately high coefficient of friction.

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