California Earthquakes: Why Only Shallow Focus?

Abstract. *Frictional sliding on sawcuts and faults in laboratory samples of granite and gabbro is markedly temperature-dependent. At pressures from 1 to 5 kilobars, stick-slip gave way to stable sliding as temperature was increased from 200 to 500 degrees Celsius. Increased temperature with depth could thus cause the abrupt disappearance of earthquakes noted at shallow depths in California.*

One of the remarkable features of the earthquakes in California is that they are limited to depths of 10 to 20 km (*1, 2*). Is the motion on a fault system as long as the San Andreas therefore also limited to these depths? Such a conclusion would seem to be at variance with modern theories of plate tectonics (*3*), which suggest plate thicknesses of several times this amount. Another possibility is that, although earthquake motion stops at shallow depths, earthquake-free motion similar to fault creep (*4*) continues to considerably greater depths. But why then is there a change in character of the sliding motion with depth? In other words, why do the earthquakes disappear? Here we report experiments that suggest that this effect may be primarily due to temperature.

Recent studies in California in which earthquake foci are located with great precision (*2, 4*) strongly support the idea that motion is taking place on preexisting faults. Some fracturing of new material may well be involved but probably on a scale much smaller than the area of the fault surface over which the stress drop occurs. Frictional sliding on fault surfaces may, then, be primarily responsible for the earthquakes. Several field and laboratory observations suggest that the earthquakes result from a large-scale form of stick-slip (*5*). For one thing, unstable (stick-slip and earthquake-producing) motion 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 in California 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 of metal foil. The foil ruptures easily at any strain discontinuity such as a fault. Foil thickness can be increased to prevent rupture, of course, but then large, unknown, and temperature-dependent constraints are imposed on the rock sample. Our procedure was to retain the thin foil but to add a sleeve of graphite between rock sample and foil (*12*). 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 (*13*) and thus to obtain the first detailed picture of the effects of temperature on friction of rocks.

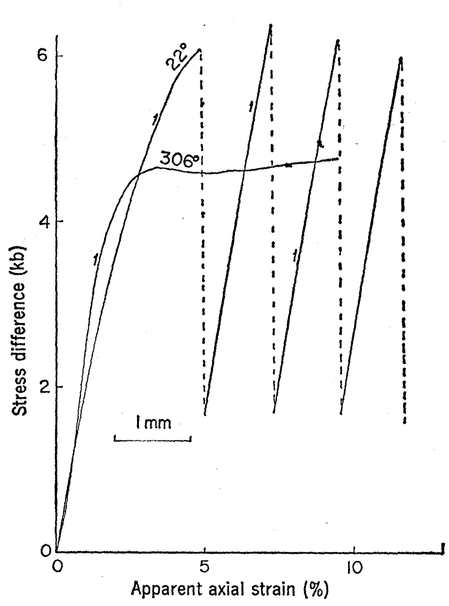

Fig. 1. Sliding on sawcuts in granite, at a confining pressure of 2.1 kb. Dotted parts of the curve at 22° are sudden stress drops. Actual displacement along the sawcut during sliding is indicated by the 1-mm bar line.

Frictional sliding was studied in triaxial experiments (*14*) in which the cylindrical sample contained a fault or sawcut. 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° to 32°).

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 normally associated 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, whereas sawcuts are nearly identical; as a result, data from faulted samples show greater scatter than data from sawcuts. For exploratory work, results from sawcuts are probably valid. Byerlee (*15*) found for granite only minor differences in friction between sawcuts and faults once some motion had occurred. The results given here are both for sawcuts and for faults.

We studied frictional sliding in Westerly granite and San Marcos gabbro (*16*) at pressures to 5 kb, temperatures to 525°C, and strain rates from 10^{-4} to 10^{-6} sec^{-1}. The samples were vented to the atmosphere through a hollow piston, so that pore pressure was presumably nearly zero.

Some results are shown in Fig. 1 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 Fig. 1) gave way to stable sliding as temperature was increased (the 306° curve in Fig. 1). 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 the strain rate nor the heating procedure appeared to affect behavior such as shown in Fig. 1. 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 Fig. 2; they are also typical for granite. The faults were formed in

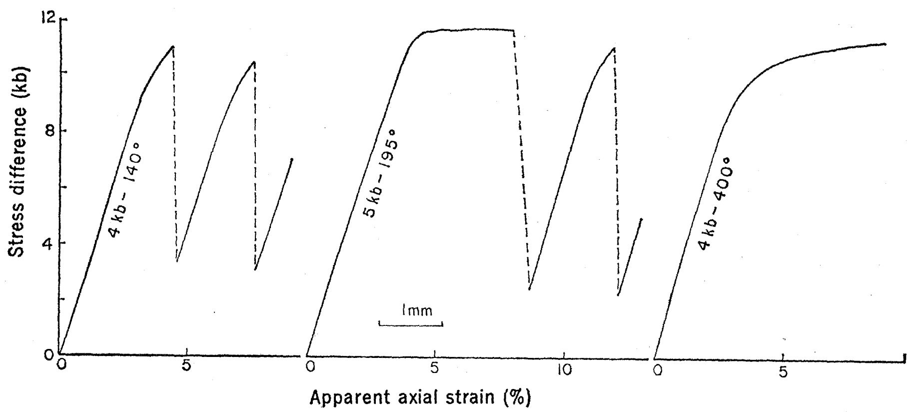

Fig. 2. Sliding on faults in gabbro. Numbers give confining pressure and temperature of experiment. Fault angle to the specimen axis was 30° ± 2°. Dotted sections of the curves are sudden stress drops. Actual displacement of the fault during sliding is indicated by the 1-mm bar line.

the samples at 0.5- to 1-kb pressure and at room temperature. Pressure and temperature were then raised to the conditions of the friction experiment. The marked effect of high temperature is again evident, although the transition between stick-slip and stable sliding appears less sharp than for sawcuts. In other words, there appears to be 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 Fig. 3 in which stick-slip, stable sliding, and stick-slip preceded by appreciable stable sliding are indicated.

Several features are evident in Fig. 3. 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 for 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 (*17*) 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 the 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 that still exist between the laboratory experiment and the field, other than the obvious scale difference. Thickness of debris on the sliding surface is also critical, and it may complicate the laboratory and field comparison. For example, when debris is absent, as on a sawcut in granite, stick-slip at room temperature occurs at all pressures above a few hundred bars. By contrast, stick-slip appears only above 1.5 kb on a fault in granite (when perhaps 0.5 mm of debris is present) and only above about 8 kb in crushed granite (when the entire sample consists of debris) (*18*). In addition, our experiments will need to be repeated with pore water pressure, for natural rocks are presumably wet. Probably the effective stress law will be followed as it is at room temperature (*18*), although additional chemical effects may be present because of the water weakening observed in certain minerals (*19*). Presumably these effects will have a further stabilizing influence and will shift the field boundary of Fig. 3 to the left, to lower temperatures. Slower strain rates than used here also need to be considered; high temperature and very slow strain rates would be expected to produce some welding or sintering, which 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 (Fig. 2, middle curve). Some way of obtaining much larger displacements in our laboratory samples is needed.

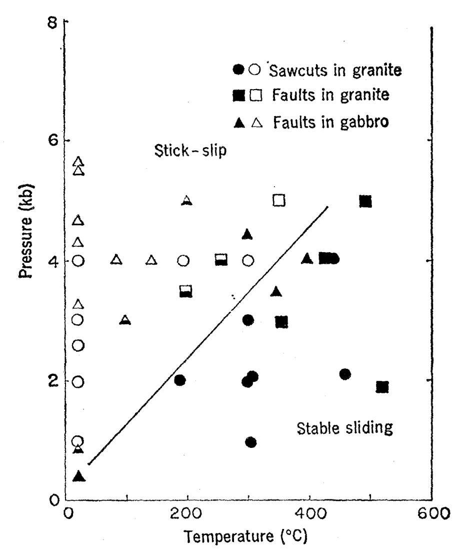

Fig. 3. Occurrence of stick-slip and stable sliding as a function of confining pressure and temperature. Open figures represent experiments in which stick-slip was observed; closed figures are experiments in which only stable sliding was observed within the 2- to 3-mm displacement along the sawcut or fault. Half-closed figures are experiments in which considerable stable sliding preceded the stick-slip.

Present results indicate that the disappearance of earthquakes at shallow depth in California could well be due to increased temperature. Estimates of temperature (*20*) suggest 300° to 500°C at a depth of 15 km. In the absence of pore fluids, these values straddle the field boundary in Fig. 3; if pore water is at hydrostatic pressure, then both fall within the field of stable sliding. In view of uncertainties in the above temperatures and the unknown influence of factors like strain rate and displacement, it is probably unwise to press the comparison between California earthquakes and our laboratory experiments further. Nonetheless, it is interesting to note that temperatures involved in both cases are comparable.

Several interesting consequences of our results are apparent, if we assume for the moment that the laboratory experiment does accurately model the rocks along the San Andreas fault. The field boundary in Fig. 3 appears to be close to the geothermal gradient. This proximity suggests that in the natural situation the lower limit of earthquakes might be quite irregular in depth. Local cold spots along the fault might result in local pockets of high seismic activity along the fault. Such features have been described in California (*2*); it would be of great interest to test this suggestion by detailed temperature measurements in the areas in question. Finally, our observations do not support the view (*3*) that earthquakes disappear because of a reduction of strength with depth; the stress difference to cause sliding actually increased, if points are compared along the geothermal gradient. For example, the stress difference to cause sliding on the fault in gabbro at 4 kb and 400°C was about 11 kb, nearly 3 times that at 1 kb and 25°C. At still higher temperatures, a drop in strength seems likely; the level at which this strength drop occurs may bear little relation to the lower limit of earthquakes.

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References and Notes

1. F. Press and W. F. Brace, *Science* **152**, 1575 (1966); J. P. Eaton, W. H. K. Lee, L. C. Pakiser, *Tectonophysics*, in press.
2. Details of the seismicity of the area are given by H. F. Reid [*Univ. Calif. (Berkeley) Publ. Geol. Sci.* **6**, 413 (1911)] and by B. A. Bolt, C. Lomnitz, T. V. McEvilly [*Bull. Seismol. Soc. Amer.* **56**, 1725 (1968)].
3. B. Isacks, J. Oliver, L. R. Sykes, *J. Geophys. Res.* **73**, 5855 (1968).
4. D. Tocher, *Bull. Seismol. Soc. Amer.* **50**, 396 (1960).
5. W. F. Brace and J. D. Byerlee, *Science* **153**, 990 (1966).
6. J. D. Byerlee and W. F. Brace, *J. Geophys. Res.* **73**, 6031 (1968); W. F. Brace, *Trans. N.Y. Acad. Sci.* **31**(7), 892 (1969).
7. C. R. Allen, in *Proceedings of the Conference on Geologic Problems of San Andreas Fault System*, W. R. Dickinson and A. Grantz, Eds. (Stanford Univ. Publications, Geological Sciences, 1968), vol. 11, p. 70.
8. J. D. Byerlee and W. F. Brace, paper presented at the annual meeting of the American Geophysical Union, Washington, D.C. (1970).
9. D. T. Griggs, F. J. Turner, H. C. Heard, in *Rock Deformation*, D. T. Griggs and J. Handin, Eds. (Memoir 79, Geological Society of America, New York, 1960), p. 39.
10. W. F. Brace, *Tectonophysics* **6**, 75 (1968).
11. Summarized by J. Handin, in *Handbook of Physical Constants*, S. P. Clark, Jr., Ed. (Memoir 97, Geological Society of America, New York, rev. ed. 1966), p. 223.
12. The rock sample was a precisely ground cylinder 16 mm in diameter and 35 mm long. The sawcut, if present, was located midway between the ends and made an angle of 30° to the cylinder axis. The 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 revealed that a stabilizing effect on sliding existed only below a pressure of 2 kb. It took the form of lowering the amplitude of stick-slip to nearly zero. The shearing stress to cause frictional sliding increased about 10 percent as compared with an experiment at the same pressure, in which a polyurethane jacket 3 mm thick was used. Because of these effects, most experiments here were conducted at or about 2-kb pressure; at this pressure results of room-temperature experiments in which the copper-graphite jacket was used were nearly identical with results from experiments using polyurethane. In any event, stabilizing effects present at room temperature would probably not be important at high temperature because of the increased ductility of the copper.
13. Our apparatus resembled in a general way the one described by Griggs *et al.* (*9*, p. 46). 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.
14. The experimental procedure resembled the one used in room temperature experiments by J. C. Jaeger [*Geofis. Pura Appl.* **43**, 148 (1959)], J. Handin and D. W. Stearns [*Trans. Amer. Geophys. Union* **45**, 103 (1964)], and J. D. Byerlee (see *15*).
15. J. D. Byerlee, *J. Geophys. Res.* **72**, 3639 (1967).
16. Petrographic details are given by J. D. Byerlee and W. F. Brace, *ibid.* **73**, 6031 (1968)].
17. J. D. Byerlee, *J. Appl. Phys.* **38**, 2928 (1967).
18. ——— and W. F. Brace, *Science* **164**, 713 (1969).
19. W. F. Brace and R. J. Martin III, *Int. J. Rock Mech. Mineral. Sci.* **5**, 415 (1968).
20. D. T. Griggs and J. D. Blacic, *Science* **147**, 292 (1965).
21. A. H. Lachenbruch, *J. Geophys. Res.*, in press.
22. P.-Y. Robin conducted the tests at room temperature. Many persons provided help in overcoming experimental difficulties, including A. Arzi, H. Heard, C. B. Raleigh, and J. Logan. The research was supported by NSF grant GA 613.

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Carbon-13 in Black Sea Waters and Implications for the Origin of Hydrogen Sulfide

Abstract. *A combination of measurements of carbon-13 and the hydrogen sulfide content in Black Sea waters with available data on the total carbon dioxide in these waters indicates that the contribution of organic sulfur to the hydrogen sulfide lies between 3 and 5 percent and increases with depth. Likely causes for the increase are increasing productivity or upward movement of the anoxic zone during the last 2000 years.*

The amount of dissolved oxygen in the Black Sea decreases rapidly with depth and reaches zero between 125 and 250 m; the depth at which the amount reaches zero depends mainly on the distance from shore (*1*). There is a thin transition zone in which small amounts of oxygen and hydrogen sulfide coexist, and at greater depth the concentration of hydrogen sulfide increases, rapidly at first, but begins to level off at 1000 m. Comparison of variations in the C^{13}/C^{12} ratio and in the concentrations of dissolved oxygen and hydrogen sulfide, respectively, reveals strong resemblances. In combination with data on the concentrations of inorganic carbon and hydrogen sulfide, the carbon-13 data allow one to calculate the relative contributions of reduced seawater sulfate and liberated organic sulfur to the hydrogen sulfide content at any depth in the Black Sea.

During the Black Sea cruise of R.V. *Atlantis II* in the spring of 1969 the water column at eight stations (Fig. 1) was sampled with Teflon-lined Nansen bottles for the determination of C^{13}/C^{12} ratios in the dissolved inorganic carbon (ΣCO_2). The samples were preserved, extracted, and analyzed according to the procedures described by Deuser and Hunt (*2*), except that oxygen was used for stripping CO_2 from the water samples. By this process hydrogen sulfide was oxidized to sulfur, and the process proved very effective in producing clean CO_2 samples for mass analysis. The C^{13}/C^{12} ratios are reported in the δ-notation where

$$\delta C^{13}(‰) = \left[\frac{(C^{13}/C^{12})\ \text{samp.}}{(C^{13}/C^{12})\ \text{stand.}} - 1\right] \times 1000$$

The reference standard is the Pee Dee belemnite (PDB) carbonate (*3*). Reproducibility of the entire procedure is better than ± 0.1 per mil.

The results of δC^{13} measurements made on 81 samples from the eight stations are plotted against water depth in Fig. 2a. Individual profiles were

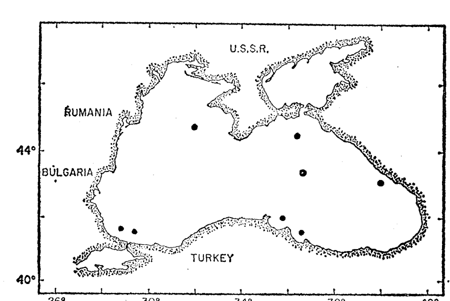

Fig. 1. Hydrographic stations in the Black Sea for which δC^{13} profiles were determined.