Fig. 2. Photomicrograph from the same hologram used for Fig. 1, showing an organism swimming 11 cm from the hologram plate.

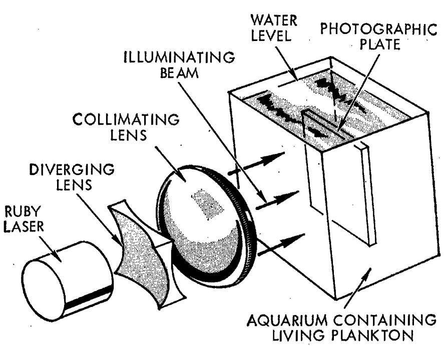

Fig. 3. Schematic diagram of apparatus used in making holograms of living plankton organisms.

gram used in Figs. 1 and 2 is in excess of 1000 cm^3. By using a conventional microscope to view the reconstructed real image from the hologram, any point in this volume may be brought sharply into focus.

The arrangement of apparatus for taking the hologram is shown schematically in Fig. 3. The distance from the front of the aquarium to the photographic plate was 14.5 cm. The aquarium was filled with sea water containing the living plankton organisms.

The "coherent" laser illuminator consisted of a ruby oscillator-amplifier with a Kerr cell Q-switch. The laser typically emitted an optical pulse of 60 nsec duration and 3 joules total energy. The coherence length of the pulse was approximately 1 cm.

In recording the hologram, high-resolution photographic plates (Eastman Kodak type 649-F, 0.04 by 4 by 5 inches in size) were used. The emulsion of the photographic plate was in direct contact with the sea water during the recording of the hologram. After exposure by the beam from the pulsed laser, the plate was removed, rinsed in fresh water, and developed with Kodak HRP developer by standard techniques.

Reconstruction of the real image was accomplished by illuminating the hologram with a collimated beam from a helium-neon continuous gas laser. In contrast to other work in the field of holographic microscopy (*1*, *4*), there was no attempt to achieve magnification with relay lenses during the recording process. Since collimated beams were used for both recording and reconstruction, the size of the reconstructed real image was essentially the same as that of the original subject (*5*).

The application of holographic microscopy to the study of plankton provides a means of viewing the organisms *in situ*. By the use of properly designed equipment it is possible to produce holograms at any depth in the ocean. The reconstructed image, representing an appreciable volume of object space, may then be searched in three-dimensional detail by conventional microscopic techniques. Data so obtained will provide accurate statistics on such matters as population density, distribution of species, and orientation of organisms with respect to physical environmental factors such as gravity, light, and movement of currents. By using a viewing microscope with a mount calibrated for *x*, *y*, and *z* axis movement, it is possible to plot the spatial relationships of the organisms. Such information should be useful in determining the existence of living domains and in investigating other spatially related ecological and environmental patterns.

In summary, holographic microscopy provides a new technique by which the investigator may obtain useful data, not readily available by other means, on dynamic microscopic systems, both living and nonliving.

CAMERON KNOX

TRW Systems, Redondo Beach, California

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5. Theoretically, some aberration is caused by the difference in the wavelengths of the recording (6943 Å) and reconstruction (6328 Å) beams and by the difference in the indices of refraction of the media in which the recording and reconstruction take place (water and air). However, there was no apparent effect at the levels of magnification used in this study.

25 July 1966

Stick-Slip as a Mechanism for Earthquakes

Abstract. *Stick-slip often accompanies frictional sliding in laboratory experiments with geologic materials. Shallow-focus earthquakes may represent stick-slip during sliding along old or newly formed faults in the earth. In such a situation, observed stress drops represent release of a small fraction of the stress supported by the rock surrounding the earthquake focus.*

Theories of the earthquake mechanism are based on two types of indirect observations, (i) the movements of surface rocks above the actual focal region and (ii) the behavior of rocks stressed in the laboratory under conditions similar to those found in the Earth. For some time following the great 1906 earthquake in California, Reid's elastic rebound theory held prominence. According to this theory (*1*), an earthquake is the result of strain release caused by sudden shearing motion along a fault. Reid's theory is reasonable in terms of the patterns of elastic radiation observed in many earthquakes (*2*), and is also reasonable when compared with laboratory experience. For example, a sample of granite or diabase stressed at several kilobars will fracture. Usually a fault is formed and stress is suddenly released.

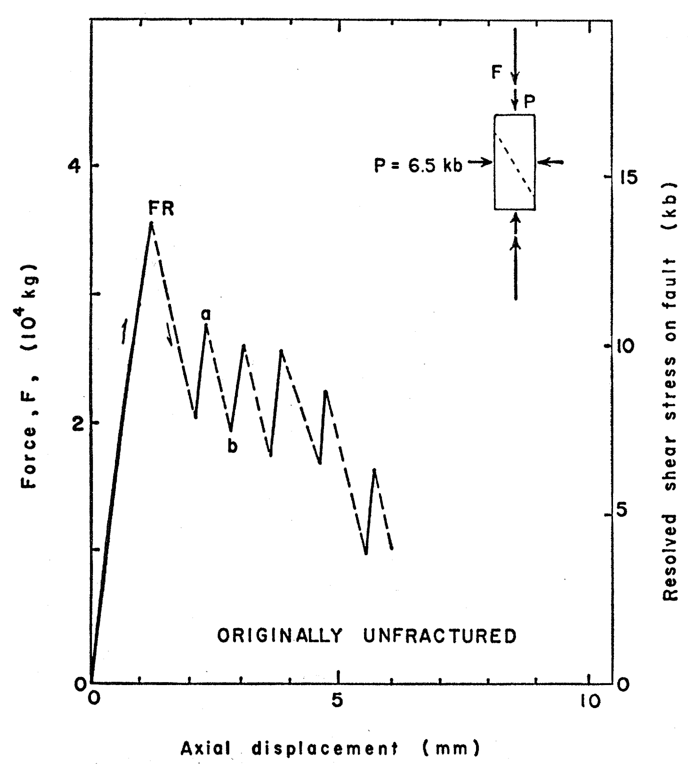
Although the Reid theory seems to provide a plausible explanation for earthquakes, it has, in recent years, been challenged. Jeffreys (*3*) and then later Orowan (*4*) and Griggs and Handin (*5*) suggested that, particularly for deep-focus earthquakes, energy release due to fracture is unlikely. They argued that fracture must be accompanied by sliding in order to release energy, and that sliding with dry friction on fracture surfaces is ruled out because of the high stress required. Another difficulty is the remarkably low stress drop associated with earthquakes. Various estimates of the stress drops in major earthquakes (*6*) give a value of about 100 bars. When rocks fault under pressure in the laboratory, however, the magnitude of the stress drop is typically a matter of kilobars or even tens of kilobars. If the rocks were initially fractured, a likely situation in a seismically active area, it is difficult to see how stress could be built up a second time to produce an earthquake by the Reid mechanism.

Recent laboratory experiments suggest a way of meeting certain criticism of the Reid theory for earthquakes with a focal depth of less than 25 km. Since the majority of destructive earthquakes in California and Japan occur at these shallow depths (*7*), the results may have some significance. At greater depths, and particularly in the upper mantle, the objections of Jeffreys and others may be valid.

When two surfaces of rock slide over one another in laboratory experiments, the motion is usually jerky rather than smooth. The reasons for this are obscure but are probably related to variation in frictional resistance along the surfaces. Typical behavior for initially unfractured granite is shown in Fig. 1. This curve was obtained (*8*) in the following way. As suggested by the small diagram above the curve, a cylinder of granite was placed under confining pressure and then loaded on the ends, in compression. The stress was increased until a fault formed. At faulting, there was a large stress drop (at 6.5 kb, a stress drop of approximately 5 kb). After this stress drop, motion on the fault ceased. Stress could be reapplied. After it reached a certain level, there was again a sudden stress drop such as at Fig. 1, *ab*. This jerky sliding could be continued almost indefinitely on the fault, with the stress building up and then being released. Each release of stress was accompanied by a small amount of slip on the fault.

In a second experiment, the sample contained an artificial fracture or a sawcut at an orientation close to that of the fault which would naturally form. Details of the sliding behavior depended on the roughness of this artificial surface; when the surface was finely ground, behavior for granite was typical of that shown in Fig. 2. Sliding was again jerky. The force-displacement curve resembled that of the originally unfaulted rock, but small stress drops punctuated the ascending, as well as the descending, parts of the curve. Stress drops here ranged from 50 to 2500 bars.

We have called the jerky sliding motion observed in our experiments stick-slip, for it resembles this well-known engineering phenomenon (*9*). Stick-slip occurred in our experiments under a wide range of conditions. Some of the samples were saturated with water under a slight pore pressure, whereas others were air-dried. The normal stress on the sliding surfaces ranged from a few bars to 17 kb. Some surfaces were smooth and slickensided, others were ground to a wide range of roughness, and still others were rough fracture surfaces which had been fitted back together. Sliding was continued in some of the samples until an appreciable layer of gouge had accumulated. Stick-slip accompanied sliding on old or newly formed fractures under all of these conditions. Elsewhere, Jaeger (*10*) found stick-slip in similar experiments with porphyry. Stick-slip is often observed with single crystals of silicate minerals. Griggs *et al.* (*11*) found that dunite, quartzite, and quartz fractured explosively under a confining pressure of 5 kb, but that strength did not drop to



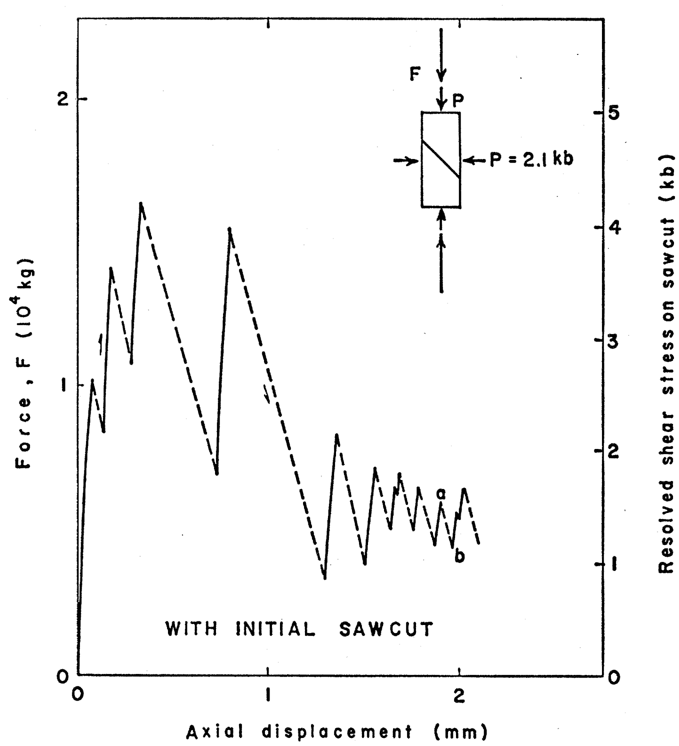


Fig. 1 (left). Force-displacement curve for the axial direction in a cylindrical sample of Westerly granite. Small diagram above the curve shows schematically how stress was applied to the sample. The sample fractured at point *FR* forming the fault which is shown as a dotted line in the small diagram. The exact shape of the curves during a stress drop (such as *ab*) is not known and is shown dotted. *P* is confining pressure. Fig. 2 (right). Same as Fig. 1 except that the sample contained a sawcut with finely ground surfaces as shown schematically (small figure) by a heavy line.

zero; the stress drop (similar to that shown in Fig. 1) was several kilobars. Bridgman (*12*) found that jerky motion accompanied the shearing of powdered compacts of brittle material even when normal pressure reached 50 kb.

Stick-slip appears to be common in geologic materials under laboratory conditions. We suggest that it might also be significant under shallow crustal conditions, and that it can be regarded as a possible source of earthquakes. An earthquake might represent one of the small stress drops associated with faulting or sliding.

The idea that the stress drop in faulting causes an earthquake is not new. There are, however, two features which we feel are new. The first is that, as in the experiments, the stress drop in an earthquake may represent release of only a small portion of the total stress supported by the rock. This could explain why the stress drop, even for fairly major earthquakes, is small relative to the strength of most rocks. The second new feature is that stick-slip provides a mechanism for sudden energy release in material which is already broken and fractured.

The amplitude of the stick-slip (several kilobars in the above experiments) is clearly greater than the 100 bars associated with earthquakes. In other experiments, particularly those carried out at high temperature and slow strain rate, sliding is smooth and stick-slip is absent. For example, Griggs *et al.* (*11*) found no jerky sliding with granite or dunite at 5 kb and 500°C. Riecker (*13*) observed that the violent snapping noted in a shearing experiment of the Bridgman type, conducted at room temperature, disappeared at 300°C and when shearing rates were slow.

It is quite possible that high temperature and slow strain rate suppress stick-slip in geologic materials. If this is true, the applicability of this phenomenon as an earthquake mechanism would be limited to very shallow depths. However, there is another factor to consider. It is known (*9*) that the amplitude of stick-slip in engineering materials does not depend solely on the material. In the laboratory, the amplitude of stick-slip can be altered drastically by changing the stiffness of the loading machine, the relative masses of sample and machine, and damping characteristics of the machine. It is conceivable that one might observe, for a given rock and given conditions, behavior, dependent on the characteristics of the loading system, ranging from faulting with complete loss of strength (through behavior similar to that shown in Fig. 1) to faulting followed by smooth sliding. At this time it is difficult to decide if the absence of stick-slip in a particular experiment means that it will not occur under these conditions in any mechanical system, or if it is simply being suppressed in that particular system. Until these effects have been sorted, comparison of stress drops from field and laboratory has little significance. However, it is clear that stick-slip with an amplitude comparable with natural earthquakes occurs under a certain range of conditions. Stick-slip deserves to be considered, in conjunction with the Reid mechanism, as one possible mechanism for shallow focus earthquakes.

W. F. BRACE
J. D. BYERLEE
Department of Geology and Geophysics, Massachusetts Institute of Technology, Cambridge

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13 May 1966

Exposure of Basement Rock on the Continental Slope of the Bering Sea

Abstract. *Profiles of repetitive seismic reflections reveal that the Bering continental slope, outer shelf, and rise overlay an acoustically reflective "basement" which extends at least 750 kilometers parallel to the trend of the slope. This acoustic basement is usually covered by several hundred meters of stratified sediments at the top and bottom of the slope; however, it is exposed in submarine canyons and flanking spurs along the main part of the slope for a distance of at least 550 kilometers northwest of the Pribilof Islands. The lithologic composition and the age of the rocks of the acoustic basement are not known. However, its probable seismic velocity of 3.1 to 3.7 kilometers per second suggests that it is composed of volcanic rocks or lithified sedimentary rocks or both. The regional geology suggests that the acoustic basement is the upper surface of folded late Mesozoic rocks which were locally intruded by granite and serpentine. The structure of the Bering slope, as deduced from the acoustic profiles, suggests that the surface of the basement has been monoclinically flexed and faulted between the shelf edge and the deep Aleutian Basin.*

Profiles of reflected seismic waves were made across approximately 3800 km of the outer shelf and the highly dissected continental slope of the Bering Sea (Fig. 1). The soundings were taken from the USNS *Charles H. Davis* (AGOR-5) by the U.S. Navy Electronics Laboratory and the U.S. Naval Ordnance Test Station during June and July 1965. The profiles were made by recording subbottom seismic reflections from subaqueous spark discharges having energies up to 38,000 joules; sparks were discharged at an average rate of 15 per minute. The basic profiling system consisted of multiple electrodes and ten hydrophones in linear arrangement. Reflected signals were processed with standard seismic amplifiers set to pass signals from 73 to 120 cy/sec.

Unlike most continental slopes, the Bering slope is not closely adjoined by a continental land mass; instead, it marks the southwestern boundary of one of the world's largest epicontinental seas and lies as much as 550 km from the nearest continental shore. An acoustic basement was detected along at least 750 km of the Bering slope and the adjoining continental shelf. The basement is exposed, probably continuously, in the steeper part of the slope for at least