Prospects for Earthquake Prediction Wane

The absence of obvious precursors to last August's moderate quake near San Francisco suggests that some earthquakes may be extremely difficult or impossible to predict

Earthquake researchers had been anxiously waiting for their first close look at a moderate earthquake in California. Last August they got it. A magnitude 5.7 quake struck 100 kilometers southeast of San Francisco near Coyote Lake on the Calaveras fault, a major branch of the San Andreas. Because it fell within a dense network of monitoring equipment centered near Hollister, 25 kilometers away, the Coyote Lake earthquake is probably the most thoroughly observed moderate quake ever to occur in the United States.

In spite of this good fortune, the data from Coyote Lake have been a disappointment to those hoping to learn more about how to predict earthquakes. Even in hindsight, no obvious phenomena that could have allowed an accurate prediction—such as clusters of small quakes, tilting of the earth's surface, or changes in the geophysical properties of the crust—have been found. This disappointment was perhaps the final blow to the optimism expressed by a number of researchers a few years ago. No one is saying any more that prediction is right around the corner.

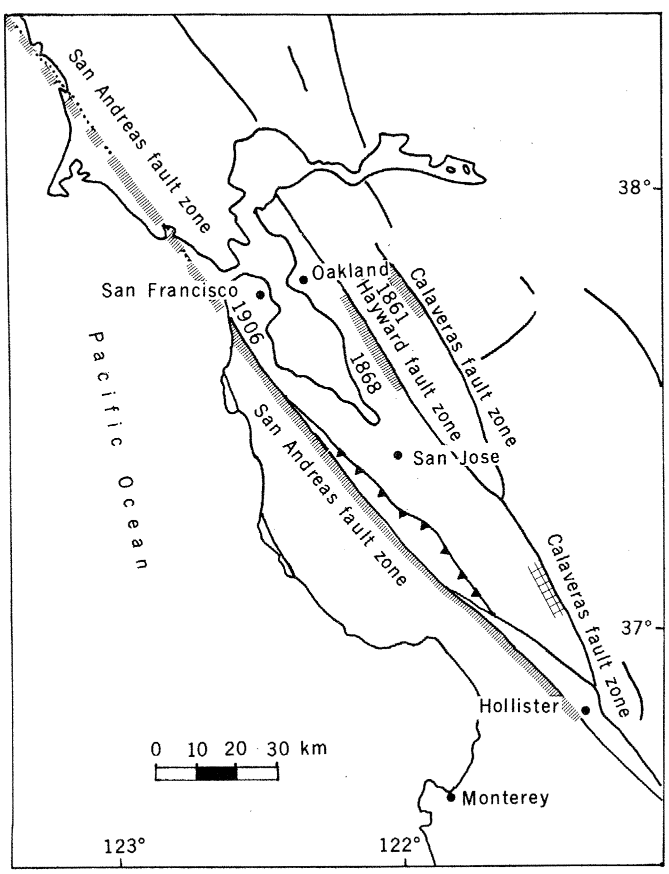
Some researchers are even pointing to the Coyote Lake quake as a possible example of a class of nonpredictable earthquakes. At best it would have been extremely difficult to predict when it would have struck. The difficulty of predicting this moderate quake, which at worst could have caused only limited damage, concerns researchers because some evidence suggests that great, catastrophic earthquakes may actually be triggered by moderate shocks.

Researchers are still analyzing their data, but preliminary conclusions are holding up. As Robert Wesson, head of earthquake studies at the U.S. Geological Survey (USGS) in Reston, Virginia, observes, "We were clearly not overwhelmed by short-term precursors." The only possible warning signals that immediately preceded the Coyote Lake shock were two of the unconventional sort that have aided foreign predictors, especially the Chinese and the Soviets. As yet, no one understands the cause of these apparent precursors, but their connection to subsequent quakes seems real, at least in some cases.

Unfortunately for American prediction specialists, the connections in this case are tenuous. The flow of a spring about 35 kilometers from the quake surged before the quake. Although the surge may have resulted from increased stress on the fault shortly before the quake, the significance of the surge is unknown because only an 8-month record is available for the spring's flow. Some cases of unusual animal behavior were reported, but they did not provide any hard evidence of a link between animal behavior and imminent quakes, according to Leon Otis and William Kautz of SRI International. Under contract to the USGS, they operate several networks of observers, one of which has Coyote Lake on its edge. Calls reporting unusual animal activities did increase before the quake, Kautz notes, but only marginally.

Scientists are most disappointed because instrumental records have not yielded any of the possible short-term precursors they had hoped to find. Although perhaps one-quarter of all moderate California earthquakes are preceded by foreshocks—the smaller earthquakes that can herald a larger quake—the dense seismometer network detected none. Even the microearthquakes (magnitude less than 3) that formed such interesting patterns of activity before the magnitude 7.7 Oaxaca, Mexico, quake of last year (*Science*, 2 March 1979, p. 860) were absent.

Also missing were any signs of changes in the shape of the earth's surface immediately before the earthquake. One way to measure these changes over



Location of the Coyote Lake earthquake. Dark bands show lengths of faults that have ruptured during major earthquakes in historical times. Hatched band on the Calaveras is the approximate length of fault involved in the Coyote Lake earthquake.

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a short period is to measure precisely the change in slope or tilt of the land at a particular spot. Premonitory changes in tilt did precede a pair of earthquakes (magnitude 4.2 and 3.9) that occurred in August 1978 on the Calaveras between Coyote Lake and Hollister near Mount Hamilton, according to E. Iwatsubo and Carl Mortensen of the USGS in Menlo Park. Unlike the situation on the San Andreas in southern California, where movement along the fault occurs only during an earthquake, the opposite sides of the Calaveras move past each other at about 12 to 15 millimeters per year in the area of Coyote Lake. Iwatsubo and Mortensen believe that the changes in tilt before the Mount Hamilton quakes resulted from a sharp increase in the rate of this creep. Because any movement at one point on a fault tends to relieve the stress there and move it farther along the fault, this rapid creep past the tiltmeter could have applied enough additional stress to precipitate the earthquakes 5 kilometers away. Of other quakes in the vicinity of the Mount Hamilton tiltmeter, however, some have shown similar patterns of creep behavior and some have not.

Another precursor that failed to appear at Coyote Lake was a magnetic anomaly. The phenomenon is little understood, but changes in stress are suspected of producing changes in the magnetization of minerals, which in turn affects the local value of the earth's magnetic field. It was the observation of a magnetic anomaly and a rapid change in tilt that prompted the successful informal forecast in 1974 of the magnitude 5.2 "Thanksgiving Day" earthquake near Hollister.

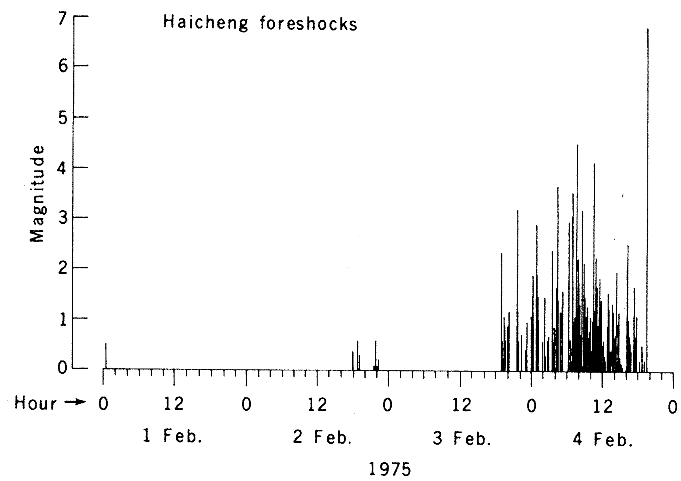
Although there were no precursors on which an accurate prediction could have been based, some of the instruments did detect long-term changes in the behavior of the fault before it broke. A creepmeter 10 kilometers north of Hollister showed that creep on the Calaveras ground to a halt during the winter of 1975–1976 and never resumed before the quake, according to Robert Buford of the USGS at Menlo Park. He had found similar behavior of a creeping section of the San Andreas south of Hollister before earthquakes of magnitude 4.0 and 5.1. Also, measurements accurate to a few millimeters of the distance between two points on either side of the Calaveras near Coyote Lake revealed a change in the way stress was accumulating during the year before the quake.

In spite of these two interesting features, the Coyote Lake earthquake has been a sharp reminder to American researchers of the fickleness of precursory phenomena. It was not the first, however. Their Chinese colleagues, who have depended exclusively on little understood precursors, had already been badly burned. Their successful prediction of the magnitude 7.3 Haicheng quake in 1975, coming on the heels of the Thanksgiving Day forecast, buoyed spirits in the American prediction community considerably. The Chinese had been able to follow a chain of precursors that began 5 years earlier and continued until only hours before the main shock. These precursors included patterns of large and small earthquakes and anomalous changes in tilt, the earth's magnetic field, water levels in wells, and animal behavior. A swarm of apparent foreshocks, evaluated in the light of the other precursors, prompted the final warning to evacuate the 90,000 inhabitants. A few hours later, the quake destroyed or severely damaged 90 percent of the buildings in Haicheng.

The city of Tangshan had not been so fortunate when a magnitude 7.8 quake struck it in 1976. More than 600,000 people reportedly died, although the Chinese have not released an official death toll. Tragically, the chain of precursors leading toward the Tangshan quake petered out after an intermediate-range warning had been issued. According to Cinna and Larissa Lomnitz of the Universidad Nacional Autónoma de México, who talked to researchers in China about the quake, Chinese scientists observed none of the abrupt changes in geophysical properties that had led to successful predictions. Without any foreshocks to narrow the area of interest, the few anomalies that were recorded in the region could not be correlated.

Chinese prediction specialists continue to rely on a purely empirical approach—the "hunt-and-peck" method, as one American put it—in which all the possible related observations are correlated without regard for underlying causes. No substitute is available at the moment, and the Chinese need predictions desperately. Their unreinforced brick-and-mortar construction crumbles under the strain of shaking by earthquakes, producing staggering death tolls as at Tangshan. Because the price to be paid for an unpredicted earthquake in China is so enormous, the Chinese believe they must endure the economic and social costs of responding to every possible precursor, even though this has led to a number of false alarms.

Although the American earthquake prediction program includes empirical studies of precursors, official policy emphasizes the necessity of understanding earthquakes on a fundamental level.



Foreshocks preceding the magnitude 7.3 Haicheng earthquake of 1975. Chinese prediction specialists correctly interpreted the large magnitude of the quakes in this swarm and their abrupt decline as a warning of an imminent large earthquake. [Courtesy of the American Geophysical Union]

Nonetheless, considerable hope had been held out until recently for the straightforward use of empirical observations in prediction. Now, even the most optimistic concede that precursors may often prove unreliable. Researchers concede as well that some earthquakes may not be predictable.

This pessimistic view is based partly on the growing understanding of how the two faces of a fault slide by one another. Unlike the ideal fault, which would be like two tabletops flush to each other, real faults seem to be rough and irregular. "Geologists in the field have recognized for years that faults are irregular," says Keiiti Aki of the Massachusetts Institute of Technology. "Seismologists have simplified them all along. But now it appears that the geologists' irregularities extend down" to several kilometers below the surface, where earthquakes actually occur. These irregularities may include bends and short offsets in the direction of the fault, bumps or rough spots on the faces of the fault, and differences in the material caught between the fault faces.

Any or all of these irregularities could

The four-story concrete and brick Tangshan People's Bank after the 1976 earthquake. [Courtesy of Earthquake Information Bulletin, *U.S. Geological Survey]*

snag and hang up fault movement. One result would be that instead of stress being evenly distributed along a fault, it would tend to concentrate at the irregularities. Thus, when the stress got high enough, the fault might rupture at one of these stress concentrations before most of the fault appears to be ready to break. Most of the jolt of the earthquake could come from the small rupture, but the stress released there could also cause slippage elsewhere on the fault. Thus, if earthquakes are to be understood, the processes in the small areas of high stress may have to be thoroughly monitored, which would be much more costly than the present observation program.

James Brune of Scripps Institution of Oceanography has pointed out, and most researchers agree, that under certain conditions, the existence of these small areas of high stress, or asperities, could also make precursors much harder to find. Brune argues that if a certain level of stress is required to produce a particular precursor, then that precursor might appear only over the small area of the asperity and not along the entire length of fault that eventually breaks. In the worst possible case, even the stress at the asperity would not be high enough to produce the precursor. In that case, the breaking point of the fault would be reached before any precursors appeared. Although the concept of a critical stress for the generation of a precursor seems intuitively reasonable to most researchers, no one knows how large that stress might be.

The evidence for the existence of asperities, on the other hand, is strong. Thomas Hanks of the USGS at Menlo Park has shown that most of the energy released during the destructive San Fernando earthquake (magnitude 6.4) came from an area only a few kilometers across. Although fault movement occurred along 20 kilometers of the fault, Hanks suggests that the jolt from the rupturing of the short length of fault at the asperity may have been strong enough to break the rest of the fault, which had not been under enough stress to rupture by itself. Of the four moderate California earthquakes that have been observed in enough detail, Hanks says, all can be interpreted in terms of such a mechanism.

The Coyote Lake earthquake may be the latest and most dramatic example of the apparent rupture of a long section of fault by the failure of a small asperity. A traditional interpretation, based on the location of aftershocks, would be that at least 15 kilometers of the Calaveras ruptured beginning near the northwest end of the section. Once begun, the break propagated about 12 kilometers to the southeast but only a few kilometers to the northwest before it stopped. The stress on the fault would be assumed to have been similar along the entire fault.

On the basis of a very preliminary evaluation of the seismic data, Hanks believes that an alternative interpretation may be more likely. Because the strongest motion recorded by local seismometers lasted only a few seconds, Hanks suggests that it could not represent the breaking of all of the 15 kilometers of the Calaveras that later experienced aftershocks. Rather, most of the strong motion could have been caused by the release of stress at an asperity at the epicenter. This stress release could then have jerked the 15 kilometers of creeping fault into seismic activity. If this were the case, Hanks says, the absence of obvious precursors would not be surprising.

Just as an asperity may have been crucial to getting the Coyote Lake earthquake started, asperities may have controlled its size. As in the prediction of time and location, the prediction of an earthquake's magnitude will be complicated by the presence of asperities. In fact, researchers are not sure what makes the difference between a moderate quake and a great earthquake. "It may well be," says William Bakun of the USGS at Menlo Park, "that large quakes are 'little ones that get away.' "

It is already apparent that great earthquakes are not simply huge versions of moderate ones, but are always composed of a number of smaller fault ruptures. Hiroo Kanamori and Gordon Stewart of the California Institute of Technology found that the magnitude 7.5 Guatemalan quake of 1976 was actually composed of as many as ten independent breaks of about 10 kilometers each that propagated along a single fault. Rhett Butler of Caltech, Stewart, and Kanamori also separated the Tangshan quake into several events.

Bakun believes that the Coyote Lake earthquake provides a clue as to why most moderate quakes do not "get away" and snowball into larger, multiple-event ones as occurred in Guatemala. The Calaveras appears to have two barriers that contained the stress released during the quake. The microearthquakes that occurred during the 10 years before the main shock as well as the aftershocks were concentrated at either end of the section of the fault and to a lesser degree at a spot in the middle. These locations correspond, Bakun says, to irregularities in the trend of the fault. Offsets in the Calaveras, where it seems to end abruptly and begin again a short distance away, occur at either end of the aftershock zone, and a slight bend coincides with the spot in the middle. Apparently, the stress released during the main shock could not break through the barriers created by the offsets to induce any seismicity on the other sides.

The latest great earthquake in southern California may have started as a moderate quake that "got away" when it broke through the obstruction that usually contains it. By studying contemporary accounts of the great Fort Tejon quake of 1857, Kerry Sieh of Caltech found that several foreshocks occurred within a few hours before it. They were about the same size, magnitude 5.5, and in the same area as quakes on the San Andreas near Parkfield that occurred in 1901, 1922, 1934, and 1966. Parkfield is at the northern end of the locked section of the San Andreas that is thought to have last broken in 1857. Sieh suspects that it was the last in a similar series of Parkfield earthquakes that finally broke through and triggered the 1857 quake.

Bakun and Thomas McEvilly of the University of California at Berkeley also speculate that great earthquakes in southern California may be initiated by a Parkfield quake, but for different reasons. They have found that both the 1934 and 1966 Parkfield quakes resulted from the concentration of stress at a slight bend in the San Andreas. This stress was transmitted through the bend when a strong foreshock broke the fault on the northwestern end of the bend. In each case, 17 minutes later the additional stress broke the fault toward the southeast, producing the main shock. This progression is usually stopped, Bakun and McEvilly suggest, by another irregularity on the fault. But once every few hundred years, they say, these moderate quakes could break through the obstructing irregularity and trigger a great earthquake.

If Parkfield quakes can be triggers, an accurate prediction of the next great quake in southern California would require not only predicting the next Parkfield quake but also anticipating whether the locked section of the San Andreas is ready to rupture under the additional stress transmitted by the Parkfield shock. In one of Brune's worst-case scenarios, a long section of a fault such as the San Andreas could be triggered without the appearance of any precursors except possibly in the small area of the triggering quake. "We really don't know if classic premonitory signals would show up along the entire fault or only on part of it," notes Barry Raleigh, head of the tectonophysics branch at Menlo Park.

Because precursors may not be available, researchers are giving increasing attention to measuring physical properties that should be more directly related to the ultimate failure of any fault. One is stress itself. In principle, the stress in the earth's crust can be measured by pressurizing a section of a drill hole, but the difficulties of working in the highly fractured rock of a fault zone are great. Acceptable approaches to measuring stress 5 to 10 kilometers beneath the surface, where earthquakes and the asperities that seem to control them occur, are only beginning to be tested. Measurement of the crustal deformation caused by accumulating stress is being expanded, but interpretation of such data is not always straightforward—witness the still enigmatic Palmdale bulge. The significance of this swelling of part of southern California remains unknown. Still, deformation could be the phenomenon most easily related to the cause of earthquakes, and Raleigh "finds it difficult to imagine how as much strain as is released during a large earthquake could build up without it being noted."

Whether these or any of the other approaches being pursued will contribute to reliable predictions must await the capturing of more—a lot more—moderate or larger earthquakes within dense instrument networks. Coyote Lake was the first. When the United States' prediction program's funding was tripled in 1977, the official view was that, considering average levels of seismicity, it would take 10 years to capture the ten quakes needed to determine the practicality of earthquake prediction. So far, earthquakes in California have not kept up that pace. Unfortunately, few instruments other than seismometers were even near the recent quake near El Centro in southern California. Obviously, patience is needed—patience to wait for many more earthquakes, both here and abroad, and patience to develop a basic understanding of how earthquakes work. "There's so much we don't know," Wesson observes.—RICHARD A. KERR

Mathematicians Amazed by Russian's Discovery

An unknown Russian discovers a new solution to linear programming problems. But his result goes unnoticed for months

A Russian mathematician, L. G. Khachian, who apparently is unknown to U.S. scientists, has made a discovery of great theoretical, and probably practical, importance. He has found a surprising new way to solve linear programming problems, which are among the most common problems solved on computers. "There is a linear programming package at almost every computer installation," says Ronald Graham of Bell Laboratories. One consequence of Khachian's discovery is related to a major problem in computer science.

A typical linear programming problem faced by a business is to select its sources of supplies so as to minimize its shipping costs. The suppliers may place some constraints on the business by requiring that all orders be at least some minimum size. The resulting problem involves finding the best solution to a set of linear inequalities by considering a function that must be maximized or minimized. In the case of the business, shipping costs must be minimized. Such problems are an everyday part of life for businesses and economists, and they also occur in such fields as engineering, biology, agriculture, and the social sciences. According to Vasek Chvatal of McGill University, linear programming problems commonly involve thousands of inequalities.

Khachian's discovery went unnoticed for months after its publication last January. Computer scientists and mathematicians explain their missing the result by saying that it appeared as an abstract in the Soviet journal *Doklady*, which they seldom read. Many, in fact, cannot read it because it is published in Russian.

Virtually no U.S. scientists were aware of Khachian's result until early summer, when Eugene Lawler of the University of California at Berkeley brought it to the attention of the computer science community. Lawler heard of it in May while attending a conference in Germany. There Rainer Burkhard of the University of Cologne showed Lawler the abstract and asked him what he knew about it. Lawler, who was unfamiliar with the abstract, had it translated and sent it out to prominent computer scientists, asking if they knew about it. None did, but all were intrigued.

Through Lawler's efforts, Laslo Lovász of the University of Szeged in Hungary and Peter Gács of the University of Rochester heard of the result. These two Hungarian mathematicians were visiting at Stanford and decided to work together in an attempt to reconstruct the mathematical proofs from Khachian's abstract, thereby establishing the validity of the result. Not only did they fill in the proofs but they also improved on the method, making it more efficient. Lovász reports that their task was "medium hard" and that it took him and Gács "a couple of days." But Lovász, at age 29, is a rising

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