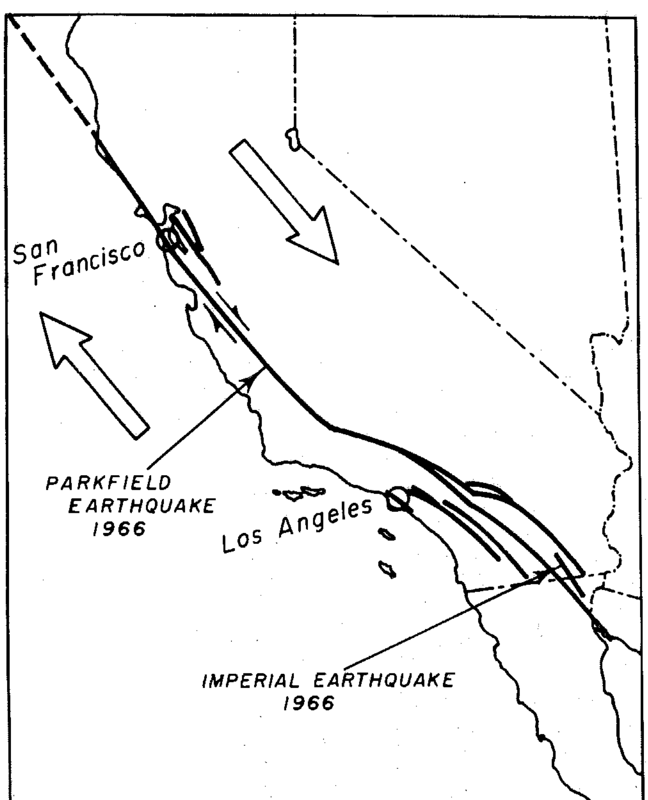
The Fault Slips

by James N. Brune

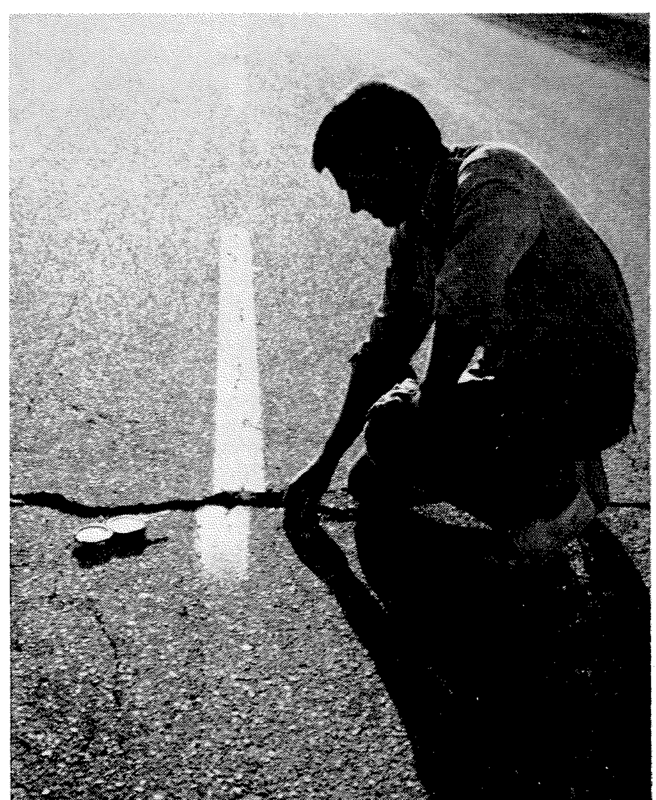
The ground convulses, buildings are twisted, statues and dishes are toppled, destructive waves are generated in oceans and bays, people panic. These are effects familiar to those who have experienced a large earthquake.

Small earthquakes, much more common than large ones, may also exhibit remarkable effects. Two recent earthquakes along the San Andreas fault (below) have pointed this out, much to the surprise of most of us in seismology. The Parkfield earthquake of June 27, 1966, magnitude 5.6, ruptured the ground for a distance of some 50 km and offset the white line on Highway 46 several centimeters. The Imperial earthquake of March 4, 1966, magnitude 3.6, offset the white line on Highway 80 about 1 cm and ruptured the ground for a distance of 10 km. This is the smallest earthquake yet known to be associated with ground breakage at the surface.

For centuries scientists, laymen, and astrologers have pondered the cause of earthquakes. The ancient Japanese believed that Japan perched upon the back of an enormous fish whose movements caused violent shaking of the land. Many other picturesque legends were developed by the ancients to explain earthquakes. A scientific approach to the explanation of earthquakes has only come about in



Map of California shows the direction of crustal movement on each side of the San Andreas fault and the location of two recent earthquakes.



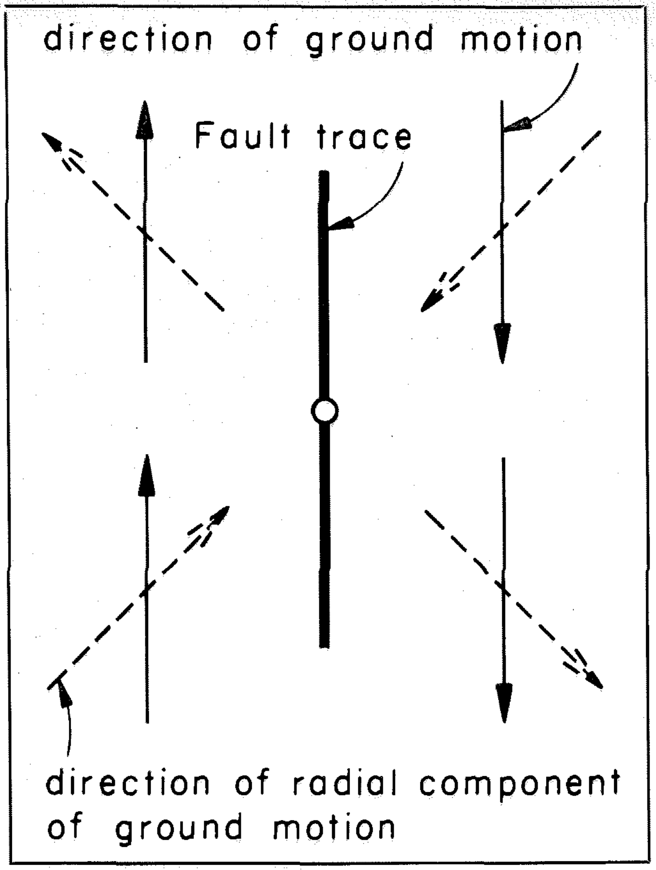
The white line on Highway 46 in central California was offset several centimeters as a result of the Parkfield earthquake of June 27, 1966.

the last century. The most impressive clue was the association of earthquakes with ruptures. For example, after the 1906 San Francisco earthquake the ground was found displaced as much as several meters along opposite sides of the San Andreas fault—the coastal side being moved to the north. This led Harry Fielding Reid to propose the elastic rebound theory of earthquakes. He suggested that strains are continuously being built up in the crust of the earth by subterranean forces of an unspecified nature. When the stresses in the rock reach the failing point, the rock breaks and slips along a plane determined by the shear stress and strength of the rock. The energy thus released propagates away from the source in the form of violent waves in the earth. These waves decrease rapidly in amplitude with increasing distance, but still may be recorded by seismographs at the most distant parts of the earth.

The elastic rebound theory has won general acceptance. It is an example of a phenomenon often observed in nature—rupture as a result of increasing strain. It explains (right) the quadrapole symmetry of first motion of compressional waves from earthquakes (i.e., in two opposing quadrants the radial component of initial motion is away from the center of the fault, and in the other two opposing quadrants it is toward the center). Other theories have been suggested for earthquake mechansim (e.g., explosive volcanic action or explosive change of state), but they have failed to explain the predominantly quadrapole distribution of first motions.

The origin of the forces that strain the crust of the earth has remained uncertain, but most recent evidence seems to suggest huge but very slow mass flow in the outer few hundred kilometers of the earth. Thus, the two sides of the San Andreas fault are driven by opposing mass flows. The pressure of the weight of the rocks keeps the sides of the fault together; when the stress reaches a critical value the fault breaks, causing an earthquake. In this simplified picture earthquakes along the San Andreas are equivalent to a large-scale chattering of two contacting frictional surfaces sheared relative to one another. Larger earthquakes occur when more energy is stored before slippage. If a long section of the fault is locked for a great length of time, energy for a very large earthquake may be stored up.

It has recently been possible to examine quantitatively the energetics of this process. Geodetic measurements carried on for many years have given us a reasonable idea of the long-term rate of motion. For example, in the Imperial Valley the observed northerly motion of the west side of the valley relative to the east side is observed to be about



The elastic rebound theory of earthquakes explains the fact that in two opposing quadrants the radial component of initial motion is away from the center of the fault, and in the other two opposing quadrants it is toward the center.

8 cm/year. About 5 cm/year is observed in central California near Hollister. Similar rates have also been inferred for spreading of the ocean floor away from the mid-ocean ridges.

If we were to observe the same rate of slip along a single crack striking through the center of a particular area, we might conclude that the fault is not locked and that energy is not being stored for a large earthquake. The actual situation is more complicated in most areas. For example, in the Imperial Valley, where there are numerous parallel faults, it is necessary to determine the amount of slip represented by the many small and moderate-sized earthquakes, most of which do not break to the surface.

Caltech's Seismological Laboratory has recorded earthquakes of magnitude greater than 3.0 in the Imperial Valley region for more than 30 years. From these data we may estimate whether the observed rate of occurrence of earthquakes is consistent with the rate of movement observed geodetically. For this purpose we use values of seismic moment, M_0, that represent the amount of torque or twisting of the ground occurring during an earthquake; it is directly proportional to the amplitude of seismic waves. To infer the rate of slip from the rate of occurrence of earthquakes we use the following equation relating moment to the average slip, $\bar{u}$, the rigidity, μ, and area of the fault surface, A: $\bar{u} = M_0/\mu A$.

To average this slip over the total cross-sectional area, A_0, we multiply by the area fraction A/A_0. The averaged slip, $\bar{\bar{u}}$, is thus given by:

$$\bar{\bar{u}} = \bar{u}\, A/A_0 = M_0/\mu A_0.$$

The sum over all events corresponds to the displacement of the two sides of the sheared zone resulting from earthquakes.

It is immediately noticed in the table below that even though the number of events increases as the magnitude decreases, the total contribution to the energy release and moment is very small for the smaller shocks. Thus, small shocks do not serve as a "safety valve" for larger shocks.

To calculate the slip represented by the total moment we must determine A_0, the cross-sectional area of the shear zone. For this we assume the depth of slippage to be 20 km, the approximate depth limit for earthquakes in California. The length of the shear zone is 120 km, making A_0 equal to $2.4 \times 10^{13}\,cm^2$. The calculated slip, 93 cm in 29 years, or about 3 cm/year, is less than half the geodetically observed rate of 8 cm/year of movement of one side of the valley relative to the other. This suggests either that stress (or potential slip) is accumulating at the rate of 5 cm/year or that a great deal of energy is being released by creep without causing earthquakes. Because of the probable existence of a large amount of undetected creep, we cannot be sure when sufficient strain for a large earthquake will have accumulated.

For the central section of the San Andreas fault between San Bernardino and the central coast ranges we may estimate somewhat more confidently the potential for a large earthquake, since here the fault consists of a single narrow zone. Essentially no earthquakes and no creep are observed along the fault at the present time, and we infer that the fault is locked and storing up energy. It may have been locked since about the time of the 1857 earthquake. If a rate of slip of 6 cm/year has occurred both north and south of this section since 1857, there is now a potential for an earthquake slip of about 7 meters, which would cause a great earthquake if released as a single event. The possibility that this energy could be released by some other mechanism (e.g., rapid creep or a series of moderate earthquakes) is remote.

To verify the ideas discussed here, it is important to measure the in-situ stress state of the rocks and thus determine directly the amount of energy available for an earthquake. Caltech is now testing several possibilities for making these very difficult measurements. It is believed that they offer the greatest hope for eventual prediction of the time and place of large earthquakes.

EARTHQUAKE SLIP IN THE IMPERIAL VALLEY, 1934-1963

Magnitude M	Energy E (ergs)	Moment M_0 (dyne-cm)	Number N	N-E (ergs)	N-M_0 (dyne-cm)
7.1	2.8×10^{22}	2.8×10^{26}	1	2.8×10^{22}	2.8×10^{26}
6 3/4	8.4×10^{21}	8.9×10^{25}	1	8.4×10^{21}	8.9×10^{25}
6 1/4	1.5×10^{21}	2.8×10^{25}	1	1.5×10^{21}	2.8×10^{25}
5 3/4	2.7×10^{20}	8.9×10^{24}	9	2.4×10^{21}	8.0×10^{25}
5 1/4	4.7×10^{19}	2.8×10^{24}	18	8.5×10^{20}	5.1×10^{25}
4 3/4	8.4×10^{18}	8.9×10^{23}	55	4.6×10^{20}	4.9×10^{25}
4 1/4	1.5×10^{18}	2.8×10^{23}	131	2.0×10^{20}	3.7×10^{25}
3 3/4	2.7×10^{17}	8.9×10^{22}	354	9.4×10^{19}	3.2×10^{25}
3 1/4	4.7×10^{16}	2.8×10^{22}	885	4.2×10^{19}	2.5×10^{25}
2 3/4	8.4×10^{15}	8.9×10^{21}	2212	1.9×10^{19}	2.0×10^{25}
2 1/4	1.5×10^{15}	2.8×10^{21}	5530	8.3×10^{18}	1.6×10^{25}
1 3/4	2.7×10^{14}	8.9×10^{20}	13825	3.7×10^{18}	1.2×10^{25}
1 1/4	4.7×10^{13}	2.8×10^{20}	34562	1.6×10^{18}	9.8×10^{24}
3/4	8.4×10^{12}	8.9×10^{19}	86405	7.3×10^{17}	7.7×10^{24}
1/4	1.5×10^{12}	2.8×10^{19}	21602	3.2×10^{17}	6.1×10^{24}
			Total E,M_0	4.2×10^{22}	7.4×10^{26}