Earthquake Prediction (II): Prototype Instrumental Networks

Even if earthquakes turn out to be predictable from geophysical phenomena taking place in the earth's crust prior to rupture, that knowledge will do little good unless the precursor signals are observed. Similarly, predictions will in themselves do little good if their result is only panic and economic chaos or if they go altogether unheeded. But what to do when and if a major earthquake is predicted has received very little attention, despite indications that geophysically based predictions may soon be a fact of life. Monitoring for precursor signals is also essentially nonexistent except for one area in central California, where the U.S. Geological Survey's National Center for Earthquake Research is conducting the first major U.S. attempt to record and study crustal phenomena from a large region. A second network is under development in southern California, however, and still others are planned in Oregon, Utah, Nevada, and Missouri.

Funds for earthquake research are now increasing rapidly, in contrast to the lean budgets of recent years. The Geological Survey, hard pressed to develop monitoring networks and to absorb the earthquake programs being transferred (by order of the Office of Management and Budget) to the agency from the National Oceanic and Atmospheric Administration, is nonetheless planning to expand its support of research. Despite this good news and the general optimism among university-based scientists about the prospects for earthquake prediction, many geophysicists are concerned over the lack of any national plan for reducing earthquake hazards and they question the strategy of research now being pursued by the Geological Survey.

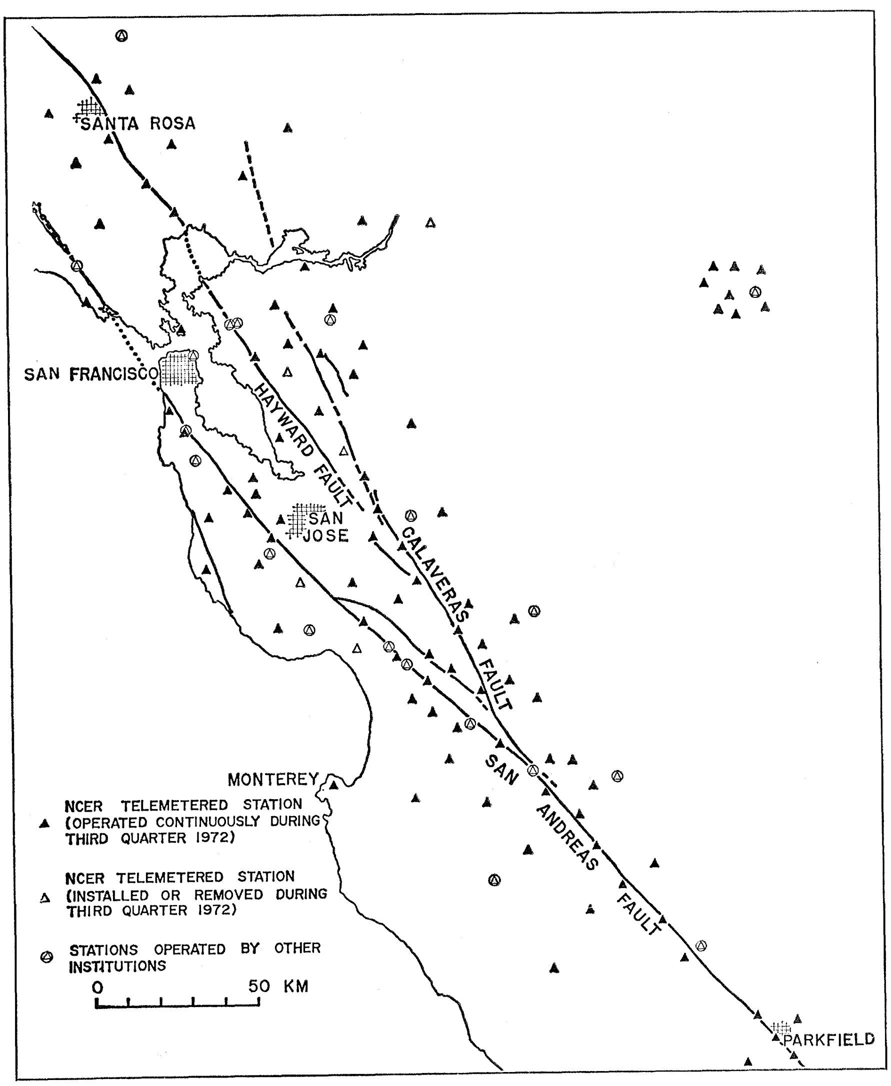

Fig. 1. Map of Central California showing active faults and seismograph instruments deployed by the National Center for Earthquake Research (NCER) and others as part of a prototype network for earthquake prediction. [Source: U.S. Geological Survey]

Field experiments conducted by the Survey, however, are credited with an important role in making possible rapid progress in the theoretical understanding of earthquake precursors. The proposal that dilatancy—an increase in volume due to small cracks which occurs just before rupture in rocks stressed to their breaking point—is the cause of earthquake precursors is now being hotly debated (*Science*, 25 May 1973, p. 851). A key tenet of dilatancy models is that fluids within the crust play a major role in triggering earthquakes—a concept that until recently would have been dismissed by most seismologists. However, preliminary results from an experiment in a Rangeley, Colorado, oil field have shown that small earthquakes can be turned off and on when fluid pressures are varied, and these results have forced reconsideration of earlier beliefs.

In the Rangeley experiment, directed by B. Raleigh and J. Healy of the Geological Survey Center in Menlo Park, California, fluid pressure was first reduced, then increased by pumping water out of and then back into wells over a period of months. Pressures were already elevated about 50 percent above the normal hydrostatic pressure because of water injected into the field as part of secondary recovery of oil. When the pressure was reduced below 4000 pounds per square inch (1 psi = 6.9×10^3 newton/m^2) at well bottom (about 1.8 km depth) along one section of a fault that passed through the field, the frequency of small earthquakes dropped to about 1 per month. Water was reinjected, and, since the pressure has exceeded 4000 psi, as many as 30 small quakes a month have been observed. The results, according to Raleigh, agree well with calculations based on the hypothesis that the fracture strength of rock (the stress at which it will break or slide along a fault) is proportional to the difference between the stress across the fault or fracture and the fluid pressure in the rock. Hence a fault can be locked and unlocked, the experiment suggests, by lowering and raising fluid pressures.

In addition to its convincing demonstration that rock can be weakened and strengthened by variations in fluid pressure in the field as well as in the laboratory, the Rangeley experiment may eventually prove to be a prototype for controlling earthquakes. Control is still a distant prospect, however; key questions are whether the technique can be used to limit the extent (and hence the destructiveness) of quakes and whether pumping water out of the ground can lower fluid pressure over an area large enough to lock a fault such as the San Andreas in California. Too little is known, for example, about the permeability of rock in the fault zone, which may be too low for a pumping technique to succeed. For the San Andreas, Raleigh estimates that wells as deep as 5 kilometers would be needed, and these would be extremely expensive to drill. Instead, more small-scale experiments (in a rock quarry) are planned as a first step.

Meanwhile intensive observations of small earthquakes and other crustal movements are being made along a 300-km section of the San Andreas fault in Central California, from Cholame to Santa Rosa. The Geological Survey has installed a network of 100 seismograph stations to monitor small quakes which it hopes will be a prototype earthquake prediction system. A separate network of geodetic markers is designed to measure the accumulation of strain along the fault and to detect creep—gradual movements or slippage along the fault without earthquakes.

More than 4000 small earthquakes were recorded and their origins located in 1972 by the seismic network. At present, determining a quake's location takes several weeks of human effort, but a computer system that will perform the analysis in several minutes is being developed at the U.S.G.S. Menlo Park Center. Automated systems, which will certainly be necessary to monitor large areas, may also have the virtue of interpreting seismic records more consistently than would a variety of human observers.

The California network is now being augmented by seismographs capable of recording horizontal as well as vertical motions, so that anomalies in the relative velocities of compressional and shear waves—anomalies observed elsewhere prior to earthquakes—can be detected if they occur along the San Andreas fault. Eventually the network will consist of as many as 200 seismographs at 120 different locations, with the result that this portion of

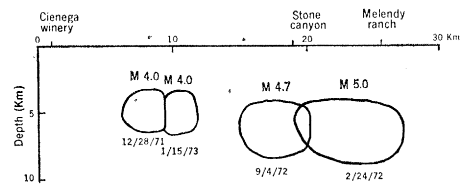

Fig. 2. Location of four earthquakes that occurred on a section of the San Andreas fault near Hollister, California. The region between the two pairs of quakes is thought to be an area of high relative stress and hence a likely site of a future quake large enough to "fill in" the seismic gap. [Source: R. Wesson, U.S. Geological Survey]

the San Andreas fault and the nearby Calaveras and Hayward faults (Fig. 1) will be the most heavily instrumented in the country.

Despite the large number of instruments, some university geophysicists believe that the Geological Survey is attempting to cover too large a region, that the instruments may be too far apart to detect seismic velocity anomalies and thus to adequately test dilatancy models for earthquake prediction. The critics would prefer a research strategy in which several carefully chosen spots would be more densely instrumented.

Nonetheless, the seismic network has resulted in what amounts to the first official earthquake prediction in the United States. Over the course of a year R. Wesson and W. Ellsworth of the U.S.G.S. Menlo Park Center observed four moderate quakes, ranging from magnitude 4 to 5 on the Richter scale in the Bear Valley region south of Hollister, California. The pattern of these quakes (Fig. 2), the simplicity of the fault geology in the region, and the identification of an apparent concentration of stress led the investigators to predict a fifth quake of about magnitude 4.5 (too small to cause damage). Rather than being based on a deterministic model of crustal processes, the prediction is statistical in nature in that its relies on the identification of a "seismic gap" in which the probability of a quake is unusually high. As such the technique exploits a special circumstance and is not likely to be applicable to many situations, but if accurate does illustrate the capabilities of the seismic network. As of mid-May, the predicted quake had not yet occurred.

Repeated geodetic surveys in California give evidence that relative motion between the American and Pacific plates has averaged about 32 millimeters per year during this century. More detailed observations of crustal movements with laser distance-measuring instruments, creepmeters, and tiltmeters are just beginning. Nonetheless measurements along survey lines close to the San Andreas fault indicate as much as 36 mm of creep per year at the surface in the section near Hollister, according to J. Savage of the U.S.G.S. Menlo Park Center, and lesser amounts have been observed along the Hayward fault closer to San Francisco. There is considerable disagreement as to whether the rate of creep is sufficient to relieve all the strain being accumulated by movement of the crustal plates, and thus as to the likelihood of a large earthquake in the San Francisco region.

Forecasts of small earthquakes as scientific experiments will not cause any great alarm, but the consequences of predictions of major quakes are a different matter. Most geophysicists believe that accurate predictions will be of substantial value in saving lives, but social scientists studying the response to geophysical hazards point out that predictions may well have significant social consequences in themselves. Among these, according to E. Haas of the Institute of Behavioral Studies at the University of Colorado, might be sharp drops in tourist trade, depressed real estate values, and other economic impacts. At the same time forecasts would allow careful emergency planning and practice alerts that might greatly reduce the chaos common in most disaster areas.

If indications of a large quake could be obtained several years in advance, as suggested by dilatancy models, then more intensive geophysical observations of the quake area could be undertaken, leading possibly to more precise warnings. In California, voters have several times refused to pass bond issues to rebuild schools known to be unsafe in the event of a major quake, but R. Wallace of the U.S.G.S. Menlo Park Center believes this attitude might change in the face of a more imminent disaster, so that legislation could be passed, and many known hazardous structures could be removed or repaired.

Experimentation with prototype networks for earthquake prediction is only beginning in California. In the eastern part of the United States there is, as one observer characterized the situation, a "vacuum of understanding" of seismic hazards. More varied and vigorous monitoring experiments will be needed to make earthquake prediction practical, as will more thought to the social implications of this nascent technology.

—Allen L. Hammond