Earthquake Prediction

HIROO KANAMORI

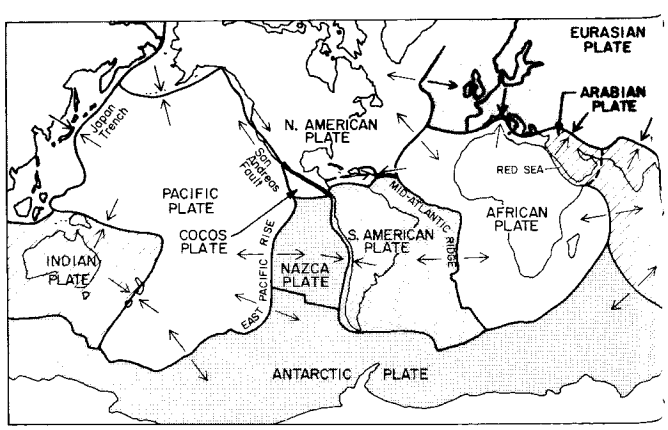
By nature, earthquake prediction is only possible with some statistical uncertainty. Methods are being developed to make this uncertainty small enough for practical purposes

The earth's surface consists of about a dozen large blocks, called plates, which are moving relative to each other. Although the cause of their movement is not fully understood, the evidence for such movement is firm. The relative motion between the plates causes strains and stresses in the earth's crust near the plate boundaries. When the stress exceeds the strength of the crustal rocks, fractures occur and elastic waves (seismic waves) are generated. An earthquake refers to either this fracture phenomenon itself, shakings caused by the elastic waves, or both.

It is probably no use repeating here how disastrous earthquakes can be—and they may be even worse in years to come, when we will have greater population concentration in urban areas, more structures, nuclear plants, reservoirs, water and gas pipe lines, and so on. Prediction, and possibly control, of earthquakes is naturally becoming an increasingly important subject on which major research efforts have been concentrated in recent years. However, an earthquake, as a fracture phenomenon, is a stochastic process, a process which is controlled by a number of accidental factors, and prediction of such stochastic processes is an exceedingly difficult task.

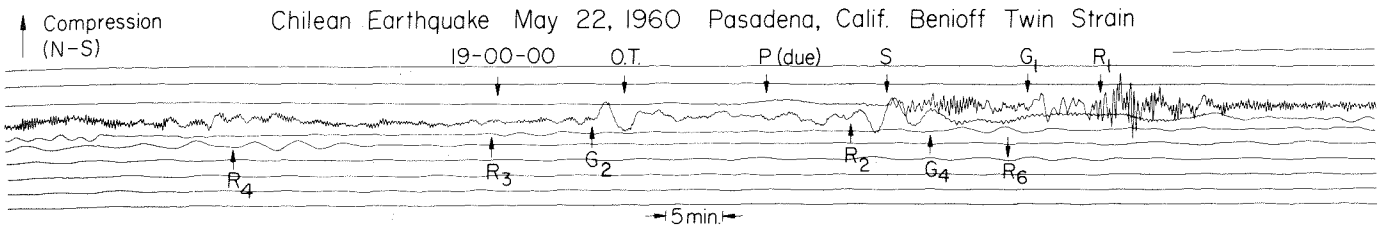
Suppose we squeeze a piece of rock. It eventually fractures, but not at a definite point. Sometimes it breaks at 5×10^{-5} strain (relative deformation), but sometimes it can withstand up to 5×10^{-4} strain. The breaking point is greatly affected by the configuration of a number of small cracks in the rock, and the behavior of the individual cracks is too complex to analyze. Thus, even if we know, by some means, that the strain in the earth's crust is about 10^{-4}, we can only say that the probability is high that an earthquake will occur, but it is not possible to tell precisely when. The question is how to reduce this uncertainty so that a useful prediction can be made.

At first this seems almost hopeless if we consider the rate of the plate motion, which is typically 10 cm/yr. This slow rate can cause a strain rate of only 10^{-6}/year or so. Since



The principal tectonic plates constituting the earth's surface. Maj earthquakes occur along the boundaries of the plates. The pointe arrows indicate the direction of the relative motion of each plate, that particular area of its boundary.

Seismogram of the great Chilean earthquake of 1960, recorded in Pasadena. R_2, R_4, and R_6 are long-period waves circling successively around the earth. These waves make up the earth's free oscillations, and convey information regarding the long-period characteristics of the earthquake source.



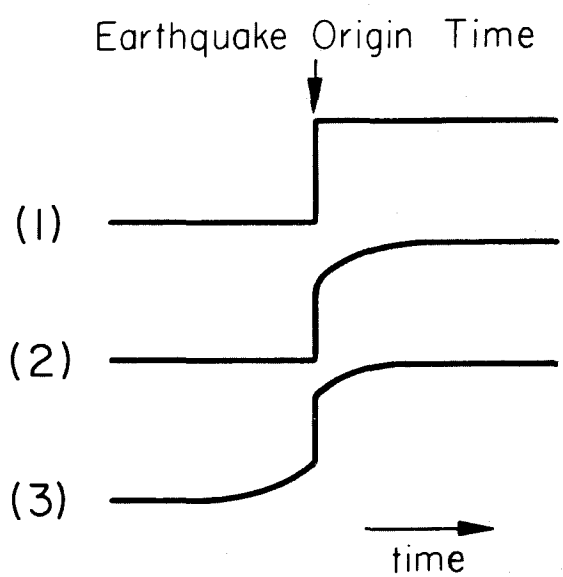
the breaking strain of the crustal rocks fluctuates approximately from 5×10^{-5} to 5×10^{-4}, this slow strain rate means a fluctuation of occurrence time of earthquakes from $(5 \times 10^{-5}/10^{-6}) = 50$ years to $(5 \times 10^{-4}/10^{-6}) = 500$ years. Obviously, this fluctuation is too large to be useful for practical earthquake prediction. How, then, can we make earthquake prediction a reality? During the past decade earthquake research has made significant progress in understanding the physics of earthquakes, thereby opening the way to the establishment of a physical basis of earthquake prediction.

An earthquake is a physical phenomenon extending over a very wide time scale, typically from 0.1 second to hours, and even to an infinitely long time. In order to fully understand earthquakes, it is absolutely necessary to study earthquakes over this wide period (frequency) range. Earthquake effects are most obvious at periods of 0.1 to 1 second because it is in this range that earthquakes are felt by people and buildings and various structures are shaken. It is, therefore, natural that the first attempt to measure the "size" of earthquakes was made in this period range. In 1935, Charles F. Richter, working with Beno Gutenberg, first director of Caltech's Seismological Laboratory, initiated an earthquake magnitude scale which later became known as the Richter Scale. Despite its very simple definition, it proved to be a surprisingly useful parameter for quantizing relatively short-period earthquake phenomena.

Gutenberg and Richter further developed this magnitude scale and applied it to all types of earthquakes in the world. This work, later crystallized in the monumental study *The Seismicity of the Earth,* truly forms the basis of seismology today.

On the other hand, development of very-long-period instruments, particularly by Hugo Benioff, Frank Press, and Caltech's technical staff, opened up a new vista in seismology which culminated in the detection of the earth's free oscillations following the great Chilean earthquake of 1960. It had been known theoretically that the earth, as an elastic sphere, may vibrate with a fundamental period of about one hour if excited by an earthquake. Much to the excitement of the world's geophysicists, this one-hour-period oscillation was detected, for the first time, by those sensitive instruments; the amplitude of this oscillation at the earth's surface was only 10^{-1} cm or so—about 2×10^{-10} of the earth's radius.

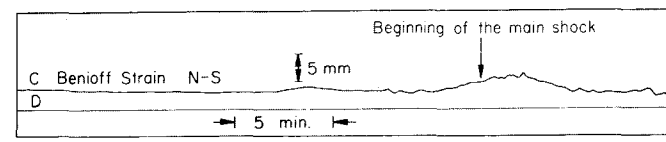
These developments in instrumentation, from short-period to long-period, as well as in various theories and analysis techniques, eventually led us to understand what is happening at the origin of an earthquake. Now it has become widely accepted that, to a good approximation, the source of an earthquake is a sudden slip (elastic rebound) across a more or less planar surface, called a fault plane. The product of the slip, D_0, and the area of the fault plane, S, gives a good measure of the size of earthquakes at long periods. For example, the San Fernando earthquake of 1971 had $D_0 \approx 2$m and $S \approx 10 \times 10$ km^2; i.e., $D_0S \approx 2 \times 10^{14}$ cm^3. In contrast, the great Chilean earthquake of 1960 had $D_0 \approx 30$ m and $S \approx 800 \times 200$ km^2, or $D_0S = 5 \times 10^{18}$ cm^3. In other words, it would take as many as 25,000 San Fernando earthquakes to make up a single Chilean earthquake. Thus, as far as physical size is concerned, the San Fernando earthquake is almost negligible as compared with the gigantic Chilean earthquake; yet the two earthquakes have equally strong social impact, and therefore are equally important from the point of view of earthquake prediction. However, prediction of smaller events would be more difficult, because their geophysical effects are less pronounced.



Different types of earthquake slip—(1) simple elastic rebound, (2) elastic rebound with postseismic slip, (3) elastic rebound with preseismic and postseismic slips.

There is no question that the seismic slip takes place more or less abruptly, as schematically shown above. However, its details are still unknown. For several earthquakes, there is fairly good evidence that the more or less jerky seismic slip was followed by a relatively slow slip, usually called creep or aseismic slip. These aseismic slips indicate that the rocks near the fault exhibit significant anelasticity; they deform gradually even after the tectonic stress is relieved by the earthquake faulting.

If they behave anelastically after the earthquake, why not before the earthquake? Although such a preseismic slip seems quite reasonable, no convincing evidence has been found. One piece of evidence, however, was found for the Chilean earthquake of 1960. In that year Benioff was experimenting with special long-period strain seismographs at Pasadena, and one of his instruments recorded very unusual long-period waves which arrived at Pasadena before the onset of the catastrophic main shock. Since Pasadena is about 10,000 km away from Chile, this observation suggests that a large-scale deformation (in terms of D_0S, $D_0S \approx 5 \times 10^{18}$ cm^3) had taken place before the main shock. Although this was indeed a remarkable observation, the excitement brought about by the detection of the free oscillations was so great that the precursor waves apparently remained unnoticed or forgotten for a long time. It was only recently that these long-period waves were interpreted properly in terms of a preseismic slip.



The very beginning of the ground displacement caused by the great Chilean earthquake of 1960, recorded at Pasadena. The arrow shows the onset time of the catastrophic main shock. A gradual motion begins before that time.

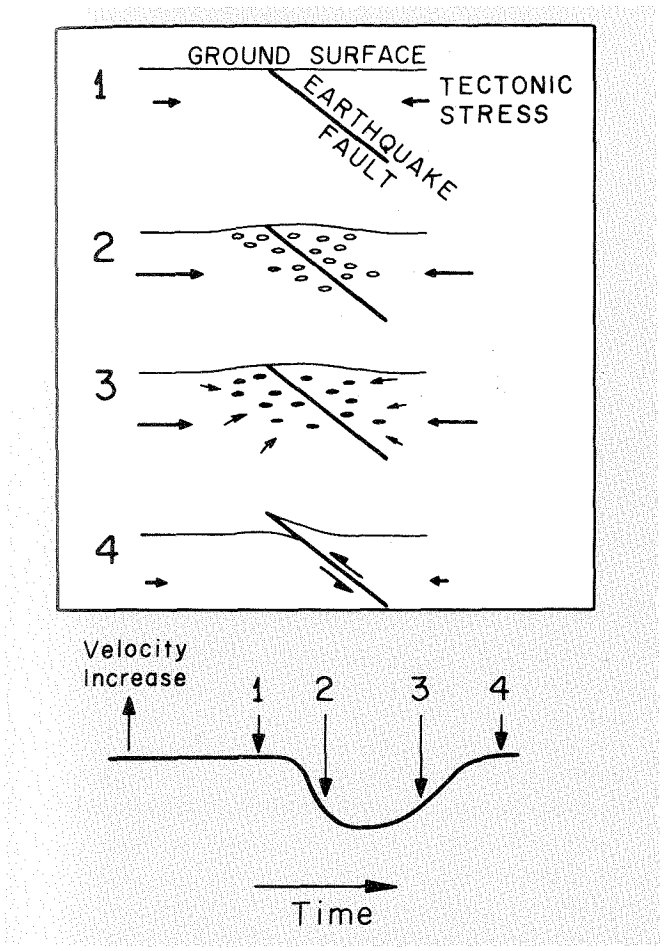
If this preseismic slip is real, and if it is characteristic of at least certain types of earthquakes, it will provide an important clue to earthquake prediction. Such preseismic slips indicate that the crustal rocks exhibit anelastic, and nonlinear, behavior before a major fracture. This anelastic deformation is eventually accelerated into the more catastrophic failure of the main shock. The details of this process and how long before the main shock it begins are not known. It may begin minutes, hours, days, or even years before the event. However, if such an accelerated process does take place before the earthquake, the range of the uncertainty in the occurrence time can be significantly narrowed by detecting the commencement, and monitoring the development, of the accelerated process.

It is expected that during this period of accelerated activity various anomalous phenomena, which may be called premonitory phenomena, might occur. Actually, such premonitory phenomena had long been suggested, directly or indirectly, on the basis of laboratory rock-failure experiments, anomalous tilts and strains in the epicentral area, anomalous geomagnetic-geoelectric disturbances, lightning, and anomalous behavior of animals, snakes, fish, and even humans. But none of these was convincing enough to attract the serious attention of seismologists.

One recent development along this line is the dilatancy-diffusion hypothesis of earthquakes; this hypothesis, put forward only two years ago, attracted literally hundreds of scientists into earthquake-prediction research. Although it is still a working hypothesis that should be scrutinized on the basis of more precise data, it gave an important direction to earthquake-prediction research.

This hypothesis says that when tectonic stress exceeds a certain limit, small cracks in the crust open up due to anelastic deformation near the crack tips, resulting in dilation. These open cracks decrease the seismic velocity.

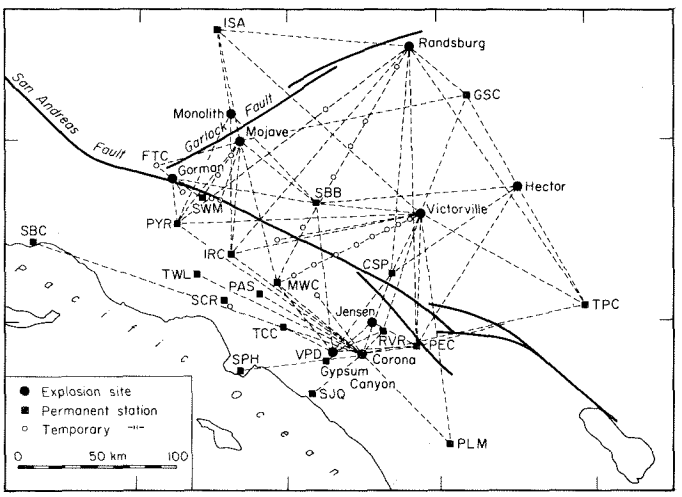
Subsequently, fluid flows from the surroundings into the dilated region increase the seismic velocity again, but at the same time lubricate the rock to trigger an earthquake. Accordingly, if the seismic velocity in a certain area first decreases abnormally and then returns back to normal, it is an earthquake alarm.



Dilatancy model: (1) Stress builds up near a potential earthquake fault. (2) Cracks open up due to anelastic deformation, and the seismic velocity decreases. (3) Fluid flows into the dilated area from the surroundings, thereby increasing the velocity and lubricating the rock to ease faulting. (4) The earthquake occurs. The diagram at the bottom shows the time variation of the velocity corresponding to each stage.

Since the time for this whole process to take place depends upon the size of the affected area, it can also tell us how large the earthquake is going to be. Caltech, along with other institutions, contributed much to this field by documenting such velocity changes for the 1971 San Fernando earthquake and several other smaller earthquakes and by developing a physical model for such a process.

Even if this dilatancy-diffusion model is not correct as it stands, it is quite possible that seismic velocity might still change due to changes in tectonic stress during the period of the accelerated process. In view of this, Caltech has now set up several profiles in southern California along which very precise measurements of seismic velocity are



Explosion sites, mostly quarries and mines (large solid circles), and seismographic stations (the square symbols are permanent stations, the open circles temporary stations) used for precise measurements of seismic velocity in southern California. Velocities are measured along the dashed lines.

repeatedly made to monitor possible temporal changes (above).

So far, only small, but definite, changes have been found for some of the profiles. These changes are much smaller than those reported elsewhere as precursory to earthquakes; at present, it is not clear whether these changes are due to dilatancy or some other causes.

The measurements have just been begun, and we have not yet been able to prove or disprove the dilatancy hypothesis. However, if the dilatancy model proves to be correct, these measurements, if continued with sufficiently close time intervals, will enable us to detect any premonitory velocity changes that take place within the network over an area larger than some 100 km in extent. This spatial extent corresponds to an earthquake the size of the 1971 San Fernando earthquake. □