Earthquakes: Prediction Proving Elusive

A few years ago, the scientific community was optimistic, even euphoric, in the wake of several successful predictions of earthquakes around the world. Today, that euphoria is gone. The optimism has not given way to pessimism but, as one administrator puts it, "There's a long, hard road ahead."

This return to a more sober realism followed a number of setbacks in areas that had seemed at first to be the most promising. The massive Chinese program that successfully predicted the major Haicheng earthquake of 1975, saving tens of thousands of lives, failed to anticipate the Tangshan earthquake of 1976, which reportedly killed over 600,000 people. The dilatancy theory, a detailed model of the microscopic events preceding an earthquake, had apparently been vindicated by 1975 as a result of successful predictions; but it has since fallen on hard times, the result of too few observations consistent with the theory. The ominous Palmdale uplift in southern California, which grabbed the attention of researchers and the public alike in 1976, continues to defy explanation. In spite of intense observation, it has yielded no definitive clues as to the possibility of a major earthquake.

Ironically, it is the lack of even moderate-sized earthquakes in California that is proving most frustrating to American researchers. Without a long period of observation, including a number of moderate or large earthquakes, it would be impossible to sort out the various geophysical phenomena that may foretell a damaging earthquake from those that are unrelated. Among possible precursory phenomena being observed, groupings of smaller earthquakes are receiving particular attention, but everything from changes in the tilt of the earth's surface to unusual animal behavior are also being considered.

The San Fernando earthquake of 1971 was the last one of magnitude 6.5 or greater on the Richter scale (a logarithmic measure of seismic wave amplitude). Most of the data gathered since the rapid expansion of earthquake research has involved events of magnitude 5 or less, but there are no clear assurances that conclusions based on these data can be extrapolated to larger, potentially destructive earthquakes.

Frustration over the dearth of moderate earthquakes in California is accentuated by the federal government's increased funding of earthquake prediction research after years of minimal assistance. Under the Earthquake Hazards Reduction Act of 1977, $14 million has been designated for prediction studies compared to $5 million in 1976. Researchers realize that the ball is back in their court and are anxious to "capture" the hoped for precursors of a moderate earthquake in their expanded observation networks.

Outside of California, two moderate earthquakes were observed recently within monitoring networks, a magnitude 6.5 event at Adak, Alaska, last November and a damaging 7.0 event on 15 January, southwest of Tokyo. The Japanese earthquake is considered to be among the most thoroughly observed ever, but experts did not make a prediction in either case although several types of unusual activity were detected prior to the quakes. This experience has pointed up the awkward stage at which earthquake prediction is today. While the ability to observe possible precursors has increased considerably, no reliable precursor has yet been found. Most researchers would now agree with James Whitcomb of the California Institute of Technology when he notes that "if there was one clear indicator, it would have been seen a long time ago."

No clear indicator was evident before the Japanese earthquake, although the observing network is among the densest and most complete in the world. Even with hindsight, the large amount of data collected is "enticing, but puzzling," according to David Hill of the U.S. Geological Survey (USGS) at Menlo Park. He and Barry Raleigh of the USGS and Hiroo Kanamori of Caltech inspected the data in Japan about a month after the quake. Although several different kinds of precursors were observed, Hill goes no further than to call the data "encouraging."

Officials of the Japan Meteorological Agency were equally tentative when they issued an earthquake information bulletin, rather than a true prediction, on the morning of 15 January for the area of Oshima Island and the Izu Peninsula 125 kilometers southwest of Tokyo. They merely cautioned that a large, potentially damaging earthquake might occur in the near future. The warning was precipitated by a group, or swarm, of unusually strong earthquakes. At the time, the swarm appeared to be accompanied by the unusual behavior of only two of the many instruments in the area. Other swarms had occurred before without being followed by a major earthquake. Three hours after the warning was made, a quake the size of the San Fernando earthquake struck between the island and the mainland, causing extensive damage and 25 deaths.

The vagueness of the Japanese prediction was necessitated by a problem common to all earthquake prediction: the lack of a long, detailed monitoring record. Without one, it has proved difficult to tell whether or not anomalous activity is a precursor foretelling a major earthquake. But as long as underlying earthquake mechanisms remain poorly understood, the only alternative appears to be to observe as many likely precursory phenomena as possible and to try to deduce those that can be used to predict the time, location, and size of major earthquakes. This, along with varying amounts of basic earthquake research, is an approach being taken by American, Japanese, Russian, and Chinese investigators. The inevitable pitfalls of the early phases of such an approach were evident in the experience with the Izu quake. American researchers in particular are increasingly hopeful that basic research will eventually help make sense out of the variety of possible precursory phenomena being studied today.

Small earthquakes and earthquake swarms have displaced dilatancy-related effects as the possible precursors of greatest interest. The hope is that these nondestructive quakes, or foreshocks, reflect the buildup of stress within the earth, which will eventually be released by the main shock. Japanese quakes are often preceded by foreshocks. Even so, those associated with the Izu quake provided no obvious information about the main shock that followed. The final swarm, which could be felt by the local inhabitants, was centered near Oshima Island, but most of the damage was done on the mainland.

The earthquakes preceding the Adak event in the Aleutians appear, with hindsight, to fall into a pattern that, if repeated in the future, could be used to make a prediction. Stephanie Price and Carl Kisslinger of the Cooperative Institute for Research in the Environmental Sciences (CIRES) at Boulder, Colorado, and Robert Engdahl of the USGS at Denver had set up a network of seismo-

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graphs in 1974 capable of detecting microearthquakes (less than magnitude 4) in the vicinity of Adak Island. This network detected two swarms about 11 and 3 months before the main shock, separated by activity slightly higher than normal. The second swarm tapered off until all seismic activity ceased about 3 weeks before. This swarm was accompanied by a group of events of magnitude 4 or greater that were the only larger earthquakes recorded in the 3-year period along the 40-kilometer zone that ruptured during the magnitude 6.5 quake. Engdahl believes that this pattern of silence and activity is similar to the pattern prior to the magnitude 7.1 shock of 1971 near Adak.

Unfortunately, not all major earthquakes have foreshocks of at least moderate size. Of the 160 earthquakes having a magnitude of 7 or greater included in their survey, Lucille Jones and Peter Molnar of the Massachusetts Institute of Technology found that only about 50 percent had foreshocks of magnitude 4 or greater. Although some of these occurred as much as 2 to 3 months before the main shock, most came within only 1 day before it.

The use of microearthquakes as precursors appears to be more promising at this time, even though it requires dense networks of seismographs. The attractive aspect of microearthquake precursors is that they may contain a good deal of information about the location and time of the main shock. For example, Karen McNally of the California Institute of Technology has separated anomalous events of magnitude 2 to 3 from the record of random activity along the San Andreas fault in central California and the San Jacinto fault in southern California. The anomalous microearthquakes are grouped, or clustered, near the eventual source of larger quakes as well as clustered in time. These clusters precede their main shocks by months or years. The size of the clusters, several kilometers across, is smaller than the eventual rupture zone of the main shock and, McNally believes, may be related to the magnitude of the main shock. Similar but smaller clustering has been observed, by Pradeep Talwani of the University of South Carolina, before smaller quakes associated with the filling of a reservoir.

The San Fernando earthquake of 1971, like many earthquakes, was not thought to have had a foreshock sequence, but Brian Brady of the Colorado Bureau of Mines detected and Mizuho Ishida and Hiroo Kanamori of Caltech further refined a subtle pattern of seismicity over a 10-year period. The first of two periods of activity coincided with the inferred onset of the Palmdale uplift and was separated from the second by an absence of activity near the final fracture zone. The characteristics of the events in the second period, as recorded in their seismograms, led Ishida and Kanamori to conclude that the final foreshocks were located within the fault itself and that the fault zone was under much higher stress than during the first period.

While the ideas of clustering, localization of high stresses, and other seismicity patterns are tantalizing, there is no consistency between different locations and insufficient records at any one location. Thus, seismicity patterns are making little contribution to earthquake prediction at this time. Successful prediction on the basis of seismicity patterns, and the likely saving of lives, has been claimed by Brady in the case of very small earthquakes, or rock bursts, in a deep Idaho silver mine. Also, preliminary studies by several groups suggest that foreshocks may be identified by changes in the orientation of their faults with time. But generally, seismologists must still watch and wait. For example, McNally and Kanamori have been watching a section of the San Andreas fault near Palmdale, where an unusually high level of microearthquakes, for that area, has been maintained since November 1976. With the current state of the art, they are unable to tell whether the activity represents a long-term change in seismicity or some sort of precursory swarm.

A Slow Earthquake?

In addition to a pattern of swarms, the Izu earthquake was preceded by the anomalous behavior of one of three volume strainmeters, or dilatometers, that may have been an indication of an otherwise undetectable, last minute buildup of strain before the final failure of the fault. The strainmeter recorded a change in stress a couple of weeks before the main shock and another change 1 day before, according to Selwyn Sacks of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, a codeveloper of the instrument.

Sacks believes that this behavior is consistent with the "slow" earthquake concept developed by him along with Shigeji Suyehiro of the Japan Meteorological Agency, Alan Linde of the Carnegie Institution, and Arthur Snoke of the Virginia Polytechnic Institute and State University. The crustal movement of a slow earthquake is about one hundred times slower than that of a normal quake. A slow quake fails to produce the higher frequency seismic signals recorded by standard seismographs and thus goes undetected, according to Sacks. But it is capable of transmitting stress from one place to another. Thus, Sacks believes that slow earthquakes may be responsible for a sudden increase of stress to critical levels only days or weeks before the final failure. This idea contrasts with the conventional view of slowly increasing stress over a period of years. If applicable in even a few cases, the effect of slow earthquakes would be to greatly complicate long-term prediction.

Another possible precursor of the Izu quake was a change at one station in the amount of detectable radon gas. The measurement of radon emanating from the ground is a widely used but poorly understood guide to changes in the rocks of the upper crust. Radon, which is produced in rocks by the radioactive decay of radium, diffuses toward the surface where it can be measured by a variety of methods. Apparently, changes in the state of stress of the rocks, among a number of other factors, can either increase or decrease the amount of measured radon. Appearing at only one station, the Izu radon anomaly was not a very compelling warning signal.

Some radon measurements from California have apparently shown very straightforward precursory phenomena and the interpretation of others remains obscure. Using a system of detectors along the San Andreas and Calaveras faults of northern California, Chi-Yu King of the USGS at Menlo Park has recorded distinct, roughly symmetrical peaks of radon emission, lasting several months, centered about two earthquakes of about magnitude 4. George Birchard and Willard Libby of the University of California at Los Angeles observed an equally well-behaved peak associated with a magnitude 4.3 quake. But since April 1977, their detection system along the San Jacinto fault southeast of Los Angeles has indicated unusually high levels of radon.

This area of the San Jacinto fault is a good example of the difficulties being encountered in using anomalous geophysical events for earthquake prediction. In addition to the prolonged high levels of radon, Birchard notes that the number of microearthquakes smaller than magnitude 2 increased during December and January and then dropped off in February and March. Of two recent quakes greater than magnitude 4, one had a foreshock sequence and the other did not, and therefore interpretation of the recent change in activity is impossible. The same area, near Anza, has been identified as a seismic gap, or an area of no recent activity, for earthquakes greater than magnitude 6. Wayne Thatcher and Thomas Hanks of the USGS at Menlo Park and James Hillman of Caltech searched the seismological records and concluded that a small section of the San Jacinto fault near Anza is locked in place and apparently has not ruptured since 1890. While most researchers would agree that the likelihood of a moderate earthquake is much greater in such a situation, no one can say when it might happen. To further complicate matters, the San Jacinto fault is on what is currently taken as the southern boundary of the enigmatic southern California uplift.

Despite the frustrations of those trying to predict earthquakes, researchers generally believe that prediction is a realistic goal. The Japanese and Alaskan earthquakes have reinforced the belief that at least some damaging quakes have precursory phenomena. But many believe that it will be at least 10 years, perhaps longer, before widespread, reliable prediction of major earthquakes is achieved.

—RICHARD A. KERR

Geodesy: Dealing with an Enormous Computer Task

In 1974, the National Geodetic Survey (NGS), which is part of the National Oceanographic and Atmospheric Administration (NOAA), embarked on a project of unprecedented magnitude. The project is to readjust the North American Datum—a network of reference points whose longitudes, latitudes, and, in some cases, altitudes must be known to an accuracy of within a few centimeters. Now halfway through their readjustment project, NGS investigators are confident that they can complete the job by 1983, as scheduled. They point out, however, that this project is one of the largest computer tasks ever attempted (about 700 hours of computer time are allotted).

The sheer size of the problem of computing the coordinates of these reference points has forced NGS researchers to deal with problems that arise, as they are fond of putting it, "from pushing the state of the art to its limits." For example, a key step in the problem is to solve about 2.5 million nonlinear equations in 400,000 unknowns. For smaller problems, this task is textbook simple. However, according to Charles Schwarz of NGS, the NGS problem is the largest system of nonlinear equations whose solution has been attempted. The size of this problem forced the investigators to deal with, and protect themselves against, the possibility that the computed solutions would be worthless, or even meaningless.

The North American Datum consists of about 200,000 points described by their longitudes and latitudes and about 500,000 points described by their longitudes, latitudes, and altitudes. This network is necessary to regional planners, engineers, and surveyors, who need accurate reference points when they make maps and specify property boundary lines, to navigators, and to geophysicists who study the tectonic movements of the earth. Coordinates of these points must be known with great accuracy because detailed maps of regions, such as cities and counties, are made by measuring distances and directions to various sites from the datum points. Any errors in the coordinates of the datum points will lead to even greater errors in the coordinates of the intermediate points whose coordinates are determined from them. In fact, it is a basic principle of engineering that the accuracy of the coordinates of reference points be at least an order of magnitude greater than the accuracy of the coordinates of such intermediate points.

The extensive network constituting the North American Datum has been built up gradually since 1807. New points were continually added and their positions determined in reference to previously existing ones. The datum was last readjusted in 1927, when the coordinates of all points then in the network were calculated with reference to a triangulation station on Meades Ranch in Kansas.

Since 1927, more than 100,000 points have been added to the network, and the network has been extended from the continental United States to include Alaska (Fig. 1). The coordinates of these added points were calculated with reference to the 1927 points, which resulted in the propagation of errors in the positions of the 1927 points to errors in the positions of the added points. These errors were, in places, as large as 10 m. Moreover, the surface of the earth itself moved since 1927. In some areas, tectonic movements as large as 5 cm per year have been observed.

It became increasingly obvious that the current datum is no longer adequate for today's uses. In 1971, a National Academy of Sciences committee recommended that the datum be completely readjusted. The new datum will span all of the North American continent. The governments of Canada, Mexico, the republics of Central America, and Denmark (which administers Greenland) have decided to add their own networks to that of the United States and have agreed to support and cooperate with NGS to make the resulting North American Datum consistent.

Since techniques for measuring positions of points relative to each other improved tremendously over the years, NGS investigators believe they will have to do a minimum of remeasuring when they readjust the longitudes and latitudes of the datum points. Instead, they will concentrate on solving simultaneously a set of equations relating the position of every point of the datum to every other point and tying the whole network to a few reference points. They plan to make use of all previous measurements of the positions of the points in the network to get the best fit to the available data. They break their task into two parts. First is a monumental problem in data management and handling; next are the actual computations of the readjustment.

Data management and handling is a problem in part because NGS had not previously computerized its files. Robert Hanson of NGS says this project is, in effect, "dragging NGS into the 20th century." The position of each point in the network was determined several times over the years, but all this data exist on paper and has to be put into a form that can be read by a computer. After 4 years of work, the NGS investigators are only about halfway through entering their data on the computer cards and validating the data. Moreover, this data base must be validated to rule out errors in observations and in data entries into the computer.

To validate the data, NGS researchers are working with small subnetworks of 50 to 200 points and solving for the positions of these points relative to each other. Schwarz reports that, as might be expected, a number of errors were detected. The magnitude of this task is reflected by the enormous number of measurements that must be dealt with. John Bossler, director of the readjustment project, notes that the horizontal control points—200,000 points whose longitudes and latitudes, but not altitudes, are to be determined—are described by some 2 to 3 million observations.

The mathematical portion of the read-

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