Reprinted from Geophysical predictions (Studies in geophysics)
National Academy of Sciences, Washington, D.C.   1978

Earthquake Prediction

3

PETER L. WARD
U.S. Geological Survey

3.1 INTRODUCTION

Earthquake prediction is a rapidly advancing area of research and development. Now is the time to start planning the utilization of the results. On February 4, 1975, a magnitude-7.3 earthquake destroyed the city of Haicheng and neighboring communities in Liaoning Province in the northeastern part of the People's Republic of China (Haicheng Earthquake Study Delegation, 1977). Ninety percent of the buildings of this town of 90,000 people were demolished. The casualties in this region would probably have been in excess of 100,000 people had it not been for the successful prediction of the earthquake and a massive evacuation of buildings hours before the earthquake struck.

The prediction began in 1970 when Liaoning Province was designated as an area deserving special seismological and geophysical attention. Observations were stepped up, and in June 1974 it was concluded that a magnitude-5 to -6 earthquake might occur in one or two years. Research and efforts at public education were increased. On January 13, 1975, the prediction was narrowed to a magnitude-5.5 to -6 event in the first six months of 1975. On February 1, foreshocks began; some homes were evacuated. The foreshock activity decreased, and at 0:30 a.m. on February 4 an earthquake was predicted for that day. By 2 p.m. the responsible local leaders had been mobilized. Evacuation and emergency preparations proceeded rapidly, and at 7:36 p.m. an earthquake of magnitude 7.3 occurred.

The Haicheng earthquake is not the first but is certainly the largest earthquake to be successfully predicted. It is especially significant because the prediction led to major life-saving action. We do not know how many predictions have been issued in China, where there is a major prediction program involving over 10,000 full-time workers and 300,000 volunteers (American Seismology Delegation, 1975). It is clear, however, that several false alarms have been issued leading to evacuation and considerable disruption. Furthermore, major earthquakes have occurred such as one of magnitude 8.0 near Tangshan on July 27, 1976, where no specific prediction was available and over

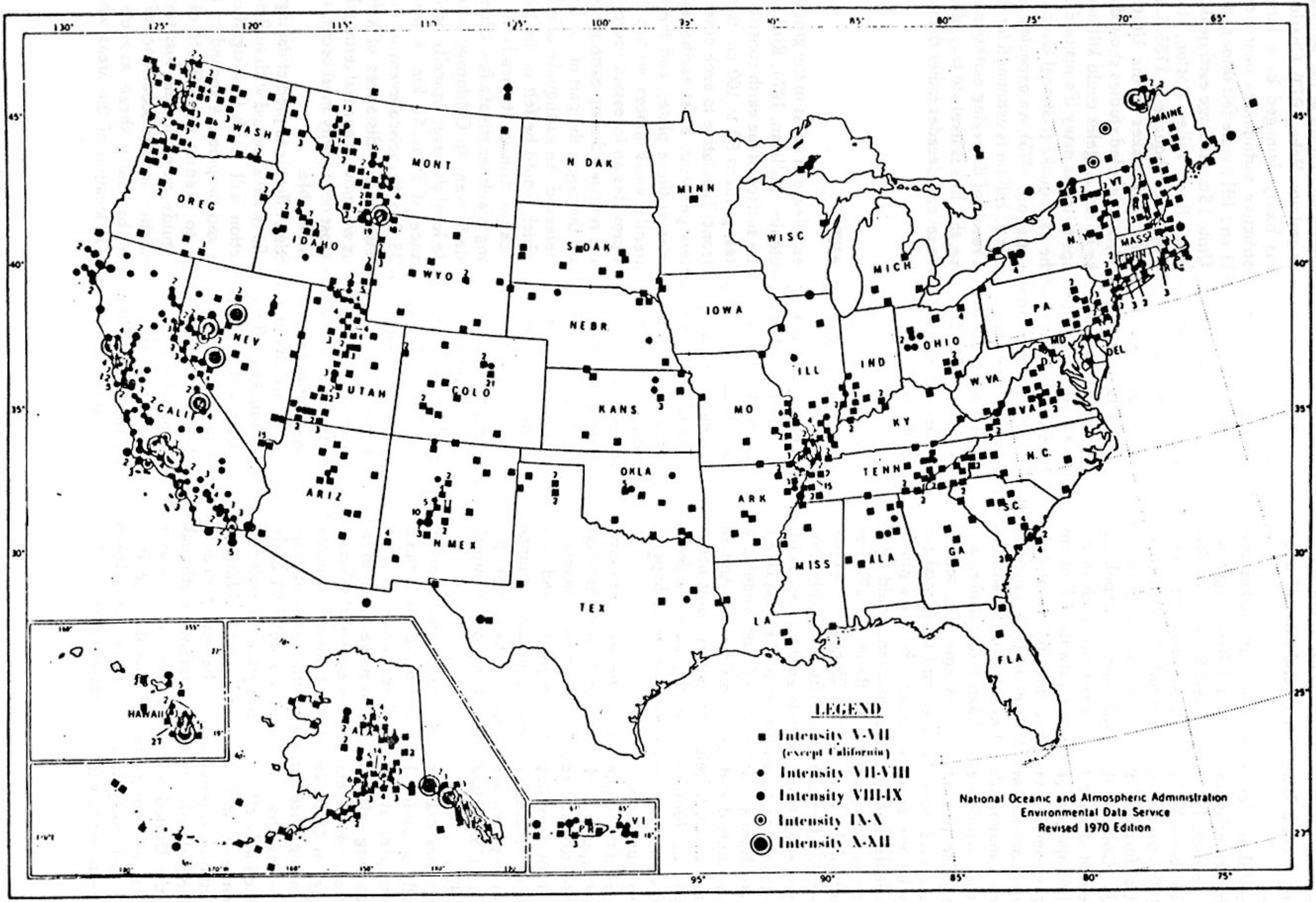

FIGURE 3.1 Historic earthquakes in the United States (1638 through 1970) (Coffman and von Hake, 1973). Earthquakes of intensity V to VII are felt but cause little damage, whereas those of intensity X cause heavy damage to well built buildings, many landslides, and bending of pipes and rails.

655,000 people were unofficially reported killed. Even in the Haicheng case the magnitude was underestimated by a whole unit. Thus preduction methods have not been perfected. Nevertheless, the Chinese have scored at least one resounding success based on several lines of scientific evidence.

Some successful predictions of small earthquakes have been issued by scientists in the United States. Aggarwal *et al.* (1975) predicted a magnitude-2.6 event at Blue Mountain Lake, New York, two days in advance. Whitcomb *et al.* (1974) predicted a magnitude-5.5 earthquake in Yucaipa, California, but it turned out to be much smaller. Healy (Golden, 1975) informally but publicly predicted an event of magnitude 5.2 one day in advance at Hollister, California. Stevenson and Talwani (1976) predicted a magnitude-2.5 event two days before at Lake Jocassee, South Carolina, and Bufe *et al.* (1977) successfully predicted a magnitude-3.2 event to occur within a three-month time window east of San Jose, California.

Thus earthquake prediction is an emerging science with some successes, some failures, and some total surprises. It may be one or a few decades before a proven system is available, but serious predictions could be issued at any time. For example, Castle *et al.* (1976) reported an uplift of the land by 15 to 25 cm over a broad area of southern California. Such uplifts, but of only about 10 cm, have preceded two moderate earthquakes. Is this uplift the precursor to a magnitude-6 or -7 earthquake in the Transverse Ranges just north of Los Angeles or perhaps a magnitude-8 earthquake on the San Andreas Fault northeast of Los Angeles? Or is this uplift not related directly to any future large earthquake? We do not know. Observations have been stepped up in hopes of resolving these questions.

The purposes of this chapter are to summarize the state of the art of earthquake prediction, to examine what might be the responses to that prediction, and, finally, to review some needs in the present prediction program and in research related to utilizing this new technology. A number of other summary papers are available on earthquake prediction (Press, 1975; Rikitaki, 1976; Panel on Earthquake Prediction, 1976).

This report concentrates on earthquake prediction that aims especially at saving lives and moveable property and, for example, at reducing the chances of an earthquake causing a dam or nuclear power plant to fail. Prediction is only one element of an earthquake hazards reduction program. Other key elements involve structural engineering to minimize damage to structures and proper land-use planning that incorporates a detailed understanding of the likely effects of earthquakes at each point within a community. In China, where most buildings fail during an earthquake, prediction has been singled out as the only practical solution to minimizing earthquake hazards. In the United States, however, most wooden frame houses will not suffer serious damage in an earthquake, and many large structures are already adequately designed to withstand earthquakes.

Earthquake hazard is a national problem. Although the most earthquake-prone areas of the United States are along the Pacific Coast, damaging earthquakes have occurred in 39 states, containing 35 percent of the population (Figure 3.1) (Coffman and von Hake, 1973). Charleston, South Carolina, was badly damaged by a large earthquake in 1886. Destructive earthquakes near New Madrid, Missouri, in 1811 and 1912 were felt throughout the Central and Eastern United States. Large earthquakes have struck the St. Lawrence River Valley. Boston, Massachusetts, was damaged by an earthquake in 1755. Life loss to date resulting from earthquakes in the United States totals just over 1630, but detailed studies show that the next major earthquake in Los Angeles could kill over 12,000 people and perhaps twice as many if a major dam were to fail because of the earthquake (National Oceanic and Atmospheric Administration, 1973). An expected average loss per year of about $1 billion is estimated for the entire United States as a result of damaging earthquakes (Wiggins, 1974). Of course, this loss is likely to take place in a few major events over several decades rather than on an annual basis.

3.2 STATE OF THE ART

An earthquake is a sudden release of stress in the ground. The theories of plate tectonics (Sullivan, 1974; Bird and Isacks, 1972) show that the surface of the earth consists of about a dozen large plates, perhaps 50 to 100 km thick, that move primarily horizontally relative to each other at rates of a few centimeters per year. Most earthquakes occur along the boundaries of these plates, and the remainder occur at apparently weak places within the plates. The plate motion provides an incessant source of stress that in most cases is released during earthquakes. The larger the earthquake, the larger the part of the fault over which the stress is released. An earthquake of magnitude 4 in California, which would be felt in the local area and is unlikely to cause damage, typically is associated with rupture along a fault length of a few kilometers or less. A magnitude-6 event in California, which would cause considerable local damage, typically breaks the surface for a distance of 10 to 20 km. A major earthquake like the 1906 San Francisco event of magnitude 8.3 breaks the surface for distances of a few hundred kilometers. Thus we know in general terms what earthquakes are, where most occur, why most occur, and that their occurrence is inevitable.

The goal of the prediction effort is to predict damaging earthquakes sufficiently far in advance and with sufficient accuracy that the prediction will result in a significant reduction in loss of life and property. A secondary but closely related goal is to predict the effects of an earthquake in order to guide rationally the loss-saving actions between the prediction and the occurrence of the earthquake. There are basically three aspects of earthquake prediction: (1) location of the areas where large earthquakes are most likely to occur, (2) observation within these areas of measurable changes (earthquake precursors) and determination of the area and time over which the earthquake will occur, and (3) development of models of the earthquake source in order to interpret the precursors reliably.

LOCATION OF EARTHQUAKE-PRONE REGIONS

Earthquakes tend to recur in the same general area over a long period of time. Thus studies of historic seismic activity (Figure 3.1) provide estimates of where earthquakes are likely to occur and what the magnitude of the largest earthquake in a given region might be. Detailed analyses of such data suggest, for example, that an earthquake of magnitude greater than 6 can be expected each year in Southern California and of the magnitude greater than 8 every hundred years (Allen *et al.*, 1965). Such analyses are useful but must be treated with care especially when data from only a few tens to hundreds of years are available. The Chinese have a remarkable historic record of earthquakes for almost 3000 years, which shows that active regions may become inactive for hundreds of years and that great earthquakes may occur in regions that previously contained only small earthquakes for several centuries (American Seismology Delegation, 1975).

At many boundaries of the large plates that move along the surface of the earth, seismic activity appears to occur in a more systematic way. After an earthquake, thousands of smaller aftershocks occur along the same section of the fault that slipped in the mainshock and thus when located show what part of the fault moved. A compilation of such aftershock zones (Figure 3.2) shows three seismic gaps in Alaska where no large earthquakes had occurred between 1938 and 1971 (Sykes, 1971). The easternmost gap was filled by the 1972 Sitka earthquake. Such gaps around the world (Kelleher *et al.*, 1974) are the regions along island-arc type plate boundaries and large transcurrent faults like the San Andreas, where large earthquakes are most likely to occur in the next few decades.

Since earthquakes result from a sudden release of stress, perhaps the most direct measure of the likelihood of a large earthquake in a given region would be to measure the level of stress or rate of change of stress. A number of techniques are being tried, ranging from building gauges for installation in boreholes, to measuring the residual stress in rocks cored on the surface, to measuring the fluid pressures required to fracture the walls of boreholes at depth. A technique has been developed to infer stress from the properties of seismic waves generated by moderate to large earthquakes in a region of interest (Archambeau, 1976). None of these methods, however, has yet proven fully satisfactory.

EARTHQUAKE PRECURSORS

Most research in earthquake prediction is aimed at measuring a wide variety of physical phenomena that may change prior to earthquakes. Over 200 cases of such precursors have been reported primarily in the Soviet Union, Japan, China, and the United States (Rikitake, 1975). Measurements of earthquake precursors can be grouped into five categories: stress changes, strain changes, effects of strain changes, changes in seismic measurements, and other changes.

Measurements of the levels or changes in stress could potentially be among the most important earthquake precursors, but, as mentioned above, no reliable technique is available even though several are under development.

Measurements of strain changes, however, have been widespread. Uplift and subsidence of areas of thousands of square kilometers by amounts of several centimeters

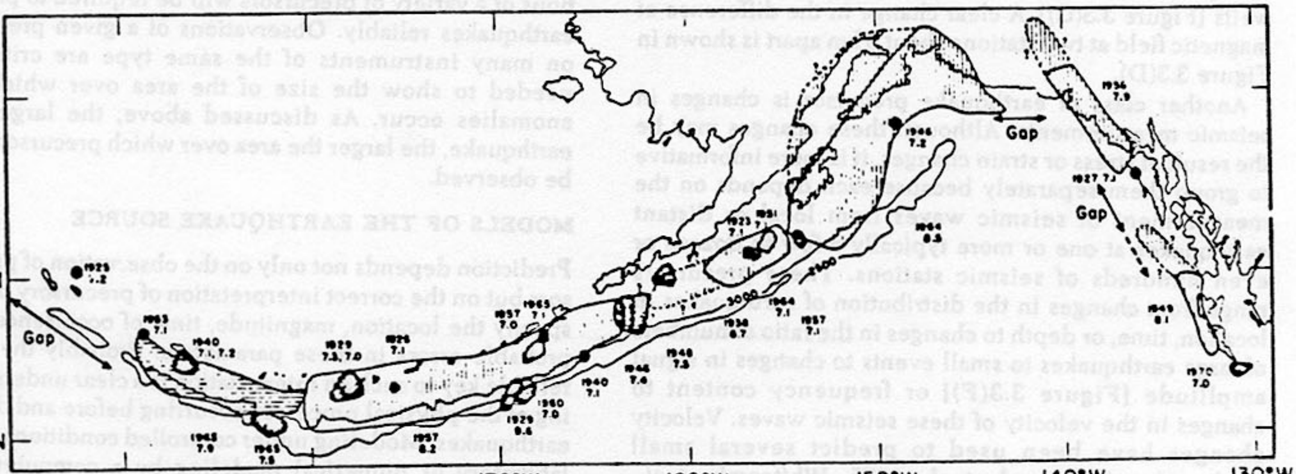

FIGURE 3.2 Aftershock areas of major and great earthquakes in the Aleutians and the northeast Pacific (Sykes, 1971). Dates and magnitudes are indicated. Contours for 2500 fm and 3000 fm are shown in the Aleutian Trench. Question marks denote uncertainties in the size of aftershock zones. Three seismic gaps are identified. The gap in southeastern Alaska was filled by the 1972 Sitka earthquake.

have been detected using standard precise leveling techniques [Figure 3.3(A)]. Such uplifts can be related to mean sea level using tide gauges, and in some cases apparent local changes in sea level have been observed prior to earthquakes. Vertical motion is also detectable using gravimeters sensitive to microgal changes in the force of gravity. Precise triangulation and trilateration techniques allow mapping of horizontal strain changes over survey lines kilometers to tens of kilometers long. New methods being developed using laser ranging to satellites or to the moon or using radio signals from distant quasars offer the possibility of measuring strain changes over distances of hundreds to thousands of kilometers. These techniques, particularly when refined to the ultimately expected precision of a few centimeters, offer a unique chance to measure plate motion and strain within the plates.

Strain can also be measured over distances of meters to a kilometer using strain meters, small trilateration networks, and tiltmeters. Over 70 detectors that measure small tilts of the ground surface have been installed in California. A clear tilt precursor is shown in Figure 3.3(B). Strain in fault zones and aseismic fault slip or creep are measured with creepmeters and alignment arrays.

Strain associated with the tidal pull of the moon or other planets can be measured using microgal gravimeters and strain meters. Many earthquake predictions issued by persons not in the mainstream of scientific research are based on alignment of planets. While it is conceivable that such small forces could trigger earthquakes, there is no clear correlation between these forces and damaging earthquakes.

Many precursory changes have been noted that are believed to result from strain in the region of impending earthquakes. These range from changes in electrical conductivity and generation of electric potentials in the ground to changes in the magnetic field and atmospheric electric fields to changes in the quality or level of groundwater to changes in the emission of various gases in well water or in the soil. One of the most remarkable changes reported so far is that of the content of radon in wells [Figure 3.3(C)]. A clear change in the difference of magnetic field at two stations about 6 km apart is shown in Figure 3.3(D).

Another class of earthquake precursor is changes in seismic measurements. Although these changes may be the result of stress or strain changes, it is more informative to group them separately because each depends on the measurement of seismic waves from local or distant earthquakes at one or more typically a few to dozens or even hundreds of seismic stations. These precursors range from changes in the distribution of earthquakes in location, time, or depth to changes in the ratio of numbers of large earthquakes to small events to changes in signal amplitude [Figure 3.3(F)] or frequency content to changes in the velocity of these seismic waves. Velocity changes have been used to predict several small earthquakes (Aggarwal *et al.*, 1975; Whitcomb *et al.*, 1974; Stevenson and Talwani, 1976), but in many other cases detailed studies have failed to measure precursory velocity changes. In some cases foreshocks have been observed to increase and then decrease prior to large earthquakes [Figure 3.3(E)], but many earthquakes are not preceded by foreshocks.

The fifth type of earthquake precursor is those that do not readily fit into the above four categories. For example, hundreds of reports over many centuries have been made of unusual behavior of animals prior to earthquakes. A detailed summary of these studies (Evernden, 1976) fails to document any totally credible report, but the sum of the reports is too compelling to ignore. There is no clear evidence as to what the animals are detecting, but it is clear that more detailed research on this subject is required.

Other precursors may exist that have not been considered so far. It is important to keep an open mind on any conceivable phenomena that might be observed to change prior to earthquakes.

Rikitake (1975), among others, showed that the time between the onset of a precursory anomaly and the ensuing earthquake is, in most cases, related systematically to the magnitude of the earthquake (Figure 3.4). In the remaining cases the precursors occurred just prior to the event irrespective of magnitude. Thus the first direct evidence of a magnitude-5 earthquake might be noticed months in advance and perhaps decades in advance of a magnitude-8 event. There is a relative lack of short-term precursors, which is a prime reason why observations of abnormal animal behavior are being considered more seriously now.

In summary, the key to specific predictions of earthquakes lies in observing and correctly interpreting precursors. A wide variety of such precursors have been observed and in a few cases used to predict events. Most of these precursors have been observed on only one instrument for a particular earthquake, and many of the signals are close to the noise level for these instruments. No one precursor is known to occur before every type of earthquake. Thus at this time it is assumed that observations of a variety of precursors will be required to predict earthquakes reliably. Observations of a given precursor on many instruments of the same type are critically needed to show the size of the area over which the anomalies occur. As discussed above, the larger the earthquake, the larger the area over which precursors will be observed.

MODELS OF THE EARTHQUAKE SOURCE

Prediction depends not only on the observation of precursors but on the correct interpretation of precursory data to specify the location, magnitude, time of occurrence, and probable errors in these parameters. Probably the most reliable key to such an intepretation is a clear understanding of the physical processes occurring before and during earthquakes. Modeling under controlled conditions in the laboratory or numerical modeling by a computer may yield insight into the processes operating in the earth.

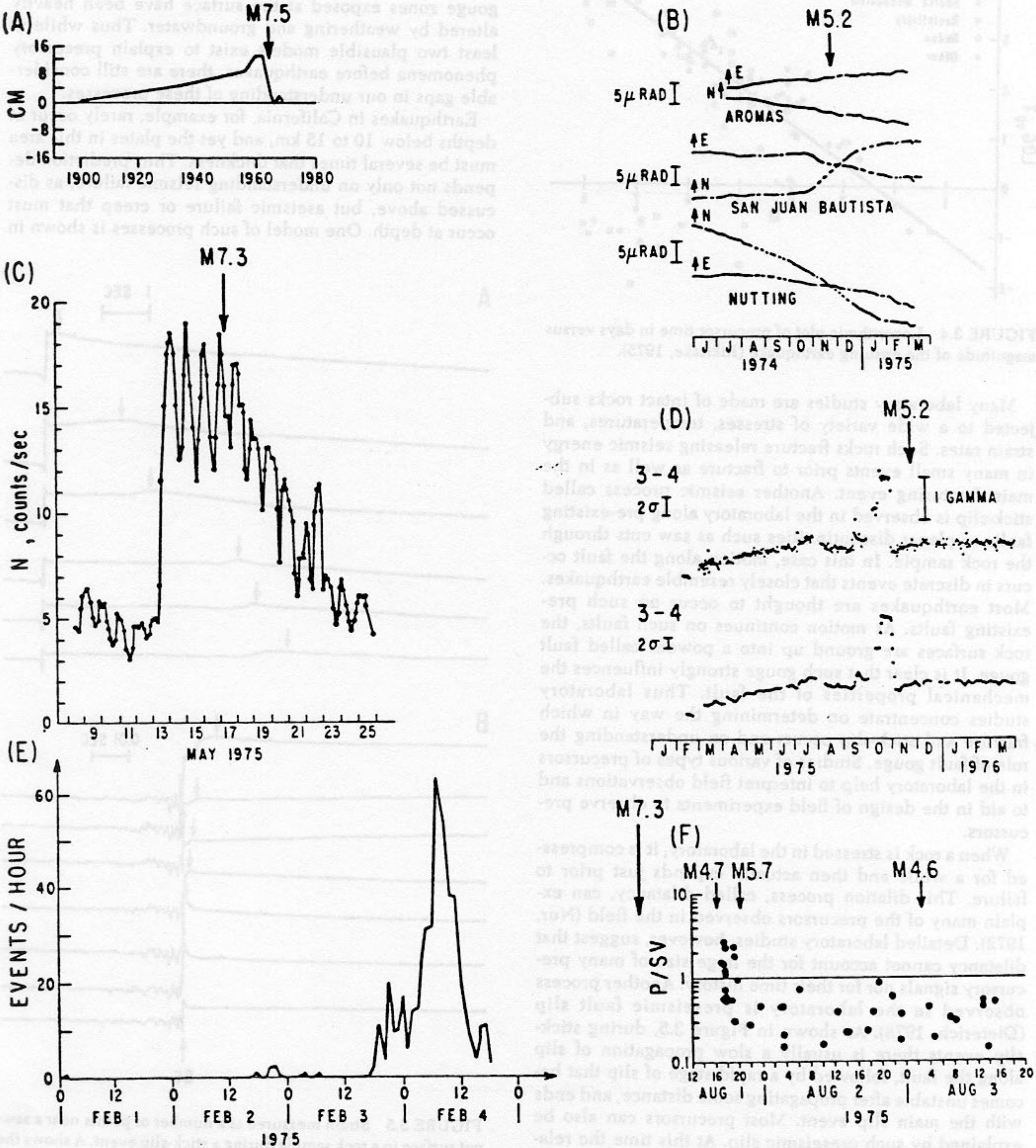

FIGURE 3.3 Examples of precursors: (A) Uplift of a benchmark 30 km east of the epicenter of the 1964 Niigata, Japan, earthquake (Dambura and Okada, 1968). (B) Changes in tilt at three tiltmeters 16 to 10 km from the epicenter of the 1974 Hollister, California, earthquake (Mortensen and Johnston, 1976). (C) Changes in radon content of well water 400 km from the Gasli earthquake, Soviet Union (Sultanxodjaev *et al.*, 1976). (D) Plot of 1-day means (top) and 5-day running means (bottom) of the total magnetic-field difference between two magnetometers 8 and 15 km from the 1974 Hollister, California, earthquake (Smith and Johnston, 1976). (E) Number of foreshocks per hour near the epicenter of the Haicheng, China, earthquake (Haicheng Earthquake Study Delegation, 1977). (F) Ratio of P-wave amplitude to S-wave amplitude for earthquakes in the epicentral region of the Oroville, California, earthquake (Mantis and Lindh, 1976). All foreshocks but one in the 1½ months before the mainshock had amplitude ratios above 1.0, whereas all aftershocks but one had ratios below 1.0. Note the mixture of amplitude ratios in the hours just before the mainshock.

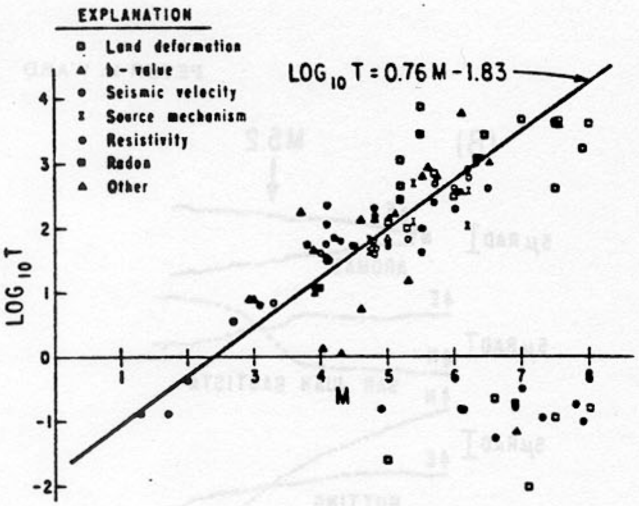

FIGURE 3.4 Logarithmic plot of precursor time in days versus magnitude of the ensuing earthquake (Rikitake, 1975).

Many laboratory studies are made of intact rocks subjected to a wide variety of stresses, temperatures, and strain rates. Such rocks fracture releasing seismic energy in many small events prior to fracture as well as in the main fracturing event. Another seismic process called stick-slip is observed in the laboratory along pre-existing faults or planar discontinuities such as saw cuts through the rock sample. In this case, motion along the fault occurs in discrete events that closely resemble earthquakes. Most earthquakes are thought to occur on such pre-existing faults. As motion continues on such faults, the rock surfaces are ground up into a powder called fault gouge. It is clear that such gouge strongly influences the mechanical properties of the fault. Thus laboratory studies concentrate on determining the way in which fracture and stick-slip occurs and on understanding the role of fault gouge. Studies of various types of precursors in the laboratory help to interpret field observations and to aid in the design of field experiments to observe precursors.

When a rock is stressed in the laboratory, it is compressed for a while and then actually expands just prior to failure. This dilation process, called dilatancy, can explain many of the precursors observed in the field (Nur, 1972). Detailed laboratory studies, however, suggest that dilatancy cannot account for the large size of many precursory signals nor for their time history. Another process observed in the laboratory is preseismic fault slip (Dieterich, 1978). As shown in Figure 3.5, during stick-slip events there is usually a slow propagation of slip along the fault, followed by a rapid stage of slip that becomes unstable after propagating some distance, and ends with the main slip event. Most precursors can also be explained by such preseismic slip. At this time the relative importance of dilatancy and preseismic slip before large earthquakes is unclear.

The role of fault gouge is particularly poorly understood. Along a fault such as the San Andreas in California the gouge zone may be meters to kilometers thick because displacements of a few hundred kilometers have taken place over several millions of years. Yet we are not even sure of the composition of fault gouge because gouge zones exposed at the surface have been heavily altered by weathering and groundwater. Thus while at least two plausible models exist to explain precursory phenomena before earthquakes, there are still considerable gaps in our understanding of these processes.

Earthquakes in California, for example, rarely occur at depths below 10 to 15 km, and yet the plates in this area must be several times that thickness. Thus prediction depends not only on understanding seismic failure, as discussed above, but aseismic failure or creep that must occur at depth. One model of such processes is shown in

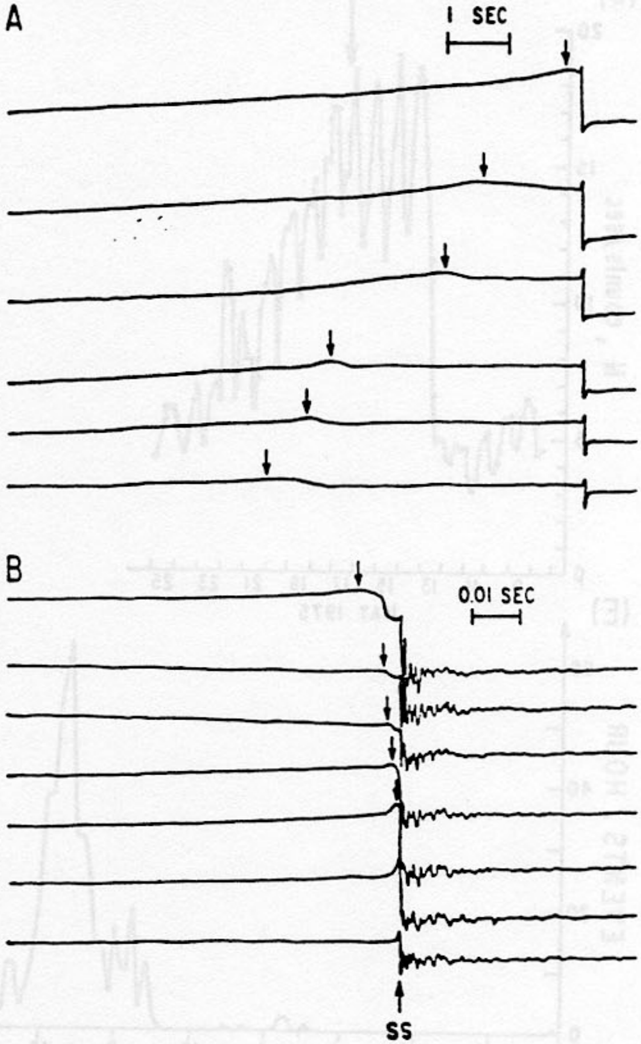

FIGURE 3.5 Strain measured at a number of points near a saw-cut surface in a rock sample during a stick-slip event. A shows the large amounts of slowly propagating preseismic slip that begin at the time shown by the arrows. B is a greatly expanded time scale showing the rapidly propagating preseismic slip just before the stick-slip event (SS) (Dieterich, 1978).

Figure 3.6 (Thatcher, 1976), where changes in the ground surface level prior to the 1971 San Fernando earthquake in Southern California are explained by two discrete events of aseismic slip at depth. During the six years before the earthquake, this slip may have propagated up an extension of the fault and finally ruptured at the surface.

FUTURE RESEARCH

The greatest need to develop a reliable prediction capability is to observe a wide variety of precursors, each on a large number of instruments for many earthquakes of magnitude 5 or greater. Such observations require installation of large networks of instruments in regions where earthquakes are most likely to occur. More techniques are needed to select these areas for detailed study. Progress will be fastest if these regions include a number of seismic gaps and other earthquake-prone regions around the world and if the resources of a number of countries, especially China, the Soviet Union, Japan, and the United States, are mobilized to the task.

Another major need is to determine the physical conditions at the depths where earthquakes occur and the properties of the rocks and fault gouge under these conditions. Such studies are necessary to constrain the numeric models of earthquakes and to apply the laboratory results to earthquakes.

The Chinese have a major national commitment involving over 10,000 workers and 300,000 volunteers. The Japanese have about 400 workers. The U.S. and Soviet programs involve closer to 200 workers each. There is already a close working relationship and exchange of personnel between the United States, Japan, and the Soviet Union. Several delegations of prediction experts have toured China, and a Chinese delegation has visited the United States.

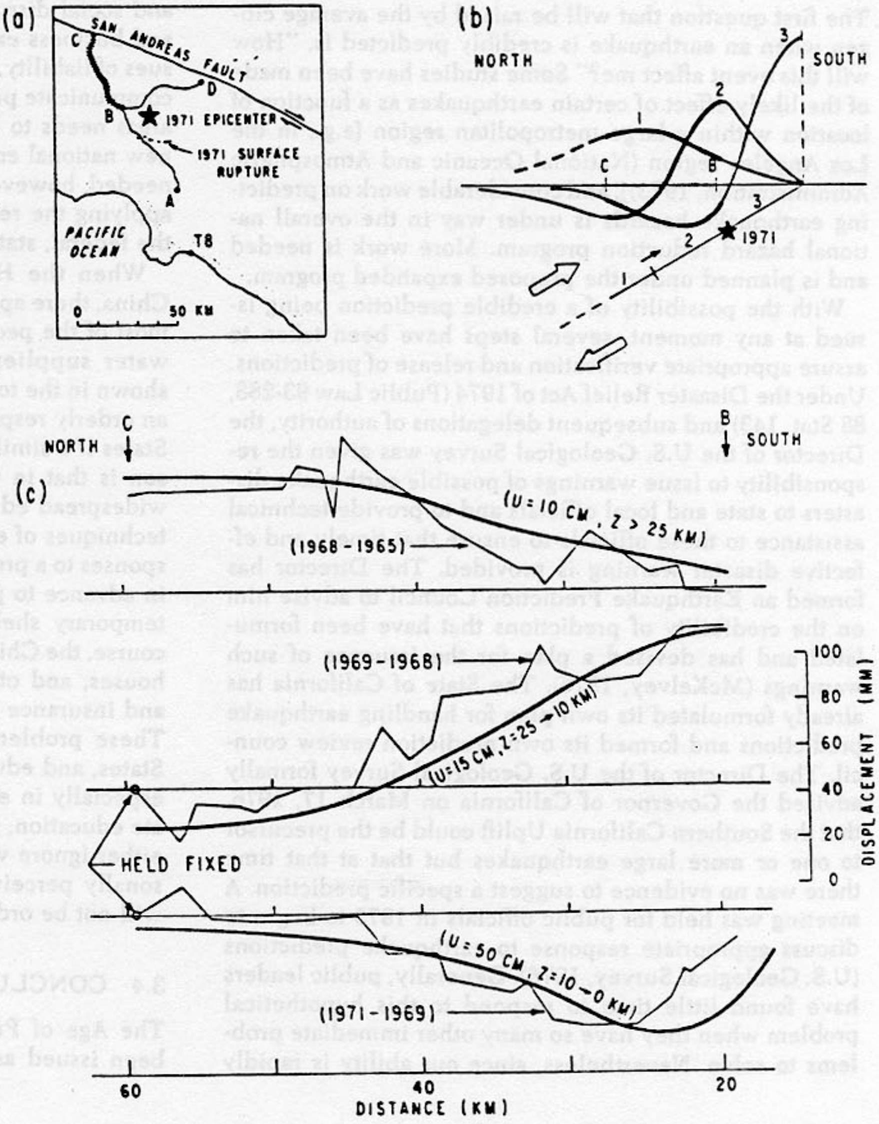

FIGURE 3.6 (a) Location of leveling lines along which localized uplift was observed prior to the 1971 San Fernando earthquake. Shown for reference are the 1971 epicenter and surface rupture and the Tidal 8 benchmark (T8) to which some of this leveling has been tied. (b) Schematic plot showing uplift profiles expected from aseismic slip on successively shallower segments of north-dipping thrust fault lying beneath the section of level line CB and outcropping at the surface trace of the San Fernando fault. The principal effect of this propagating slip is to produce successive sharp reversals in the sense of tilting of the level line CB. (c) Changes in elevation along the north-south leveling route CB for three successive time intervals. Smooth curves show a fit to these data for slippage, *U*, on successively shallower segments of a 30° north-dipping thrust fault. Depth below the surface is Z (Thatcher, 1976).

The U.S. program has been funded for several years primarily through the U.S. Geological Survey at a level of about $5 million. A $2 million increase was made in 1976, specifically to study the Southern California uplift. In 1976, an Advisory Group on Earthquake Prediction and Hazard Mitigation was appointed by the President's Science Advisor. They recommended three options for an expanded program in the U.S. Geological Survey and the National Science Foundation not only for earthquake prediction but for earthquake hazard reduction, engineering, and research on methods to utilize these results. Budget requests for a 2.5-fold increase in the program in 1978 were submitted by the President to the Congress and have been approved. Thus the United States is beginning a major new thrust in earthquake research. It is hoped that significant advances toward a reliable prediction capability can be made within a decade.

3.3 SOCIETAL RESPONSE TO EARTHQUAKE PREDICTIONS

The first question that will be raised by the average citizen when an earthquake is credibly predicted is, "How will this event affect me?" Some studies have been made of the likely effect of certain earthquakes as a function of location within a large metropolitan region [e.g., in the Los Angeles region (National Oceanic and Atmospheric Administration, 1973)], and considerable work on predicting earthquake hazards is under way in the overall national hazard reduction program. More work is needed and is planned under the proposed expanded program.

With the possibility of a credible prediction being issued at any moment, several steps have been taken to assure appropriate verification and release of predictions. Under the Disaster Relief Act of 1974 (Public Law 93-288, 88 Stat. 143) and subsequent delegations of authority, the Director of the U.S. Geological Survey was given the responsibility to issue warnings of possible earthquake disasters to state and local officials and to provide technical assistance to these officials to ensure that timely and effective disaster warning is provided. The Director has formed an Earthquake Prediction Council to advise him on the credibility of predictions that have been formulated and has devised a plan for the issuance of such warnings (McKelvey, 1976). The State of California has already formulated its own plan for handling earthquake predictions and formed its own prediction review council. The Director of the U.S. Geological Survey formally advised the Governor of California on March 17, 1976, that the Southern California Uplift could be the precursor to one or more large earthquakes but that at that time there was no evidence to suggest a specific prediction. A meeting was held for public officials in 1975 to begin to discuss appropriate response to earthquake predictions (U.S. Geological Survey, 1976). Generally, public leaders have found little time to respond to this hypothetical problem when they have so many other immediate problems to solve. Nevertheless, since our ability is rapidly increasing to predict earthquakes, considerably more effort is needed in devising appropriate responses of public officials to these predictions. Some responses will need to be made immediately after a prediction is issued when there will not be much time to think.

The Panel on Public Policy Implications of Earthquake Prediction (1975) issued a detailed report. Among their many recommendations, they emphasized that there were many legal questions that should be cleared up prior to the first credible prediction of a damaging earthquake. A primary question is the liability of a person issuing a prediction, issuing a warning as to how to respond to a prediction, or, for example, requesting or simply allowing his or her employees to report for work at the time of a predicted earthquake. Another key question is what powers federal and local officials will have to expend funds in advance of a credibly predicted disaster.

A detailed socioeconomic study of the likely effects of an earthquake prediction (Haas and Mileti, 1976) shows that the first credible prediction with an extended lead time is likely to cause severe local economic depression and social disruption unless responsible public officials and business executives take decisive steps to clarify issues of liability, insurance, and financial assistance and to communicate properly with the public. Research in these areas needs to be stepped up and is planned under the new national earthquake program. Considerable effort is needed, however, and is only now getting under way for applying the results of this research to policy making at the federal, state, and local levels.

When the Haicheng earthquake was predicted in China, there appears to have been an orderly response by most of the people. Buildings were evacuated, food and water supplies organized, and, for example, movies shown in the town square to keep people occupied. Such an orderly response would not be as likely in the United States if a similar prediction were to be issued. One reason is that in China there has been an aggressive and widespread education campaign on earthquake hazards, techniques of earthquake prediction, and appropriate responses to a prediction. Local officials had been prepared in advance to provide the necessary emergency actions, temporary shelters, medical supplies, and the like. Of course, the Chinese people own their industry, farm land, houses, and other property collectively so that liability and insurance are not problems as in the United States. These problems need to be addressed in the United States, and educational programs need to be intensified, especially in earthquake-prone areas. Without appropriate education, there is a good chance that the public will either ignore valid predictions because they cannot personally perceive the threat or that the public response will not be orderly and constructive.

3.4 CONCLUSIONS

The Age of Prediction is here. Some predictions have been issued as well as some false alarms. It may be a decade or many decades before a proven prediction system is available. Nevertheless, a credible prediction could be issued at any moment, and preparation to respond to such a prediction should begin now. Unlike many scientific methods, earthquake prediction cannot be developed in a laboratory and suddenly unveiled as a proven method. Evidence could be observed at any moment that may save people's lives, and it should not be withheld. Scientists in the field realize that they must provide such evidence with a responsible interpretation immediately to the public. They also realize that there is a finite chance of issuing a false alarm. Furthermore, it is clear that a credible earthquake prediction could, in the worst case, cause more social and economic disruption than the ensuing earthquake. Earthquake prediction is a rapidly advancing area of research and development that offers the possibility to save many lives and significantly reduce economic losses if scientists, civic leaders, policy makers, and all citizens are prepared to respond effectively. The time to prepare is now.

REFERENCES

Aggarwal, Y. P., L. R. Sykes, D. W. Simpson, and P. G. Richards (1975). Spatial and temporal variations in t_s/t_p and in P-wave residuals at Blue Mountain Lake, New York: Application to earthquake prediction, *J. Geophys. Res. 80,* 718.

Allen, C. R., P. St. Amand, C. F. Richter, and J. M. Nordquist (1965). Relationship between seismicity and geologic structure in the southern California region, *Bull. Seismol. Soc. Am.* 55, 753.

American Seismology Delegation (1975). Earthquake research in China, *Trans. Am. Geophys. Union 56,* 838.

Archambeau, C. B. (1976). Earthquake prediction based on tectonic stress determinations, *Trans. Am. Geophys. Union 57,* 290.

Bird, J. M., and B. Isacks (1972). *Plate Tectonics,* selected papers from the *Journal of Geophysical Research,* Am. Geophys. Union, Washington, D.C.

Bufe, C. G., P. W. Harsh, and R. O. Burford (1977). Steady state seismic slip—a precise recurrence model, *Geophys. Lett. 4,* 91.

Castle, R. O., J. P. Church, and M. R. Elliott (1976). Aseismic uplift in southern California, *Science 192,* 251.

Coffman, J. L., and C. A. von Hake (1973). *Earthquake History of the United States,* NOAA Publ. 41-1, 208 pp.

Dambura, T., and A. Okada (1968). Crustal movements before and after the Niigata earthquake, in *General Report on the Niigata Earthquake of 1964,* Tokyo Electrical Engineering College Press, Japan, pp. 129–139.

Dieterich, J. H. (1978). Preseismic fault slip and earthquake prediction, *J. Geophys. Res.*, in press.

Evernden, J. F., ed. (1976). *Abnormal Animal Behavior Prior to Earthquakes,* A conference convened under the National Earthquake Hazards Reduction Program, U.S. Geol. Survey, Menlo Park, Calif., 429 pp. Available from NTIS, Springfield, Va., PB 263-485.

Golden, F. (1975). Forecast: Earthquake, *Time,* Sept. 1, 1975, pp. 36–40.

Haas, J. E., and D. S. Mileti (1976). *Socioeconomic Impact of Earthquake Prediction on Government, Business, and Community,* Inst. of Behavioral Science, U. of Colorado, Boulder, Colo., 40 pp.

Haicheng Earthquake Study Delegation (1977). The prediction of the Haicheng earthquake, *Trans. Am. Geophys. Union 58,* 236.

Kelleher, J., J. Savino, H. Rowlett, and W. McCann (1974). Why and where great thrust earthquakes occur along island arcs, *J. Geophys. Res. 79,* 4889.

Mantis, C., and A. Lindh (1976). The Oroville foreshocks and an apparent coseismic change in fault plane orientation with short term precursor, *Trans. Am. Geophys. Union* 57, 956.

McKelvey, V. E. (1976). *A Federal Plan for the Issuance of Earthquake Predictions and Warnings,* U.S. Geol. Survey Circ. 729, pp. 10–12.

Mortensen, C. E., and M. J. S. Johnston (1976). Anomalous tilt preceding the Hollister earthquake of November 28, 1974, *J. Geophys. Res. 81,* 3561.

National Oceanic and Atmospheric Administration (1973). *A Study of Earthquake Losses in the Los Angeles, California, Area,* 331 pp.

Nur, A. (1972). Dilatancy, pore fluids, and premonitory variations of t_s/t_p travel times, *Bull. Seismol. Soc. Am.* 62, 1217.

Panel on Earthquake Prediction, NRC Committee on Seismology (1976). *Predicting Earthquakes: A Scientific and Technical Evaluation—With Implications for Society,* National Academy of Sciences, Washington, D.C., 62 pp.

Panel on Public Policy Implications of Earthquake Prediction (1975). *Earthquake Prediction and Public Policy,* National Academy of Sciences, Washington, D.C., 142 pp.

Press, F. (1975). Earthquake prediction, *Sci. Am. 232* (5), 14.

Rikitake, T. (1975). Earthquake precursors, *Bull. Seismol. Soc. Am.* 65, 1133.

Rikitake, T. (1976). *Earthquake Prediction,* Elsevier, Amsterdam, Holland, 357 pp.

Smith, B. E., and M. J. S. Johnston (1976). A tectonomagnetic effect observed before a magnitude 5.2 earthquake near Hollister, California, *J. Geophys. Res. 81,* 3556.

Stevenson, D. A., and P. Talwani (1976). Recent seismic activity near Lake Jocassee, Oconee County, South Carolina, preliminary results and a successful earthquake prediction, *Trans. Am. Geophys. Union* 57, 290.

Sullivan, W. (1974). *Continents in Motion: New Earth Debate,* McGraw-Hill, New York, 399 pp.

Sultanxodjaev, A. N., I. G. Chernov, and T. Zakirov (1976). Hydrogeoseismic precursors to the Gasli earthquake, Reports of the Academy of Sciences of Uzbekistan, No. 7, pp. 51–53.

Sykes, L. R. (1971). Aftershock zones of great earthquakes, seismicity and earthquake prediction for Alaska and the Aleutians, *J. Geophys. Res.* 76, 8021.

Thatcher, W. (1976). Episodic strain accumulation in southern California, *Science 194,* 691.

U.S. Geological Survey (1976). *Earthquake Prediction—Opportunity to Avert Disaster,* U.S. Geol. Survey Circ. 729, 35 pp.

Whitcomb, J. H., H. Kanamori, and D. Hadley (1974). Earthquake prediction: Variation of seismic velocities in southern California, *Trans. Am. Geophys. Union* 55, 355.

Wiggins, J. H. (1974). Budgeting justification for earthquake engineering research, a report prepared for the National Science Foundation, J. H. Wiggins Co., Redondo Beach, Calif.