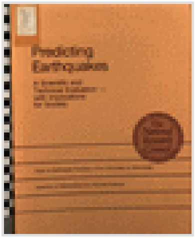

Predicting Earthquakes: A Scientific and Technical Evaluation, With Implications for Society (1976)

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Predicting Earthquakes

A Scientific and Technical Evaluation — with Implications for Society

Panel on Earthquake Prediction
of the
Committee on Seismology

Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. July 1976

NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

In early 1976, more than 23,000 lives were lost in a major earthquake in Guatemala. Fault breakage occurred along a 200-kilometer segment of a major fault that is similar in many ways to the San Andreas Fault of California. Most of the casualties resulted from collapse of non-earthquake-resistant dwellings. A timely warning of the impending earthquake, advising residents to go out-of-doors and remain there until the quake was over, would undoubtedly have saved the lives of most of those killed and prevented tens of thousands of injuries.

The purpose of this report is to evaluate the current state-of-the-art in earthquake prediction and to assess the outlook for the future. Throughout the history of man, earthquake predictions have been the focus of folklore, myth, sorcery, and even charlatanism. It is not unexpected, therefore, that the current interest in prediction as a subject for serious research has been met with considerable scientific and public skepticism. Even today, seismologists disagree about the validity of a number of the claims of successful scientific earthquake predictions, and express widely varying degrees of optimism concerning the outlook for the future. It was in this context that the Committee on Seismology formed the Panel on Earthquake Prediction, to advise government officials, scientists, and citizens in earthquake-threatened regions about our capability in earthquake prediction--insofar as scientific opinion in this field can now be summarized and evaluated. The Panel included scientists of a wide spectrum of viewpoints and prejudices concerning the subject prior to starting their discussion, but it is fair to say that even the most anti-prediction Panel members became more optimistic concerning our earthquake-prediction capabilities during the course of the Panel's deliberations.

The Panel is convinced that a critical technical evaluation of earthquake prediction--solely on the basis of its scientific merit and promise--is a necessary first step. The report presents this scientific and technical evaluation, although problems of justification, funding, and planning cannot be completely separated and are considered briefly herein. Four recommendations are included whose urgency is such that they should not wait for further studies.

Clarence R. Allen, Chairman
Panel on Earthquake Prediction
Committee on Seismology

ACKNOWLEDGMENTS

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During the course of the study the Panel worked in coordination with the Panel on Public Policy Implications of Earthquake Prediction of the National Research Council's Advisory Committee on Emergency Planning.

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SUMMARY

The members of the Panel on Earthquake Prediction have reviewed the major research efforts in earthquake prediction by investigators of all countries. The following statements summarize the Panel's views.

1. Earthquake prediction holds great potential for saving lives, reducing property damage, enhancing the safety of critical facilities, and helping make possible more-rapid restoration of normal living after an earthquake.
2. Anomalous physical phenomena precursory to some earthquakes have been clearly identified.
3. The physical nature of precursory phenomena is complex, and current models to explain them are crude; improvement of these models will require considerable effort in the field and laboratory, as well as in theoretical studies.
4. Some small earthquakes have been predicted in a scientifically credible way, and most researchers are optimistic that we will eventually be successful in predicting larger earthquakes as well.
5. Of about ten types of recognizable phenomena thought to be precursory to earthquakes, some may, in fact, be due to other causes and yield false alarms. Successful routine prediction will probably require the use of several techniques.
6. At present, the ability to detect and locate an impending earthquake requires a dense distribution of instruments in the quake area. Improved observational networks in areas of high earthquake probability are mandatory if we are to gain the fundamental knowledge on which to build an effective earthquake-prediction program.
7. Predictions of earthquakes should specify time, magnitude, place, and probability. However, even a statement that does not specify time or magnitude, or a statement that an earthquake will not occur in a particular place or at a particular time, would be beneficial.
8. Neither the present state-of-the-art nor the present distribution of instrumentation permits socially useful predictions on a routine basis. Therefore, at this time, an expression such as "area of intensive study," as used in Japan (See Appendix B), might reflect more accurately the confidence level of interpretations of the observed phenomena in some areas than would an actual prediction.

9. A scientific prediction will probably be made within the next five years for an earthquake of magnitude 5 or greater in California. With appropriate commitment, the routine announcement of reliable predictions may be possible within 10 years in well instrumented areas, although large earthquakes may present a particularly difficult problem. The apparent public impression that routine prediction of earthquakes is imminent is not warranted by the present level of scientific understanding.

10. Until formal procedures for issuing predictions have been established, predictions made by responsible scientists should be accompanied by sufficient backup data for full evaluation by the scientific community.

11. During the development of an earthquake-prediction-and-warning capability, there will be unavoidable errors and false alarms. The public must be made aware of this prospect, and the development of any procedure to issue warnings must accommodate it. Even the ultimate system probably will not be infallible.

12. The rate of development of a reliable earthquake-prediction capability operating on a routine basis will depend to a large extent on the amount, rate, and deployment of funding. Progress in improving the state-of-the-art in the early growth period will be particularly sensitive to the level of support. The Panel believes that an effective program will require a 10-year commitment of effort, and that a large increase to several times the current annual Federal expenditures would be cost effective and would be in the national interest.

13. The scientific and technical aspects of earthquake prediction have advanced to the point at which the development of systems for associated societal response should be addressed promptly in a formal manner. A prediction capability will be of little value if societal response procedures are not formulated concurrently.

14. In a realistic attack on the earthquake-hazard problem, the development of an earthquake-prediction program and the upgrading of earthquake-engineering design and construction are complementary and equally necessary, and should be carried on at the same time.

RECOMMENDATIONS

The primary purpose of this report, as stated in the Preface, is to review the state-of-the-art and the future outlook of earthquake prediction. The Panel had no initial intention to make specific recommendations, and in particular to make recommendations with respect to funding. When the study was completed, however, it was apparent to the Panel that four areas are of sufficient urgency that such recommendations are needed now and should be acted on without delay. They are:

1. *The United States should now make a national commitment to a long-term program aimed at developing a reliable and effective operational earthquake-prediction capability.*

Based on an assessment of worldwide observations and findings over the past few years it is the Panel's unanimous opinion that the development of an effective earthquake-prediction capability is an achievable goal. In recent years, several isolated earthquakes have been successfully predicted by scientific criteria. These results and other studies indicate that with appropriate commitment and level of effort, the routine announcement of reliable predictions may be possible within 10 years in well-instrumented areas, although very large earthquakes may present a particularly difficult problem. A truly effective national program will require a significant increase to several times the current annual expenditures for prediction research. If the 10-year research effort is successful, subsequent implementation of the resulting earthquake-prediction capability, for all seismic areas of the United States and on a continuing basis, will require a comparable national commitment.

2. *A representative group of competent scientists should be formed now to advise the federal government at the highest levels on the progress and needs of its earthquake-prediction program.*

United States research in earthquake prediction now looks so promising, and its social consequences are potentially so profound, that an advisory unit should be established to provide advice about the progress and needs of the effort to the highest levels in the federal government, preferably directly to the Executive Office of the President, i.e., to the Director of the Office of Science and Technology Policy. Such a group, made up of non-governmental scientists, would report periodically on the status of the total U.S. earthquake-prediction effort, identify gaps and overlaps in the national research program, advise on the establishment of an earthquake-warning procedure, and maintain a broad overview of the program's needs and funding.

3. *A formal procedure should now be established for evaluation of earthquake predictions and for advising relevant agencies and groups concerning their validity.*

Predictions are now being put forth by various groups--formally or informally--and responsible public officials and agencies are becoming concerned as to how to evaluate these predictions and react to them. The Panel believes that the time has come for a formal body to be created to evaluate all such earthquake predictions. The purpose of such a body should not be to censor or restrict individuals and organizations in the making of responsible predictions, or to make predictions itself, but to serve as the filter between those who issue predictions and those who are obliged to react to them. Such a procedure would encourage responsibility among prediction makers since all predictions would be subject to thorough and systematic scrutiny by their scientific colleagues. In view of the tremendous responsibilities of such a body and the potentially profound impact of its judgments, it should be broadly representative of the seismological community. Representatives of concerned public agencies should be encouraged to attend its meetings as observers. An evaluation group of this type, made up of scientists from a variety of institutions and agencies, has already been established in the State of California.

4. *Research, planning, and development both of an integrated operational prediction capability and of an effective social-response capability should be carried out concurrently and in coordination.*

Consideration of social-response problems should be given priority comparable to that of developing prediction technology. If this is not done, we may learn how to predict earthquakes before we know what to do with the predictions when we get them. To avoid this unacceptable circumstance, we must mount a research and planning effort of major scope, closely integrated with the scientific and technical development of prediction capability. The effort must be problem-oriented and highly interdisciplinary: many issues require the attention of sociologists, social psychologists, lawyers, political scientists, organization theorists, experts on command and control, and experts from other disciplines. In the final operational earthquake-warning-and-response system, an authoritative scientific and technical prediction capability and an effective social response capability will be equally important.

INTRODUCTION

Great excitement currently exists among seismologists over major achievements in our efforts to predict earthquakes. Various physical phenomena precursory to earthquakes have been reported by careful observers for many centuries. In the past, seismologists tended to discount most of these reports, but measurable physical precursors are now coming under intense scientific scrutiny, and many appear to be valid and significant. Indeed, several scientific predictions have already been successful, although those that we have been able to fully evaluate are all for small earthquakes. Few seismologists now doubt that physical precursors to earthquakes do in fact exist. But are they sufficiently consistent and uniform to permit development of a routine and reliable prediction system? And will techniques useful for predicting small earthquakes also work for large earthquakes--the only ones of real social importance?

If our capability to predict earthquakes does become a major scientific reality, it will be the second large advance in the earth sciences in the last decade. The first has been the concept of plate tectonics, which developed explosively over about the past 15 years and was generally accepted by the late 1960's. In many ways, this concept was a major stimulus to the work on prediction.

Small earthquakes have been successfully predicted by reputable investigators in the United States, Japan, and the Soviet Union, and several large, damaging earthquakes may already have been successfully predicted in the People's Republic of China. In each of these areas, many failures and false alarms have also occurred. There is not at present a sufficient scientific basis for issuing, with a high degree of confidence, an authoritative prediction that will affect large urban areas. When this will be possible depends to a large extent on the support and effort devoted to this problem. In any case, the time is at hand to alert public officials, government agencies, and the public to the fact that a truly useful prediction capability is a real possibility within the foreseeable future. The basic and applied research done in this field now and in the future must be bold yet tempered with wisdom, to assure that society can benefit at the earliest time while avoiding premature overreaction.

The benefits to society from accurate earthquake prediction will be substantial in the saving of lives and of property. It has been estimated that knowledge of an impending great earthquake, a year or more in advance, could result in a large reduction in losses. The savings would result from measures taken to strengthen buildings and their contents, reduce the fire hazard, increase dam safety, enhance nuclear power-plant safety, and the like. For still-shorter-term predictions (e.g., one week), substantial savings of lives would result from temporary measures such as the evacuation of dangerous buildings and the mobilization of emergency forces.

Permanent measures to reduce earthquake hazards, such as better engineering design, improved land-use planning, and upgraded building codes and construction practices, will continue to be needed even though earthquake predictions may eventually become completely reliable. There are serious uncertainties concerning community response to a prediction and concerning the impact of an incorrect prediction. These are currently under study by other groups.

This report by the Panel on Earthquake Prediction of the Committee on Seismology presents a brief résumé of the scientific bases for earthquake prediction, a summary of current status, and a statement of outlook. Appendixes A and B review in some detail the background and progress of prediction studies in the United States, the Soviet Union, Japan, and the People's Republic of China.

WHAT CONSTITUTES AN EARTHQUAKE PREDICTION?

An earthquake prediction must specify the expected magnitude range, the geographical area within which it will occur, and the time interval within which it will happen with sufficient precision so that the ultimate success or failure of the prediction can readily be judged. Only by careful recording and analysis of failures as well as successes can the eventual success of the total effort be evaluated and future directions charted. Moreover, scientists should also assign a confidence level to each prediction; it is clear that--particularly in the early stages of the effort--some predictions will merit considerably greater assurance than others, but even low-confidence predictions should be considered and evaluated. A prediction of locality without specification of time, while valuable in itself, and constituting the principal basis of present-day seismic zoning maps, is not an acceptable prediction in the sense that the word is used in this report.

It is clear that the time uncertainty for some predictions will necessarily be much greater than for others. Very broad time predictions (e.g., "within 25 years") can have significant value in encouraging permanent social responses such as the development of realistic building codes, land-use planning, and long-term disaster preparation. Nevertheless, we recognize that the word "prediction" is more commonly interpreted--particularly by the public--to imply a much smaller time uncertainty. The expression "short-term prediction" as used here means an earthquake prediction that has a sufficiently precise time estimate, close enough to the time at which the prediction is made, so that only temporary or transient, but nevertheless very significant, social responses are possible--such as the alerting of emergency forces, possibly emergency strengthening of certain special structures, and the evacuation of questionable structures or areas.

Even in the absence of evidence adequate to permit a low-confidence prediction, unexplained geophysical anomalies in a given area may still be of sufficient concern to cause it to be designated an "area of intensive study." This designation has been used in Japan to avoid undue public alarm in situations where no realistic prediction is possible in spite of recognized anomalies that are possible precursors to earthquakes and that clearly warrant accelerated investigation.

Any capability for reliable prediction, no matter how long the time scale, is more useful than none at all. For the highly seismic State of

California, we can now say only that certain densely populated areas will almost certainly experience a great earthquake at some time within the next 100-200 years. Although effort and money are now being expended to design structures so as to avoid collapse during such an earthquake, a great deal is being left undone because of the lack of a sense of urgency that a more precise short-term prediction might induce. For example, many structures in metropolitan areas of high population density and high seismicity will surely fail in a great earthquake, but because of the lack of precision in our estimates of the time of their occurrence it is unlikely that much will be done to avoid such disasters. A reliable prediction that a great earthquake will occur at a given place and time would alert utility companies to possible difficulties and induce community leaders to take actions that would minimize loss of life and property damage.

METHODS OF ATTEMPTING PREDICTION

Two methods of study are being used by scientists in their efforts to predict earthquakes--statistical methods and geophysical methods. The first uses the catalogued history of earthquakes in a region as a key to estimating when and where such future events may occur. The second involves the observation and interpretation of certain changes in the physical environment in earthquake-prone regions as indicators of an impending event.

STATISTICAL METHODS

The occurrence of earthquakes, especially those that have caused casualties or damage, has been documented throughout historical time. In China, earthquake catalogues span several thousand years. In California, statistically useful catalogues span only a few decades. The quality of statistical analyses of catalogued earthquakes improves with the acquisition of more information. Unfortunately, the number of recorded earthquakes is insufficient to allow statistical evaluations for small areas and small times periods.

A number of earthquakes sufficiently large for statistical inference may be tabulated for a large area over a short time interval or for a small area over a long interval, but seldom are data available in adequate numbers for a small area over a short time interval. For example, the worldwide locations of earthquakes for only a short interval of time (Figure 1) yields considerable information about the non-uniform distribution throughout the world of the regions in which earthquakes are likely to occur. About 140 earthquakes of magnitude 6 or greater occur in many parts of the world each year. Statistically, the map (Figure 1) can tell us that a large earthquake is likely to occur during a relatively short time interval somewhere within a number of known areas totaling between 1 and 10 percent of the earth's surface. Such a statistical statement is obviously unsatisfactory as an indicator or predictor of a specific hazard.

Similarly, from a catalogue spanning several decades or longer, for a specific seismically active region measuring a few hundred kilometers on a side, it is possible to estimate the likelihood of occurrence of a large earthquake. However, such a likelihood statement, or "generalized

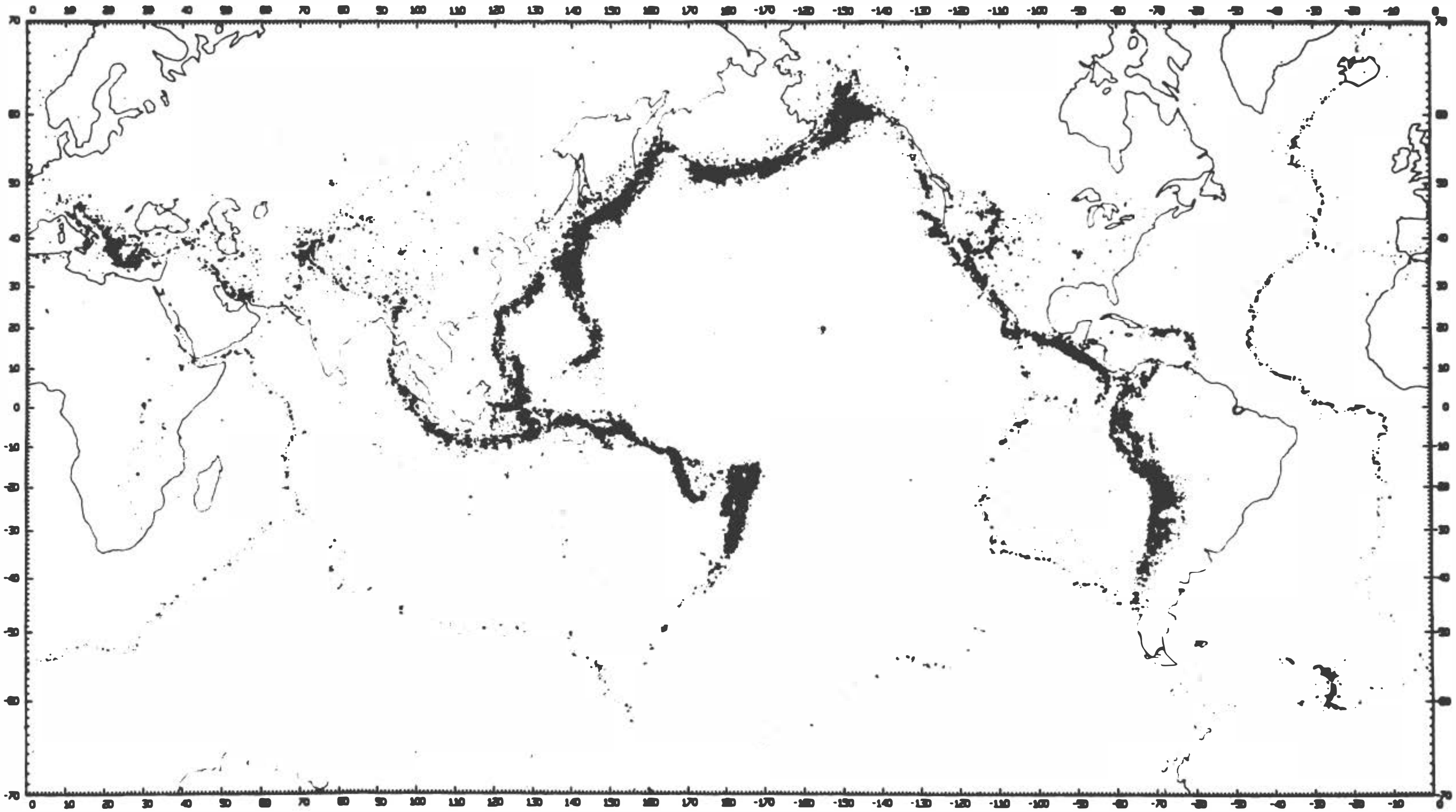

Figure 1. Seismicity of the Earth, 1961-1967, ESSA, CGS Epicenters (From M. Barazangi and J. Dorman, *Bulletin of the Seismological Society of America*, Vol. 59, No. 1.)

prediction," is usually inadequate to permit taking specific preparatory measures in advance of any hazard. In Southern California, for example, about 5 earthquakes of magnitude 6 or greater occur in 20 years, but without more precise information no immediate preparatory action has been possible.

It is possible to provide information about probabilities of occurrence of large events in selected restricted intervals of both space and time (e.g., in a given area during a 5-year period). Unfortunately, these probabilities are so low that such estimates cannot permit preparations for specific events. Whether the rates of occurrence of earthquakes in a specific location and time period are high or low, such estimates can only give information about likelihoods of occurrence or risk. As the space-time windows are narrowed, the reliability of statistical risk assessments becomes poorer.

But statistical risk statements have value. They can be used as input in developing criteria for the design of earthquake-resistant structures and to other measures for reducing the damaging effects of earthquakes, in planning for remedial action following earthquakes, and in the development of a strategy of deployment of often scarce instrumental resources for use in more-direct prediction studies. As noted in the previous section, however, such generalized probability statements are a far cry from the short-term predictions that are visualized by most people as the primary objective of the present research effort.

The simplest analysis of the occurrence of earthquakes in a specified interval of time and space usually leads to the recognition that earthquakes are occasionally clustered; that is, they are not randomly distributed throughout this space-time interval. For example, in a region as small as Southern California, both the space and time sequences for earthquakes can be shown to be significantly non-random. One reason for space non-randomness is that earthquakes tend to be concentrated on specific earthquake faults. Much of the time, non-randomness is due to aftershocks that are known to be clustered in a short time interval following the parent event. When aftershocks are removed from the Southern California catalogue so that only a residual catalogue of large events remains (i.e., aftershock-producing events), the residue is random. A statistical result that yields randomness is discouraging for the identification of specific space or time intervals in which to concentrate scientific effort.

In another example, the map of world-wide earthquake epicenters shows that earthquakes are not spread out randomly over the surface of the earth but instead are concentrated in specific regions. This fact has contributed to the construction of the plate-tectonics model of the motions of the surface of the earth. The earth's surface is divided into a relatively small number of rigid plates, each of large areal extent. These plates are in motion relative to each other, probably driven by large-scale processes in the earth's interior. When the plates come into contact, the effect of "friction" at the edges results in earthquakes. Thus, the locations of earthquakes shown in Figure 1 delineate the edges of the plates.

An effort is now being made to identify clustering or anti-clustering, i.e., the presence of a concentration of events or a scarcity of events, in space and time. This effort uses generalizations drawn from fundamental geophysical processes to modify the statistical analysis. Efforts to discern such clustering include the following:

1. Studies of seismicity "gaps" along plate margins. These are regions where no earthquakes have taken place in recent times, although there is relative motion of adjacent blocks. These temporarily quiescent regions are likely zones for future large events. Parts of the San Andreas fault zone in California currently display the seismic-gap phenomenon.
2. Studies of migrations of epicenters along and near plate margins, both on the scale of thousands of kilometers associated with plate margins and of hundreds of kilometers associated with smaller, extensively faulted regions. It is known that one earthquake can trigger another; aftershocks are clear evidence of this. After a large earthquake, there is a redistribution of the stress field both in the short-distance range, causing aftershocks, and to a smaller extent at long distances. The altered stress field might cause a distant region to reach criticality earlier than it would if it were isolated from neighboring earthquake zones.
3. Studies of triggering of earthquakes by non-seismic effects. Many attempts have been made to correlate earthquakes with obvious astronomical effects such as time of day, and season of the year. These have been unsuccessful. Attempts are continuing to seek associations of earthquakes with more-subtle geophysical phenomena that can "prestress" (or add stress to) a seismic zone that is already near the critical state. One phenomenon being investigated as a possible triggering stress is the periodic tide in the solid earth.

It is unlikely that the extension of earthquake catalogues in time would result in a large improvement in the precision of statistical analysis, since such extensions usually involve only a small number of years of data. One exception to this is the possibility that the dates of large earthquakes of the distant past can be obtained by historical methods, including archaeology. Here, analysis of records from those few places where long-term historical catalogues are available, e.g., China, Japan, and the Middle East, may be of value. But, in general, in order to make up for the lack of comprehensive long-term historical records in the United States and in other parts of the world, we must improve statistical analysis by taking geophysical models into account.

GEOPHYSICAL METHODS

Geophysical methods involve searching for, identifying, and monitoring changes in the physical state of the earth that are precursory to earthquakes. Unlike statistical methods, these observations and interpretations have the ultimate capability of leading to prediction of magnitude, time, and place of individual events. The statistical methods, at present, are being applied almost independently of the physical state of the earthquake environment; the geophysical methods, conversely, are concerned in the main with the detailed short-term physical state of matter and at present have little relationship to the long-range statistical evidence of earthquake occurrence.

Current interest in the observation of precursory phenomena was sparked by contacts between American and Soviet scientists in 1971 during the quadrennial Assembly of the International Union of Geodesy and Geophysics. Soviet seismologists, after 25 years of intensive observations in the Garm region of Tadjikistan, reported a 10 percent decrease in the ratio of the velocity of compressional waves relative to that of shear waves (V_p/V_s) for some time period prior to earthquakes of moderate size, in comparison with the normal value of this ratio. The impending earthquake was signaled by a return of the V_p/V_s ratio to a normal value immediately before the earthquake. The duration of these precursory anomalous seismic-velocity ratios appeared to be longer for larger earthquakes. Subsequently, it has been found that the duration of the anomaly may be a few days for a magnitude-3 earthquake and, by extrapolation, 40 years or more for a magnitude-8 earthquake. The Soviet scientists also observed other precursory phenomena.

Spanning an even longer period, Japanese scientists observed that significant changes in elevation of the ground surface preceded some large earthquakes. Most notable among these observations were precursory elevation changes associated with the Niigata earthquake of 1964. Historical accounts tell of significant changes in elevation associated with other huge historical earthquakes.

Stimulated by these and other reports of precursory anomalies in grophysical measurements, an effort was mounted in the United States to seek such anomalies in this country as well. Changes in the ratio of velocities of seismic waves were reported prior to earthquakes in the Blue Mountain Lake area of New York; these changes had many of the characteristics of the Soviet observations. By reviewing seismic records for the period preceding the San Fernando earthquake of February 1971, it was later found that this earthquake was preceded by similar anomalous seismic velocity ratios. Since then, anomalous changes in tilt directions, variations in radon concentration in ground water, variations in compressional velocity, anomalous magnetic fields, anomalous electrical resistivity, the relative abundances of large and small earthquakes, and the overall level of seismic activity have all been proposed, and on occasion used, either to forecast or "hindcast" earthquakes. Only infrequently have anomalies observed by several methods shown precursory indications of the same earthquake. This is partly because of an inability to focus all the different types of experiments on the same area.

Part of the problem of studying these phenomena is the relatively short time-baseline for the accumulation of the needed data. This has led to false alarms--that is, anomalies corresponding to no subsequent earthquakes. It has also led to failure to predict, since some events have occurred without evident precursory anomalies.

In the discussion above, the geophysical methods have been presented as phenomenological in character. Models for the change in physical state of the material in the vicinity of an earthquake focus have been proposed that are capable of accounting for the observed precursory anomalies. Such models take advantage of the anomalous behavior of materials as they approach the critical fracture condition. Investigators in the United States have proposed that the observed changes in the velocity ratio can best be explained by the phenomenon of rock dilatancy. In this model, the velocity ratio decreases initially because of the growth of cracks and the related increase in volume of the rock mass near the focal region as stresses build up prior to the earthquake. This phase is followed by one in which the velocities return to normal prior to failure. Two hypotheses have been proposed to explain the velocity recovery. In one, water flows into the cracked region immediately preceding the earthquake, causing the velocity ratio to return to normal; the increase in water pressure also serves to weaken the rock. This hypothesis has been termed the dilatancy/diffusion model. In the other hypothesis, most of the cracks close up in the dilated region prior to fracture because of the growth of certain naturally selected cracks. These closures increase the velocities and also increase the pressure of the water in the pore spaces in the rock. This has been termed the dilatancy/crack-closure, or dilatancy/instability, model. Further experimental and theoretical work must be done to resolve the differences between the two models or to develop a more definitive model that might, when much more is known, even be different from those discussed above. In any case, it is likely that the focal region is highly complex, studded with anisotropy and non-linear rheology and with complex electrical and mechanical properties.

It has been proposed that these dilatancy models can explain the wide variety of observed precursory phenomena, including changes in seismic velocity and electrical resistivity, land uplift and tilt, fluid flow, rate of radon emanation, frequency of occurrence of small earthquakes, and the relative abundance of large and small earthquakes.

As yet, only the roughest of linkages exist between the models of precursory phenomena and observations of them in the field. Furthermore, no satisfactory models yet exist for determining the extent to which a given fault will tear, once rupture has been initiated, and hence for estimating the probable magnitude of an earthquake. However, the empirical data suggest that the magnitude of an earthquake may be predetermined by the extent of the physically anomalous zone and the duration of the anomalous episode.

CURRENT CAPABILITY FOR EARTHQUAKE PREDICTION IN THE UNITED STATES

This section discusses the present U.S. capability for earthquake prediction in terms of recent developments, observational capability, and laboratory and theoretical studies, including the fracture process and the state of development of physical models to explain the precursory observations. Also discussed are critical weaknesses of the program.

HISTORY OF THE U.S. PREDICTION EFFORT

During the early 1960's, a large percentage of the seismological research in the United States (exclusive of that related to seismic prospecting for petroleum) was part of the Nuclear Test Detection Program of the Advanced Research Projects Agency of the Department of Defense. The Nuclear Test Detection Program in many ways converted seismology into a modern observational science, using arrays of seismic detectors, digital processing of data, and the application of information theory in signal processing. In its early stages, the Test Detection Program concentrated mainly on radical improvement of basic research in seismology and on the modernization of seismic instruments on a worldwide scale. In the early 1960's, the Worldwide Network of Standard Seismographs, consisting of about 125 stations recording short- and long-period information, was installed. The worldwide nature of the network, the availability of microfilm records, and the sensitivity of the instruments used revolutionized the experimental side of seismological research.

In 1965, following the great Alaskan earthquake of March 27, 1964, an ad hoc panel of eminent scientists, appointed at the request of the President of the United States, drew up a 10-year plan for a major U.S. program in earthquake prediction. Both the U.S. Geological Survey and the U.S. Coast and Geodetic Survey began small-scale efforts in research on the subject in the following year, and interest rose among university scientists, who were supported mainly by the National Science Foundation. No major federal effort was mounted for earthquake prediction, however, until 1973, when funds for this purpose were added to the U.S. Geological Survey's budget and the seismological research effort of the National Oceanic and Atmospheric Administration of the Department of Commerce was transferred to the Geological Survey in the Department of the

Interior. By 1973, because of these efforts and because of the promising results of the observations by scientists in Japan and the USSR, seismological researchers in the U.S. began to turn their attention to earthquake prediction.

The U.S.-USSR Working Groups in Earthquake Prediction have established a relatively small but quite vigorous program of joint field, laboratory, analytical and theoretical studies in earthquake prediction and related fields. This program was established under the aegis of the 1972 Agreement between the U.S. and USSR on Cooperation in the Field of Environmental Protection. The work has been organized into four areas: (1) field investigations of earthquake prediction; (2) laboratory and theoretical investigations of the earthquake source; (3) mathematical and computational prediction of places where large earthquakes occur and evaluation of seismic risk; and (4) engineering-seismological investigations. Successful projects to date include the establishment of a joint seismograph network near Garm, Tadzhik SSR, to search for seismic forerunners to larger earthquakes; the establishment of a joint seismograph network around the Nurek Reservoir, Tadzhik SSR, to study reservoir-induced seismicity; the study of the spectral content of earthquakes using the Soviet "frequency-selecting" seismograph system and American broad-band, digitally recording equipment; collaborative laboratory studies of the effects precursory to failure and sliding in rock samples; the application of pattern-recognition techniques to the prediction of earthquakes; the establishment of a joint strong-motion network in the Tadzhik SSR; and the collaborative instrumentation and testing of buildings subjected to earthquake-like motions simulated by explosions.

Exchange of information with Japan is facilitated by joint Japanese-U.S. symposia on earthquake prediction, supported by the National Science Foundation. Four meetings have been held, in Japan (1964) and in the U.S. (1966, 1968, and 1973), under the auspices of the U.S.-Japan Cooperative Science Program.

In 1973, the RANN Division of the National Science Foundation became a major source of support for engineering seismology and for research into public policy issues related to earthquake prediction. The U.S. Nuclear Regulatory Commission is now supporting seismological research concerned with seismic hazards to nuclear power plants and the seismological criteria for siting nuclear power plants. The National Aeronautics and Space Administration has started a long-range program aimed at adapting technology from the space program to possible future uses for earthquake prediction and hazard reduction.

The responsibility for issuing earthquake predictions and other assistance measures specified in the *Disaster Relief Act of 1974* was assigned to the U.S. Geological Survey in 1975.

OBSERVATIONAL CAPABILITY

The success of earthquake prediction depends on appropriate field observations more than on any other factor.

Instrumentation

Most instrumentation likely to be useful in field monitoring has been developed or is in an advanced stage of development. Improvements in accuracy and stability, fieldworthiness, and installation techniques are needed for certain devices. In particular, strainmeters, geochemical monitoring instrumentation, and 3 wave-length electro-optical ranging devices, among others, still require some development. New instruments that yield great improvement in resolution have also been proposed and may ultimately prove useful, especially if they can be installed at adequate depth to remove environmental noise effects. At present, however, most development has been completed or is near completion, and rapid deployment of a wide variety of sensors is possible. Considerable improvement in resolution still seems likely in geodetic systems based on satellite and extra-terrestrial positioning systems.

Seismic Stations

Most of the field-monitoring effort at present is concentrated in California. About 300 seismic stations have been installed, and about half of them are involved in experiments related directly to prediction of earthquakes. The remainder can be used indirectly for earthquake prediction since their function is to locate small earthquakes. The time distributions of earthquakes, e.g., foreshocks, may be useful in earthquake prediction. Improvement in evaluation of real-time seismic data from these networks is needed.

About 120 other instruments have been installed in California for the continuous monitoring of strain, tilt, and fault creep, many in the past year. Because the instruments are too sparsely distributed, no clear precursory signals have been detected by more than one or two instruments for any earthquake. The present networks can be expected to record an earthquake of magnitude 5 or greater, in a densely instrumented area, every 3 to 4 years.

A smaller number of similar instruments have been installed in Alaska, Nevada, Utah, Missouri, Washington, and New York.

Crustal-Strain and Elevation Measurements

Some 1,200 monumented lines, 20 km in average length, have been measured by laser-ranging devices to accuracies of 5×10^{-7} strain. Yearly, 500 such lines are measured, in California and Nevada primarily, and several thousand kilometers of first-order level lines are available for re-leveling in seismically active areas of California and Nevada. The repeat intervals are long, greater than 5 years for most lines (though more frequent for a few). The leveling data have recently proved to be the basis for finding a large area of possibly precursory uplift in Southern California along the San Andreas Fault. Very little leveling, 300 km per year, is done specifically for earthquake research, however, so that the bulk of the measurements are not made on a timely schedule.

Numerous instruments for the local measurement of strain are operational, including such devices as laser strainmeters.

Other Field Measurements

Measurements are made intermittently along a 40-km-long section to determine the electrical resistivity of the San Andreas Fault in Central California by active and passive methods. Self-potential measurements are being conducted at about 20 sites in central California.

Radon emanation from soils and subsurface waters is monitored weekly at about 30 sites in California, and measurements also are carried out at Blue Mountain Lake, in New York State. The level of effort is small and evaluation of the technique will require a decade or more at present levels.

An array of 7 magnetometers with 1/4-gamma sensitivity is operating in a continuously recording differential mode in the densely instrumented section of the San Andreas fault near Hollister. One of the best-defined precursory anomalies yet observed in California was recorded on the San Juan Bautista magnetometer prior to the 1974 Thanksgiving Day earthquake ($m = 5.2$). No other anomaly of comparable duration and signal-to-noise ratio has been observed in the 2 years of recording on any of the magnetometers in the array.

Surveying with magnetometers by registering differences at sites spaced 10 km apart has been conducted semi-annually along two long lines in California. This is an inexpensive technique for searching for long-term changes in a local field. Gravimeter surveys designed to detect elevation changes of greater than a few centimeters are possible now, but have only been attempted on a limited basis.

Use of ground-water-level variations for predicting earthquakes has received little attention here by comparison with efforts in China. A few wells are now being monitored in the Hollister area.

Aberrant animal behavior has been noted, especially by Chinese observers, but no systematic program to search for such possible precursors has been initiated in this country.

LABORATORY STUDIES

Most of the conceptual underpinnings of the physical models now used to explain earthquake precursors derive from laboratory experiments. Dilatancy and precursory fault creep, both instabilities that lead to failure, were observed in the laboratory long ago. The search for other possible precursors, e.g., changes in electrical resistivity, seismic velocity, and microseismicity, was begun by workers in the U.S. and Japan a decade ago under the controlled conditions available to laboratory experimentalists. Field experiments designed to test some of these models for the pre-failure process have lagged because they are difficult to perform. On the other hand, precursory phenomena observed in the field have guided laboratory experimentalists in recent years to rapid advances in our understanding of the physical bases of earthquake phenomena.

Roughly 30 percent of the present laboratory capability for high-temperature and high-pressure rock-deformation experiments is used for relevant earthquake-prediction research. Two of these laboratories have been very productive training centers for geophysicists currently active in earthquake research.

Experiments on the rheological (flow) behavior of rocks have primarily been concerned with steady-state flow at high-temperatures. The rheology at moderate temperatures is experimentally more difficult, and is currently given little attention. The subject is an important one, however, because deformation of the lower crust and uppermost mantle is involved in large earthquakes. Most current research focuses on the details of the failure process preceding brittle fracture, which is, in effect, the "laboratory earthquake." Dilatant cracking and fault creep precede the sudden failure, and accelerate unstably very near the time of fracture. New experiments are under way to study these processes at greater than room temperature. Studies of faulting as a dislocation along a sliding surface between two large blocks are now under way and should yield direct observation of precursory phenomena and earthquake source parameters.

MODELING OF EARTHQUAKE PHENOMENA

Part of any large-scale program of earthquake prediction must involve the development of models of the earthquake process. These conceptual models are syntheses of laboratory and field observations and interpretations. They are of necessity simplifications of the complexities of nature: irregular geometries are modeled by simple ones; empirical designations of rheological processes are fitted by simple functional expressions. Evaluation of the consequences of predictions from theoretical models has a feedback on the laboratory-experimental and field-observational programs. One recent example of this feedback has been an attempt to assess whether it is possible to determine conventional focal parameters of earthquakes, such as stress drop, magnitude, fault length, etc., from seismograms, and indeed what parameters should be used to describe an earthquake.

Models of the pre-history and history of a seismic event must have three ingredients: (1) the rheological relationships connecting the stresses in the rocks and the deformational response of the rocks to those stresses; (2) the distribution of the sources of force (stress) that ultimately provide the impetus for a repetitious, sequential earthquake history; and (3) the geometrical constraints on a dynamical earthquake system. Intimately connected with the need to know this information for the relevant parts of the earth is a need to have reliable information regarding certain basic geophysical parameters: temperatures in the earth's interior, perhaps to considerable depth; the location and characterization (size and physical properties) of major inhomogeneities in the crust and upper mantle of the earth; and as much characterization of the properties of materials (such as porosities, elastic parameters, etc.) in seismically active regions as possible. Temperatures are important because the rheological properties of matter are strongly temperature dependent, as well as dependent on many other parameters, including stress and strain rate. Characterization of lateral inhomogeneities is important especially in seismic regions near ocean-continent boundaries, such as California and Alaska, where the thicknesses and physical properties of various major layers in the earth's interior are changing. Porosities influence the role of water in the entire sequence of events leading up to and following an earthquake.

Rheological Information

The rheological relationships most often used in building models come from laboratory investigations. Unfortunately, these experiments are difficult to carry out under conditions that closely simulate the actual earthquake environment. These laboratory results are obtained from experiments that are necessarily brief (minutes, hours, or days) compared with the recurrence rates of large earthquakes (tens and hundreds of years). Hence, in this and in other areas of the prediction problem, there is considerable extrapolation based on the time-scale differences. An assumption often is made that the relationship of magnitude to precursor time for large earthquakes can be derived from that for small earthquakes. The immediate vicinity of shallow earthquake faults is described by the rheology of brittle fracture, especially in the stages before earthquakes when the stress fields are relatively large and the temperatures relatively low. But in devising a systematic approach to modeling, a rheology of the earth relatively far from the active segments of earthquake faults, where the stresses may be relatively lower, is also important. Parts of the crust and upper mantle must also move in large earthquakes, albeit more slowly. Physical models of the response of materials to low stresses, in both high- and low-temperature regimes, will help determine the amount of intraplate strain accumulation as well as the motions of the earth in the region vertically below active zones of shallow earthquake faulting, as in California. Are the present rheological models, often obtained from steady-stress laboratory experiments, applicable to the transient physical changes that characterize earthquakes, and to the associated slower creep motions of the regions far from the active fault zones? What is the response to applied stresses of a system permeated by many flaws (e.g., dilatant cracks)? What is the behavior of earth materials approaching ultimate failure? Is there a different rheological behavior for unfaulted material than for a material crossed by major faults? We cannot yet answer these questions in detail, and models of earthquake events usually assume simplified answers in order to be able to proceed with the analysis.

Source of Deformation

Most models of the primitive sources of power for earthquakes refer to plate tectonics to describe the mobility of the outer parts of the earth. Dynamical descriptions of the means of propulsion of the plates often refer to the presence of heat sources; these heat sources, and boosters to the driving system such as phase transformations, are usually imagined as applying stresses to a relatively rigid lithosphere (the outer 100 km of the Earth). But is the lithosphere completely rigid, except in the neighborhood of earthquake fault zones, or is it capable of absorbing strains? Do intraplate earthquakes indicate the presence of inhomogeneous stress fields at distances of a few hundred kilometers or more from major fault zones, or can these events be ignored in the modeling of major fault zones such as the San Andreas? Information about the relative motions within and between plates can be obtained by long-range geodetic studies, such as very-long-base-line interferometry, multilateration techniques, etc. The role of deformations derived from plate-tectonic sources in contemporary models is to provide a build-up in the neighborhood of an earthquake fault of stress that is uniform with time. But is the assumption of a uniform rate of increase justifiable? Can rates of motion of plates derived as averages over millions of years of Earth history, be applied to obtain rates of recurrence of large earthquakes?

Investigations of the distributions of stresses capable of causing individual earthquakes must also focus on the residual stresses left behind in the wake of earlier earthquakes. The stress field after an earthquake represents a prestress of an earthquake fault for subsequent events. But these residual stresses must also undergo relaxation due to aftershocks and aseismic creep. The degree to which faults are inhomogeneously prestressed by residual stresses, and indeed to which the regions within some tens of kilometers of the fault (and by extension the entire intraplate space) are inhomogeneously stressed, may be important in the modeling problem, since it is most likely that these residual stresses considerably affect the conditions of occurrence of future events.

Geometrical Influences

The orientation of earthquake faults, offsets of these faults, the way in which they terminate, and the distribution of inhomogeneities in physical properties (including rheological properties) are all complexities that influence the construction of models. In most cases, these factors are unknown in the real earthquake environment because of the presence of geological complexity, including burial of earthquake faults.

Mathematical and Numerical Models

Thus far, theoretical computations have been for extremely limited and simplified systems; even these are very complicated to evaluate.

Numerical models of simplified systems have been computed at great expense, but the ability to generalize from these is questionable. Results from these theoretical studies have thus far had little impact on broad-scale programs of observation and laboratory work except to indicate the direction such work might take.

SOME PROBLEMS AND DEFICIENCIES

Over the past few years, important first steps have been taken and a pilot program has been launched in the United States for earthquake prediction. As significant as this effort is, it is much too small in comparison with the magnitude of the problem, and it has many critical omissions and serious weaknesses.

The greatest weakness in the present U.S. program of earthquake prediction is the inadequacy of field projects aimed specifically at detecting and understanding earthquake precursors. The U.S. effort is limited both in the kinds of observations and experiments performed and in areal coverage. Field observation is concentrated in California, leaving other seismically active parts of the country essentially uncovered. However, even in California, because of limited resources, not all necessary field measurements are being made.

The People's Republic of China, the USSR, and Japan are several years ahead of the U.S. in the field observations aimed specifically at detecting and understanding earthquake precursors. Most of the data on changes in electrical resistivity, radon emanation, changes in water level in wells, and changes in land elevation come from these three countries.

As another example, basic research during the last 15 years on flow of fluids in porous media, crack propagation, dilatancy, and physical properties of rocks has played a pivotal role in development of current theories of the physical basis for precursory effects of earthquakes, but much is still unknown. It is clear that a great deal of additional basic research in these areas will be needed before it will be possible to predict earthquakes on a routine basis in the United States. Theoretical modeling is also necessary as an aid in establishing the physical basis of earthquake prediction, and there is an urgent need to improve our observations of geochemical indicators such as radon, our in-situ stress measurements, our rock-mechanics research, and our theoretical studies of the dynamics of faulting.

Geodetic measurement of crustal movements is probably the most widely used technique for earthquake prediction in China, the USSR, and Japan. Geodetic surveying is very time-consuming and expensive, however, and comparatively little effort has been devoted to such measurements in the United States. Attempts have been made in the United States to develop other instruments, such as tiltmeters, in the hope that they might, at less espense, detect the same kinds of crustal movements. But it is not certain that these other methods will be as successful as geodesy. The development of technology for measuring elevations rapidly and inexpensively with an accuracy ranging from millimeters to a few centimeters could essentially replace the time-consuming process of geodetic leveling. With these accuracies, measurements made only weeks or months apart could show small but significant changes in elevation. Obviously, there is a great need for state-of-the-art geodetic measurements with earthquake prediction specifically in mind.

At present, very few measurements of strain and tilt over baselines ranging from meters to kilometers in length are being made in the United States with earthquake prediction specifically in mind. The Japanese, on the other hand, have installed long-base-line tiltmeters at 17 stations in various parts of the country. Many Japanese scientists feel that very short-base-line observations of tilt (for lengths of less than one meter) are likely to sense local inhomogeneities rather than precursory effects of earthquakes. New generations of inexpensive strain meters and long-base-line water-tube tiltmeters are now becoming available. It is extremely important that such instruments be installed in many of the seismic areas of the United States, including, for example, the area of current anomalous uplift near Palmdale, California. In particular, it is important to establish several small arrays, with dimensions of about one kilometer, that would include several types of strain- and tilt-measuring instruments, as well as to perform repeated geodetic leveling of the array. Such arrays, which might also include gravimeters of micro-gal accuracy, would help to answer unresolved problems about measuring tilt over very short baselines and to ascertain which of the various techniques are most reliable for earthquake prediction.

Although these deficiencies are serious, they could be corrected in a relatively short time with the proper emphasis and increased level of effort. Trained personnel, laboratories, and instrumentation exist. Any needed improvements in these areas can be made in a few years.

CURRENT SUPPORT AND DISTRIBUTION OF EFFORT

Japan, the USSR, and the People's Republic of China have major programs of earthquake prediction and hazards reduction. As discussed elsewhere in this report, an extensive program of earthquake prediction was initiated in China in 1966. Although it is difficult to measure the level of effort in China in terms of dollars, members of the U.S. Seismological Delegation who visited China in October 1974 estimate that the Chinese are making an effort with a value equivalent of $100 million a year specifically for earthquake prediction. Similarly, a very large effort under way in the USSR appears to involve a major commitment by the seismological community. The Soviet effort in earthquake prediction appears to be considerably larger than that in the United States, although it probably is not as large as the commitment in China. Support for earthquake prediction in Japan is about the same as in the United States, but a comparison is difficult to make because the costs of specific items of equipment and materials are less in Japan. About $4 million were allocated by the Japanese government in 1975 for earthquake-prediction research, not including salaries, overhead, and many other expenses that would bring the total current effort to about $10 million a year.

During FY 1976, about $10-11 million were spent by the United States Government for research in earthquake prediction and its social implications (see Table 1). Some of this money was spent on research in engineering seismology, however, only a part of which is related to earthquake prediction.

To put these expenditures into perspective--it has been estimated that a great earthquake today, such as the 1906 San Francisco earthquake or the great earthquake on the San Andreas Fault near Los Angeles in 1857, could claim more than 10,000 lives and cause damage exceeding $10 billion.

The apparently successful prediction of a major earthquake (magnitude 7.5) that occurred in northeastern China on February 4, 1975, may have saved thousands of lives. It is our understanding that, as a result of this prediction and its timely social implementation, most people in this densely populated region went out-of-doors shortly before the earthquake and remained there until the danger was over. It seems clear from this example that a truly effective program of earthquake prediction

TABLE 1

FY 1976 Budget Related to Earthquake Prediction*

National Science Foundation - RANN	$1,700,000
National Science Foundation - Earth Sciences	2,552,000
U.S. Nuclear Regulatory Commission	85,000
U.S. Geological Survey	5,000,000
National Aeronautics and Space Administration	1,300,000
	$10,637,000

*Based on information provided by the above agencies.

and hazard reduction in the United States could well also result in a great reduction in the loss of lives in future large earthquakes and in substantial reduction of property loss. As noted elsewhere in this report, such a program would require an increase to several times the current annual funding for prediction research.

The U.S. Geological Survey has been designated as the lead agency for the federal earthquake-hazards-reduction program, and it has developed both in-house research and external contracts programs to carry out this mission. During the first year of its external grants program (FY 1975), the Survey awarded about $2 million to universities, private industry, and state geological surveys. Proposals for support totaling more than $13 million were submitted to the Survey, and members of the review panel judged at least $7 million worth of this proposed research to be of very substantial potential value. Despite this, a large portion of the $2 million of external funding was, necessarily, used for the operation of seismological nets required to obtain basic information relevant to earthquake prediction. Very little remained for the development of new technology, the support of basic research on earthquake precursors, stress measurements, or laboratory and theoretical studies in earthquake prediction.

Ten years ago, about two thirds of the total U.S. research effort in seismology, exclusive of petroleum exploration, was centered in the universities. Support of university research led to major breakthroughs in the detection of underground nuclear explosions and in discriminating them from earthquakes, in the formulation of some of the basic ideas of plate tectonics, which have revolutionized the earth sciences, and in development of an understanding of processes such as dilatancy, which have been crucial to modern theories of earthquake precursors. Similarly, scientists working in some of the research laboratories of major petroleum companies have developed important insights into the physical properties of rocks and porous media. Basic research in these laboratories and the universities contributed greatly to the development of the "Bright Spot" method for the direct detection of buried hydrocarbons by seismic methods. It is critically important to ensure that the wide variety of expertise available in the United States in universities, industry, and various federal and state agencies be used effectively in attacking the earthquake-prediction problem. To concentrate too much of the effort in any one agency or group would be to fail to take full advantage of the resources and diversity of viewpoints available.

SOCIAL IMPLICATIONS

Successful earthquake predictions can lead to great reduction in loss of life, to smaller but still important reductions in quake-caused property damage, to enhancement of the margin of safety of critical facilities such as dams and nuclear reactors, and to more-effective and rapid restoration of normal living after the quake. The long-range goal of social policy with respect to earthquake predictions should be realization of these benefits.

Little social benefit can result from earthquake predictions, no matter how accurate and precise they are, unless careful planning for response to those predictions has been undertaken and unless appropriate response agencies are prepared to implement those plans. Such planning must take into account uncertainties about the time and magnitude of a predicted quake. And the design of prediction systems intended for operational use rather than for research should be responsive to the needs of social-response agencies as well as to the state of prediction technology. Much can be learned from past and current successful prediction-and-response programs for floods, hurricanes, and tornadoes.

Several recent studies have focused on prediction of and public response to natural disaster (White and Haas, 1975), and the recent report on *Earthquake Prediction and Public Policy*, prepared by the NRC Panel on the Public Policy Implications of Earthquake Prediction (1975), focused specific attention on the social, economic, political, and legal implications of earthquake prediction. Our brief discussion, consistent with the conclusions of the latter report, will address primarily the interface between systems for predicting earthquakes and systems for societal response.

Prediction capabilities will depend, for a long time to come, on relatively dense instrumentation of highly seismic areas. At present, amply instrumented regions in the United States have been chosen more on the basis of seismic activity than of social importance. Consequently, early successful predictions are likely to be for areas of relatively low population density. Eventually, a decision will have to be made about when and where to install instrumentation intended primarily to provide socially useful warnings rather than research data. The time for that decision may be as much as ten years away, but in any case, such a decision would be inappropriate until the whole warning-and-response system has been carefully thought through and planned.

Public Release of Predictions

Scientists and administrators concerned with the possibility of drastic public reaction to unsound or premature predictions have debated whether earthquake predictions should in fact be released to the public until a formal mechanism has been established for doing so. Earthquake predictions cannot be kept secret; the word will get out one way or another. Moreover, issuing a prediction publicly puts a burden of proof on the competent scientist--puts his scientific reputation on the line, so to speak--and may therefore encourage a strong sense of responsibility about the technical basis and timing of a prediction.

Unsound and premature predictions will certainly be made, and public response to a prediction is likely to be very expensive. Decision-makers therefore need guidance about whether to respond to an earthquake prediction, and how to respond, if necessary. In the Panel's opinion, the best compromise between the scientist's freedom to make his view public and society's need to be protected from costly responses to false alarms is to form an official body to scrutinize and evaluate such predictions as soon as possible after they are made. If such a reviewing body concludes that a prediction is not well grounded in evidence, that conclusion, reached in time, is likely to obviate the costs of a needless social response. Such a conclusion about one prediction would almost certainly lead to social discounting of future predictions from the same source. The possibility that this might happen should tend to encourage a high level of responsibility among predictors. If such a reviewing body should in effect endorse a prediction, on the other hand, undertaking an appropriate social response to that prediction would then become an urgent task.

With or without such a reviewing body, predictions will undoubtedly be made over the next decade by competent scientists and agencies, and by others. The Panel strongly believes that earthquake predictions should be accompanied by estimates of confidence level and by sufficient backup data so that their merits can be evaluated.

One advantage of acquiring experience in social response to earthquake predictions even before operational prediction systems are developed is that it can offer guidance concerning response to false alarms as well. In any prediction system, including an operational one, false alarms are inevitable. Their numbers can be decreased only by increasing the weight of evidence required before a prediction is issued, thus increasing the possibility that a real earthquake may not be predicted or that its prediction may be later than it might have been otherwise. But too high a false alarm rate is likely to lead to public complacency and thus make more difficult the task of public agencies trying to respond to warnings. The appropriate trade-off between false alarms and unpredicted earthquakes is a difficult question of social policy. Any evidence about response to false alarms that can be gathered will be helpful in the design of an operational prediction system. In any case, that operational system will have to be protected, both in its procedures and in its public representation, from the consequences both of false alarms and of unpredicted earthquakes. If a useful but fallible technology exists, its failure in one or more instances should not be allowed to prevent its later use. The experience of the National Weather Service with false alarms and missed predictions, as well as with successful predictions, in its attempts to predict tornadoes indicates that such problems are not insoluble.

Moving Toward an Operational Earthquake Warning System

Thinking about the design of operational earthquake-warning-and-response systems should begin now, in time to permit thorough cost-benefit analysis of alternative designs. Such design thinking and cost-benefit analysis should be done by collaborating groups of experts, including seismologists, earthquake engineers, experts on social warning systems, other social scientists, and representatives of the governmental agencies, especially state and local, with which such operational systems must routinely interact.

It seems likely that an operational prediction-and-warning system will issue seismological data routinely and special warnings when appropriate. Warning categories will probably be small in number but very explicit, as are those now used for hurricanes and tornadoes, and response agencies should have pre-planned lists of things to do in response to each category of warning. These definitions and boundaries will help seismologists and others in converting earthquake prediction as a scientific achievement to its use as a social tool.

Response Agencies

The report by the NRC Panel recommends that the primary responsibility for planning and responding to earthquake predictions should be assigned to federal, state, local, and private agencies with broad concern for community and economic planning and for disaster preparedness and response, rather than to newly formed agencies established especially to deal with earthquake prediction and warning or to agencies primarily concerned with emergency response.

Any operational prediction agency should be organized around seismological rather than political boundaries. Response agencies, on the other hand, are mostly under local control, organized in a manner that respects political boundaries. Thus, a potential conflict exists between the geographic basis of a prediction and the jurisdictional boundaries of response agencies. While the resulting political problems could presumably be worked out for predictions with a reasonably remote date or a relatively large time uncertainty, they would be more difficult to resolve under the time pressures that would be generated by a prediction that an earthquake is only hours away. Consequently, social responses to earthquake predictions can probably be considered under two headings: planning for future earthquakes, and responding to imminent earthquakes.

The problem of command and control for the immediate pre-earthquake and post-earthquake periods will probably require special organization. Needs will exist for backup communications, on-the-scene law enforcement, fire control, utilities management, and the ability to quickly muster recovery teams with heavy equipment. One of the principal concerns of individuals in or evacuated from a disaster area is protection of life and property. Compliance with emergency measures is much more likely if such protection can be relied on.

Perhaps the most serious potential undesirable consequence of earthquake-prediction capability is complacency about other kinds of preparation for earthquakes. Prediction cannot prevent earthquakes, so good earthquake engineering design in siting and building, and appropriate land-use planning, will continue to be as indispensable when a prediction capability exists as they are now.

Since we have relatively little experience in planning for the consequences of earthquakes, and still less in planning for exploitation of a prediction capability, major efforts to study these problems in advance are needed now. Investigative groups should be ready to study social response to earthquakes as they occur. As social-response mechanisms evolve, simulations will help to study their effects and to train those who must operate them.

Earthquake prediction, like other technological capabilities, can be used well or poorly. Used well, as we have said, it holds great potential for saving lives, reducing property damage, and smoothing the return to normal post-earthquake living.

OUTLOOK FOR THE FUTURE

We can now assess the prospects and the promise of earthquake prediction on the basis of real data and observations. The Panel unanimously believes that reliable earthquake prediction is an achievable goal. We will probably predict an earthquake of at least magnitude 5 in California within the next five years in a scientifically sound way and with a sufficiently small space and time uncertainty to allow public acceptance and effective response. A program for routine announcement of reliable predictions may be 10 or more years away, although there will be, of course, many announcements of predictions (as, indeed, there already have been) long before such a systematic program is set up.

Research on prediction continues, with definite successes and promising prospects. To achieve an effective prediction system, more fundamental research and field testing are required.

There are many gaps and unresolved problems in our understanding of earthquake phenomena. How does the earth's crust behave before, during, and after an earthquake? How large are the stresses responsible for earthquakes? How do the physical and chemical properties of the inhomogeneous crustal rocks change under stress in the earth? What type of observable phenomena do these changes produce? Neither the current theoretical models nor the available laboratory and field data answer all these questions. A better understanding of the whole process from the accumulation of strain to the dynamics of earthquake faulting is necessary for a scientific approach to earthquake prediction.

The principal uncertainties in our knowledge concern two questions: (1) If well-identified precursory phenomena occur, will they, in fact, be followed by earthquake? (2) For the various possible precursory phenomena, how large and of what character must deviation from base-level values be before they can be regarded as true signals of an impending earthquake?

Earthquake-magnitude predictions will most likely be based essentially on the duration of an observed precursory episode, as suggested by the Soviet observations, but many observations will be needed to achieve a high confidence level for such predictions. Another method for estimating magnitude might be to determine the areal extent of observed anomalous phenomena; presumably, more-widespread areal anomalies will be associated with larger earthquakes because of the larger extent of faulting. This attractive possibility requires observational and experimental tests. Another attractive model, quite at odds with this one, suggests that the magnitude of an impending earthquake will depend on the dynamical conditions governing the extension of a fracture. This proposal suggests that magnitude/areal-extent relations hold only for smaller events and that larger events "break out" of a confined focal zone into regions that do not display precursory anomalies.

Though short-term precursors have been reported for a few small and moderate earthquakes, we are still very uncertain about the precision with which such phenomena can be used to estimate the time of occurrence of a future large earthquake. For example, we do not know whether we could recognize precursory phenomena extending over a period of 40 years, or whether we could forecast the termination time of the anomalous period with sufficient precision to be of real value. Even if some precursors of large earthquakes last too long to permit satisfactory prediction, numerous historical observations and instrumental measurements of anomalous phenomena, such as sudden uplifts of the land, occurring a few hours or days before great earthquakes give us hope that other precursors can be found that will permit prediction without excessive temporal uncertainty. Study of these processes and effects may ultimately give us a capability for reliable prediction of moderate and large earthquakes.

Recent intensive efforts to identify velocity changes prior to moderate-size earthquakes have resulted in many disappointments as well as encouragements, and we doubt that any single phenomenon will alone constitute a basis for a successful monitoring program for earthquake prediction. Our best prospect for reducing false alarms to a minimum is through a system that would monitor a wide variety of physical parameters rather than rely on a single kind of observation such as velocity changes. Obviously, a much better understanding of the physical processes that occur before and during earthquakes would help immeasurably in determining which parameters should be monitored.

It has become apparent from the available observations that earthquakes may be preceded by different physical changes in different geographic and tectonic regions. Observable earthquake precursors that are prominent in one region, such as the San Andreas fault in California, may not be observed in other regions, or even on other faults in California. For example, the kinds of velocity changes that preceded the Blue Mountain Lake earthquakes in New York State have not been observed as strong precursors of San Andreas earthquakes. On the other hand, anomalous ground tilts may have preceded some San Andreas earthquakes. It may turn out that earthquake prediction will be based on different sets of criteria in different regions rather than on a single universal criterion that applies to all regions. These differences will require monitoring in many different earthquake-prone regions if earthquake prediction is to be achieved in all vulnerable parts of the nation (or the world).

Thus far, all documented earthquake predictions have been made on the basis of data and observations from dense networks of instruments in epicentral areas. The outlook for predicting earthquakes with instruments remote from the epicentral areas, or "teleprediction," is not certain. It is reasonable to assume that in the near future predictions will be made primarily by the networks in epicentral areas. Remote observations may give some indications, however, and may be useful in identifying areas that are good candidates for close monitoring.

On the basis of present experience and understanding, it is reasonable to say that reliable prediction of smaller earthquakes will precede that of larger earthquakes. Small earthquakes occur frequently, their precursors occur over a short period of time, and their sources can be defined with regional networks. Routine prediction of earthquakes of magnitudes 6 or less may be possible in well-instrumented areas within the next ten years. Large earthquakes occur infrequently, and may require monitoring over a much longer period of time to test the prediction capability. Experience with smaller earthquakes no doubt will be applied to larger ones. To accelerate this process and to test techniques for predicting larger earthquakes, we must instrument and monitor different active areas simultaneously. Only in this way can we obtain adequate data about larger earthquakes during the next 10 to 20 years.

In addition to long-term data that will be obtained from future instruments, a significant history of seismological and earth-deformation data is recorded in existing bulletins and instrumental records. Although much of this older information is of insufficient precision or relevance to be of use in studying possible long-term precursors to major earthquakes, careful analysis of these existing records is important. For example, two relevant searches are those for possible anomalies in long-term tide-gauge data, and possible variations in earthquake travel-times to long-established seismographic stations in regions of large earthquakes.

Earthquake control is likely to be farther in the future than earthquake prediction. Nevertheless, prediction may permit identification of regions in which studies could be made of the feasibility of earthquake control by fluid injection or by other means that may be developed. Earthquake-control experiments have been tried successfully on a small scale in an oil field at Rangely, Colorado. Before earthquake control can become a reality, however, much more must be known about the physical processes involved, including the magnitudes of the stresses, permeability and porosity of rocks, and variations of fluid pressure along fault zones. Studies such as those at Rangely, as well as a number of laboratory studies now under way, should improve our knowledge in this area--and ultimately our capability to modify or control at least some types of earthquakes. Additional studies in more representative tectonic regions must now be undertaken to fully explore the feasibility of earthquake control.

The outlook for the future of earthquake prediction and control depends on the extent of the national commitment and the size of the national program. With optimum support, the routine announcement of reliable predictions--meeting criteria of time, space, size, and probability of occurrence--may be possible in ten years in well-instrumented areas, although very large earthquakes may present special problems. The size of the program and the level of support must be consistent with the magnitude of the task and the available trained manpower.

In the interests of making the most significant advances in the shortest period of time, the wide variety of expertise currently available in the United States in universities, private industry, and various federal and state agencies should be applied to the earthquake-prediction problem. We believe that a truly effective program will require a commitment for ten years that includes a large increase to several times the current annual funding. Much of the effort would be concentrated on intense instrumentation of a few experimental areas of high seismicity. If this 10-year research program is successful, subsequent implementation of the resulting earthquake-prediction capability for all seismic areas of the United States, on a continuing basis, will probably require a comparable national annual commitment.

Research in predicting earthquakes has progressed to the point where it is advisable that a continuing overview of the program be presented to the Executive Branch of the United States Government at regular intervals, since its ramifications will affect large segments of our society. The setting up of a representative group of competent scientists to accomplish this advisory task is one of the recommendations of this report. Similarly, planning should begin now for organized societal response to earthquake prediction. It is essential that we develop a prediction capability and effective response system in concert if the nation is to benefit immediately from this new development when it arrives.

Now is the logical time to make a national commitment to an effective earthquake-prediction-and-response program, and to allocate the necessary resources to the task.

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APPENDIX A

EARTHQUAKE-PREDICTION RESEARCH IN THE UNITED STATES

M. Nafi Toksöz

In the United States, efforts in earthquake prediction have evolved in two directions:

1. Studies of seismicity and recurrence times, statistical prediction, and risk evaluation based on statistical information.
2. Deterministic prediction based on changes in measurable physical parameters during the interval prior to the earthquake.

There have also been experiments during the past decade in the direct control of earthquakes through injection of fluid into the fault zone.

In U.S. attempts at earthquake prediction, the earliest emphasis was on statistical methods. At present, however, the deterministic techniques hold great potential. This appendix briefly reviews the work and results in the U.S. in earthquake prediction and in experiments toward earthquake control.

SEISMICITY AND STATISTICAL PREDICTION

It is generally accepted that seismicity patterns of the past hold the key to those of the present and the future. An area that has experienced earthquakes in the past will most likely have similar ones in the future, and the frequency and magnitudes of these future earthquakes can be generally estimated from the frequency-magnitude relationships of those of the past. Thus, early attempts to predict earthquakes were based on the seismic history of the area being studied. Using such historic and statistical data, an earthquake risk map (Figure 1) was prepared for the United States(1). This map has been used extensively in construction codes and in planning.

The major shortcoming of the statistical approach has been that it provides neither exact locations nor reliable recurrence intervals for the larger earthquakes(2). Statistical techniques have been used in many studies to search for periodicities or other trends conducive to more definitive prediction of earthquakes. Most of these studies suffered from the unavailability of data covering sufficiently long time periods. The historic data, based on observer reports rather than

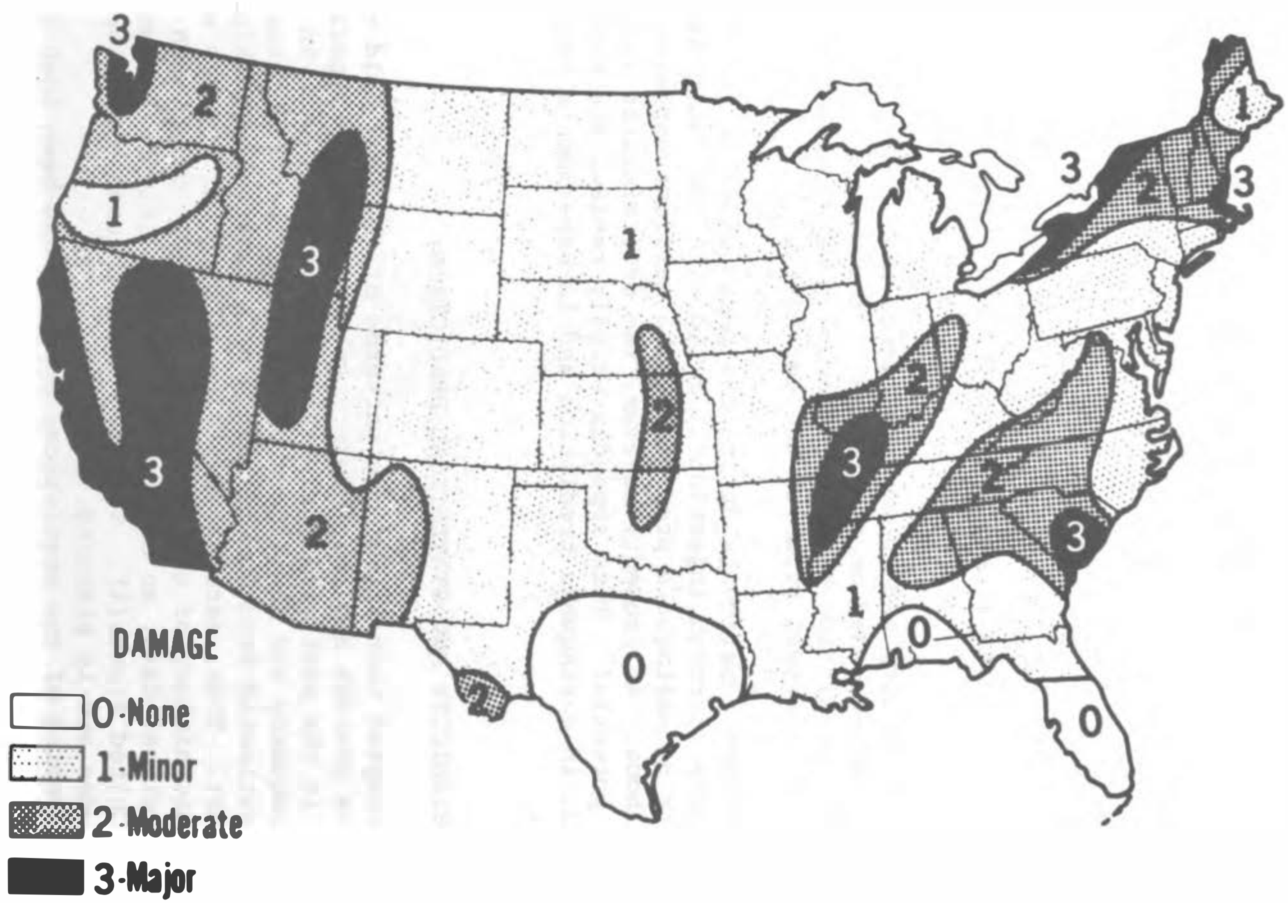

Fig. 1. Seismic Risk map of the United States, published in 1969 by ESSA/Coast and Geodetic Survey. The map shows four seismic risk zones: Zone 0, areas with no reasonable expectancy of earthquake damage; Zone 1, expected minor damage; Zone 2, expected moderate damage; and Zone 3, major destructive earthquakes may occur (1).

instrumental measurements, were homogeneous neither in time nor in space. Development of seismograph networks has improved data quality, but this data base covers a time span of only a few decades, and the statistical analysis of these data has shown no well-defined periodicities. Once the clustering due to aftershocks is removed, the time distribution of earthquakes can best be fitted by a Poisson model(3, 4, 5), in which events occur randomly in time but the mean number of events per unit time is constant, and equal to the variance.

The study of time-space patterns of earthquakes, which is still in a preliminary stage, may hold some promise. Simply defined, the idea is based on the concept that strain accumulates over a wide region along a plate boundary (or seismicity belt); each earthquake releases the strain energy over an area defined by the extent of faulting or of the aftershock zone. Seismic gaps along a fault that is active elsewhere--i.e., areas in which no earthquakes have occurred for long periods of time--may be the most likely sites for future earthquakes. This idea has been explored for earthquakes in the Aleutians(6, 7) and in the North Anatolian fault zone(8). Although more definite and quantitative studies are still required, the available results are encouraging. This type of study, combined with geodetic measurements and theoretical strain-field calculations, may be able to pinpoint the highly strained areas for very close monitoring. Other studies employing pattern-recognition concepts(9), being conducted now, may provide a multi-parameter approach to the probability of an earthquake in a given area.

In summary: At present, the greatest potential of the statistical approach to earthquake prediction is to identify risky areas requiring careful monitoring, rather than to determine the exact time and location of future earthquakes.

DETERMINISTIC METHODS OF EARTHQUAKE PREDICTION

In recent years, significant advances have been made in identifying physical changes that preceded earthquakes. (See Reference 2 for a detailed discussion.) Most notable among these have been the changes in seismic compressional and shear-wave velocities and of their ratio (V_p/V_s), and changes in electrical conductivity, water pressure, ground tilt direction, and surface elevations in and around the earthquake source. With the aid of laboratory measurements, these precursory phenomena have been related to the physical process of dilatancy(10, 11, 12, 13, 14, 15) put forth by U.S. and USSR investigators.

The models are based on laboratory fracture studies(16). Prior to failure, the stressed rock undergoes a volume increase or becomes "dilatant." Dilatancy is produced by the formation of cracks within the rock and increased porosity. In the U.S. "dilatancy-diffusion" model, at the initial stage of dilatancy, originally saturated rock becomes undersaturated. Then water flows into the source region and resaturates the rock. This process takes place slowly because of the low permeability of most crustal rocks. Saturation and subsequently increasing pore-fluid pressure then reduces the rock strength, and failure (i.e., the earthquake) occurs. With the release of stress as a result of the earthquake, the rock returns to the "non-dilatant" state. In the "dilatancy-instability" model, rapid development of cracks during the first stage of dilatancy is followed by gradually accelerating deformation in the fault zone before the earthquake with a concomitant decrease in shear stress. Outside the weakened shear zone, the cracks close again as the stress decreases and the velocity ratio increases prior to failure. The conditions that preceded earthquakes, and their effects on observable physical properties, are shown schematically in Figure 2. As discussed in the following section, the definitive field observations in the United States have been of changes of the seismic velocities or the velocity ratios and directions of the ground tilt. Additional precursory phenomena have been observed in the USSR, Japan, and China. These are discussed in greater detail in Appendix B.

Precursory Velocity Changes

Field tests of the feasibility of earthquake prediction have been carried out in the United States primarily using precursory changes in seismic velocity. Most of these studies were made after the earthquakes had occurred. In one case, however, a small (M = 2.6) earthquake was actually predicted several days before it occurred (the Blue Mountain Lake earthquake, discussed below). So far, earthquake prediction based on seismic velocity changes has been applied to earthquakes associated with thrust, normal, and strike-slip faulting. Both local and teleseismic travel times have been used in these studies. For thrust-type events in New York State and California the results are encouraging. For others, the preliminary results are not yet definitive.

The thrust-type earthquakes for which precursory travel-time or velocity changes were analyzed were those in the Blue Mountain Lake area of New York State(12), the San Fernando earthquake of February 9, 1971 (11), and the Pt. Mugu earthquake of February 21, 1973(17). The pertinant data for these earthquakes are shown in Figures 3a, 3b, and 3c. These results are convincing. They imply compressional velocity changes in a fairly large area (at least a few times the fault dimension) around the earthquake source. The compressional velocity or V_p/V_s velocity ratio first decreases to a minimum, and then rapidly recovers to the normal value. The earthquake follows this recovery. The duration of the anomalous period is related to the earthquake source dimensions and the magnitude(11, 18). Thus, the method predicts not only the time but also the magnitude of an impending earthquake.

The actual prediction of the Blue Mountain Lake, N.Y., magnitude M = 2.6 earthquake was made on the basis of this type of data(13). These data are shown in Figure 4. Based on the rapid drop of V_p/V_s ratios in the figure, and on the seismicity pattern, both the magnitude and the time of this earthquake were predicted correctly. The graph for the third event at Blue Mountain Lake, which includes additional data obtained or reduced after the earthquake, shows a characteristic behavior pattern also seen in the graphs for the other thrust events illustrated (Figures 3b and 3c).

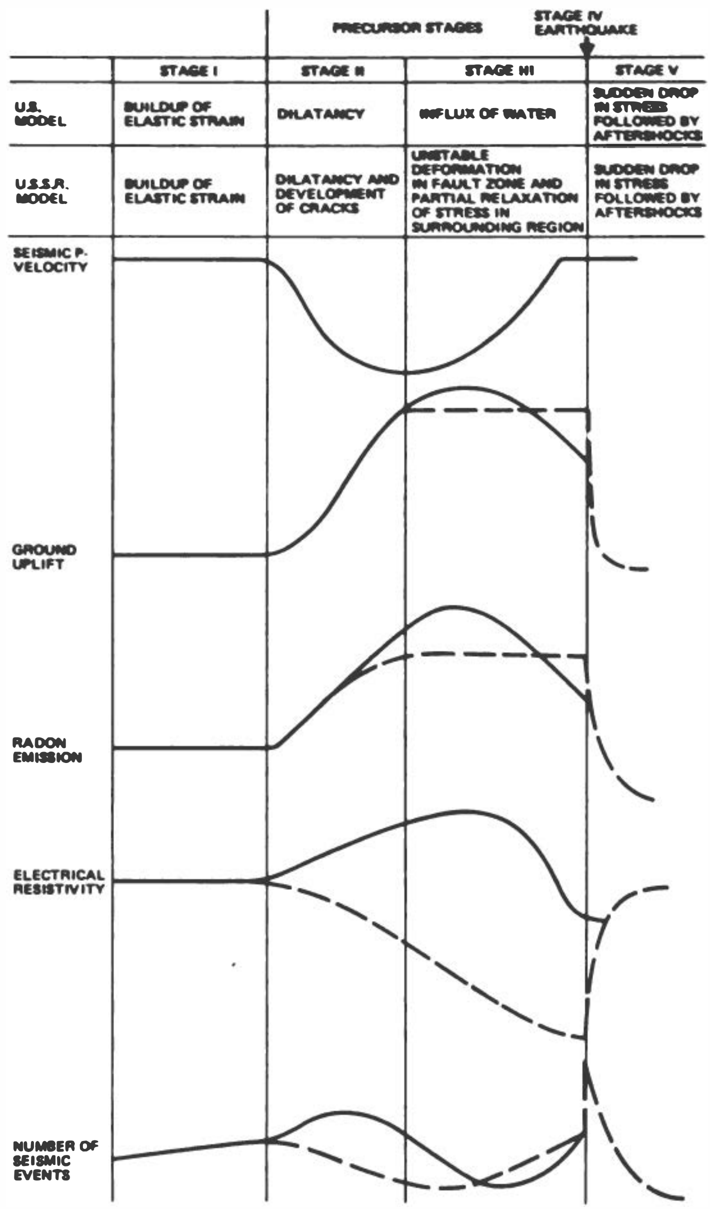

Fig. 2. Schematic diagrams of expected changes in some physical parameters as a function of time before, during, and immediately after an earthquake according to two models developed in the U.S. and USSR. The solid lines represent the "dilatancy-instability" model developed in the USSR. The dashed line is the "dilatancy-fluid flow" model of the U.S. The five stages are listed and the description of events at each stage is given at the top. Radon emission may be a function of both water flow and rate of creation of new surface area by the growth of cracks. The expected behavior of electrical resistivity in the ground has not yet been measured with sufficient accuracy to resolve between the models (14, 15).

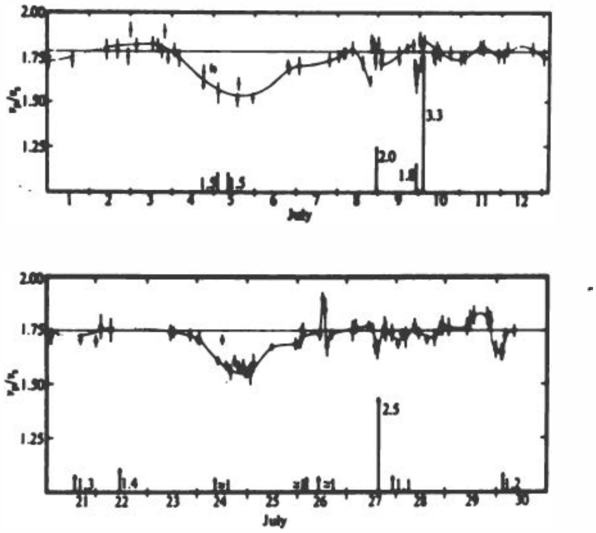

Fig. 3a. Velocity ratio V_p/V_s as a function of time for two events in the Blue Mountain Lake, N.Y., earthquake swarm of 1971. The magnitudes of individual events are given along the time axis next to arrows designating the events. Bars on data represent estimated errors in data.(12).

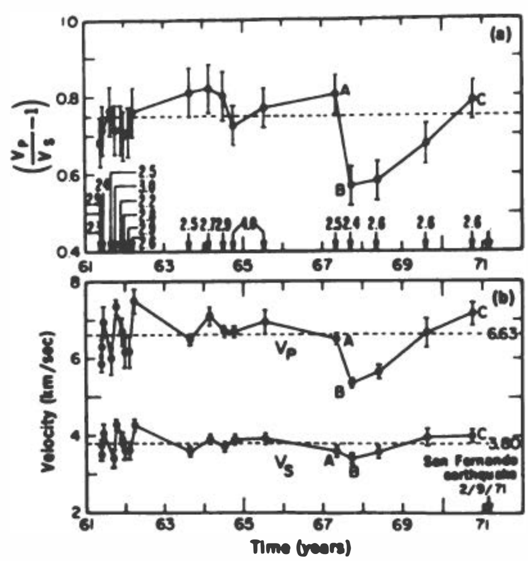

Fig. 3b. Variation of (a) seismic velocity ratio (V_p/V_s - 1), and (b) seismic compressional (V_p) and shear (V_s) velocities as a function of time before the San Fernando earthquake (magnitude = 6.6) of February 9, 1971. The velocity measurements are between Pasadena and Riverside, California stations. Each point corresponds to an earthquake whose magnitude is given along the time axis in each figure. The maximum estimated error due to time readings is shown by bars.(11).

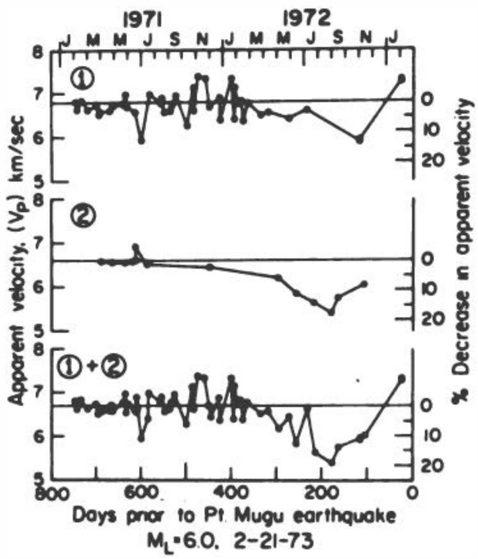

Fig. 3c. Apparent velocities before the Point Mugu earthquake as determined from the recordings at seismic stations of the Santa Barbara channel array. Upper curve shows data from earthquakes at San Fernando Valley, middle curve from Los Angeles Basin.(17)

Whether this method is also applicable to non-thrust earthquakes is not yet clearly resolved. Analysis of travel-time data from earthquakes and quarry blasts in California did not show precursory velocity anomalies over large areas preceding some strike-slip-type earthquakes in the Bear Valley section of the San Andreas Fault(19, 20) or for the Borrego Mountain Earthquake in 1958(21). It was not clear from these studies whether there were no precursory velocity changes or whether the dilatancy was confined to a very small region immediately at the source area, such that its effects could not be determined within the accuracy of the data. More-recent results based on P-wave travel-time residuals immediately at the source region of the February 24, 1972, earthquake near Bear Valley(22) suggested a velocity decrease prior to the earthquake. Unlike the thrust-type events, the apparent anomalous zone for this strike-slip earthquake may have been small and probably confined to the volume defined by the aftershocks. A similar observation of undetected velocity changes prior to the earthquake was documented on the basis of explosion data for the June 1, 1975, Galway Lake earthquake in Southern California(24). Thus, for strike-slip earthquakes along the San Andreas, the available data seem to indicate that precursory velocity changes, if they do indeed occur, probably are confined to the immediate focal region, and do not extend to a large area around the source. This may also be true for some strike-slip earthquakes in Japan(23).

Changes of S-wave velocities have not been studied as extensively as those of P-waves. Shear-wave anomalies preceding an earthquake have been observed, but the magnitudes of these anomalies are smaller than those for P-waves.

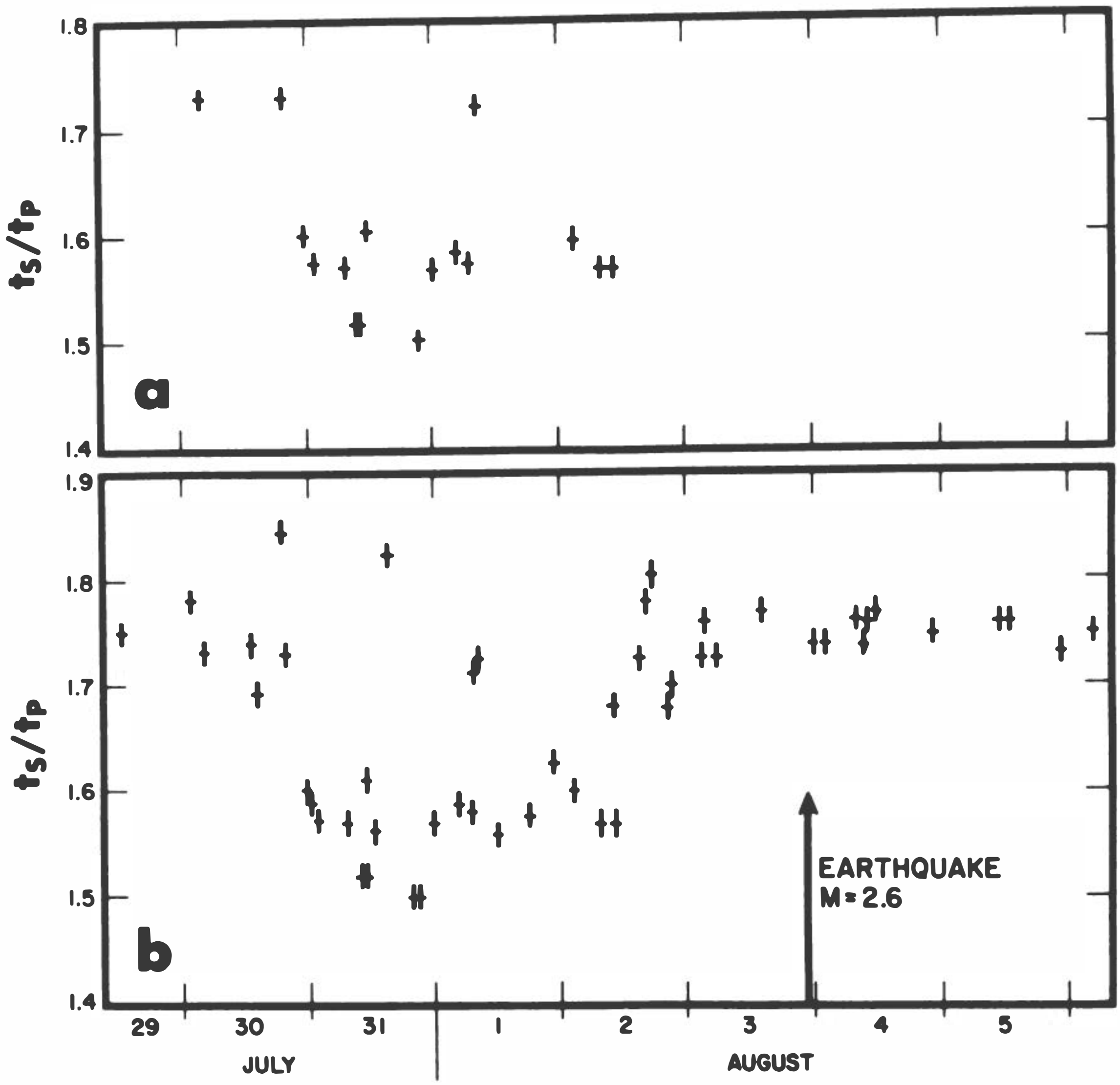

Fig. 4. Travel-time ratios (ts/tp) for the August 3, 1973, Blue Mountain Lake earthquake predicted by Aggarwal et al.(13). The upper figure (a) shows data that were available at the time of the prediction. The lower figure (b) shows all the data, with quarry blast and other earthquake travel times analyzed after the earthquake.

The extension of these studies to areas remote from the monitoring instruments, and to larger earthquakes, is being accomplished using travel-time residuals(25). Although these interpretations are model-dependent, they may broaden the data base since large amounts of such data are available for intermediate and large earthquakes of the past.

Laboratory studies of the effect of stress on rock properties have been important in understanding the field observations and putting together the dilatancy model(9, 13, 15). In the laboratory, rocks exhibit anomalous changes of physical properties near fracture stress. The magnitudes of the changes, however, are not always consistent with changes observed in the field prior to an earthquake(26). The rocks and conditions in the earth's crust near the fault zones are very complex and may be affected by factors not incorporated in the laboratory experiments. The laboratory studies still provide very valuable data necessary for developing a physical model and better understanding of earthquake processes.

Changes in Direction of Ground Tilt

The most consistent precursory phenomenon for San Andreas earthquakes has been change in the tilt direction(27). The measurements made with shallow-borehole tiltmeter arrays along the northern San Andreas indicate that there are definite and significant changes in the tilt direction prior to a local earthquake or earthquake cluster (Figure 5). During inactive periods, the records indicate systematic (secular) tilting of as much as one microradian per month in some fixed direction. Tilt directions change a few weeks to months before local earthquakes with magnitudes M = 3 to 5 as seen on instruments located within 10

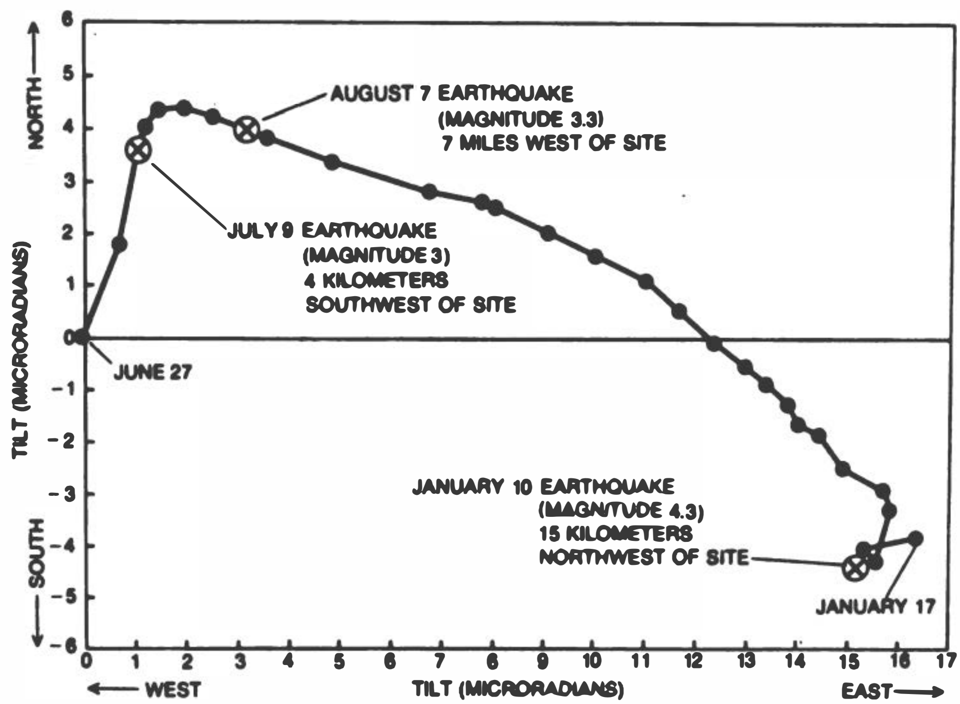

Fig. 5. Tilt-direction changes before local earthquakes. Cumulative weekly mean tilt vectors (circles) from June 27, 1973 to January 17, 1974 observed at the Nutting site 7 km southwest of Hollister. Local earthquakes are shown as stars (⊠). North and east are the positive ordinate and abscissa, respectively.(15, 23)

fault lengths of the source. This effect has already been seen for more than 20 events. The mechanism responsible for the tilt-direction change is not yet clear, but it does not appear to be simple dilatant volume expansion(28).

In Summary: Precursory velocity and tilt-direction changes seem to have occurred for the earthquakes studied. However, some major questions still remain: Do velocity changes occur as a function of time without being followed by earthquakes? Are some earthquakes not preceded by velocity anomalies? Do tilt-direction changes occur prior to all local eathquakes both on the San Andreas and in other regions? Does the relationship between magnitude and precursor-time hold? These questions and some others need to be answered before a true assessment of the deterministic methods can be made.

Other Observations

A number of other kinds of measurements, in addition to the seismic-velocity changes described above, are being conducted to identify precursory changes in crustal properties prior to earthquakes. These measurements are being guided by observations in other parts of the world, by laboratory results, and by theoretical studies. They include geodetic measurements, and measurements of strain, creep (both horizontal and vertical motions of the crust), electrical conductivity, magnetic anomalies, and groundwater pressure, among others.

Most of these measurements were begun relatively recently and do not span sufficiently long time periods for clear-cut evaluation of their potential usefulness in earthquake prediction. Some of the preliminary work on magnetic anomalies(29, 30) and electrical conductivity(31) is encouraging.

Groundwater-pressure fluctuations show some correlation with creep rates(32).

Geodetic(33, 34) and creep measurements(35, 36) have produced the most data to date. Analysis of these data, and of records of earthquake distribution along the San Andreas(37), have provided information about crustal movements and strain fields along some segments of the fault. These kinds of information, as discussed in the early paragraphs of this report, can be very helpful in identifying areas for extensive monitoring. The most recent example has been the identification of the Palmdale uplift in California(38). Although the causes or the implications of this uplift are not understood, this is clearly an area of anomalous behavior that should be watched carefully. A much larger body of measurements of changes in strain, tilt, and elevation is necessary to identify regions for extensive studies. Both the conventional measurements and new techniques utilizing reference points in space (quasars, the Moon, artificial satellites) will provide data on crustal movements.

EARTHQUAKE CONTROL EXPERIMENTS

Earthquake control experiments in the United States have produced significant results bearing on our understanding of the occurrence of earthquakes and increasing the possibility of earthquake-risk reduction. Since the discovery of the relationship between the 1962-65 earthquake sequences near Denver, Colorado, and the disposal of waste fluids by injection into a deep well at the Rocky Mountain Arsenal, earthquake control has become an important research topic.

A well-planned field experiment was initiated in 1967 by the U.S. Geological Survey at the Rangely Oil Field in western Colorado. Since a large number of wells were available, water could readily be injected into or pumped out of the source area and the pore pressure monitored. Meanwhile, an array of seismometers monitored the resulting changes in seismic activity.

The results show an excellent correlation between fluid injection and earthquake activity, as illustrated in Figure 6(39). When the fluid pore pressure reached a threshold level (3,700 psi in this case), earthquake activity increased. When pressure dropped as a result of water withdrawal, the seismic activity decreased.

The generation of earthquakes in the field under controlled conditions can also be used to study and test the precursory changes in physical properties of a rock mass before earthquakes occur.

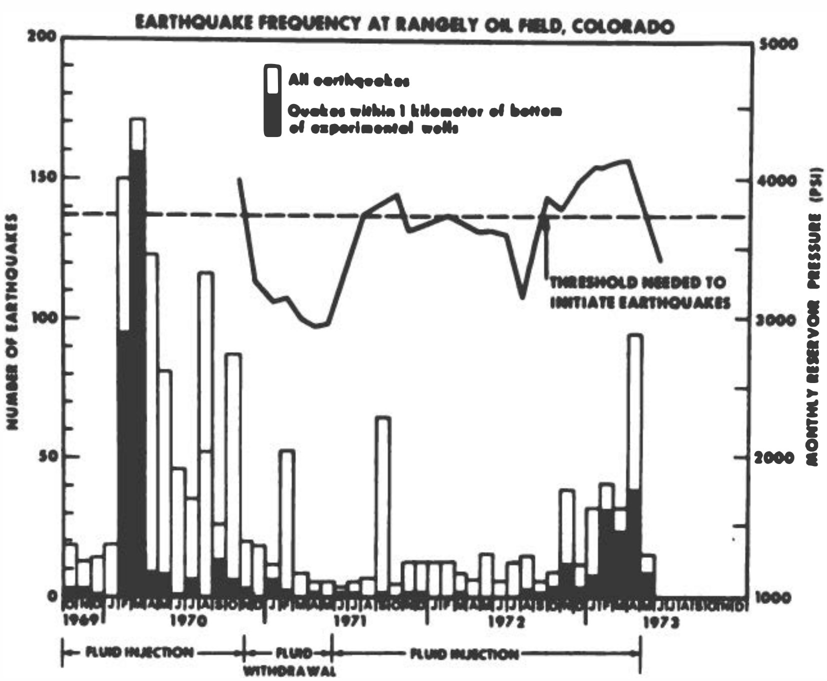

Fig. 6. Earthquake frequency at the Rangely oil field, Colorado and its relation to reservoir pressure(39).

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APPENDIX B

EARTHQUAKE-PREDICTION RESEARCH OUTSIDE THE UNITED STATES

Lynn R. Sykes

PROGRAMS OF EARTHQUAKE PREDICTION OUTSIDE THE UNITED STATES

General Review of Foreign Programs and Exchanges

Japan, the U.S.S.R., and the People's Republic of China all have national programs of earthquake prediction and earthquake-hazards reduction that have been functioning for a number of years. The Japanese program, funded by the Japanese government and now going into its third 5-year segment, has been described in detail in a number of publications. The Japanese program of earthquake prediction has had a great influence upon U.S. seismologists. Until about 10 years ago the subject of earthquake prediction was greeted with a great deal of skepticism in the United States, was often placed in a category with astrology, and was not considered a proper subject of scientific study. In recent years, however, the research in earthquake prediction in Japan and the Soviet Union has caused a major change in attitudes in the United States. U.S. and Japanese scientists have met four times during the past 10 years for U.S.-Japan Conferences on Earthquake Prediction. These conferences have provided a very important medium for exchanging information and ideas about earthquake prediction and related research.

The Soviet Union has had an active program of earthquake prediction and hazards reduction for more than 10 years. Following the destructive Khait earthquake of 1949 in the Garm region of the Tadjik Republic, Soviet seismologists in the early 1950's put into the field the Complex Seismological Expedition to record and study the spatial distribution of earthquakes, their variations with time, and other statistical properties. The program of scientific research in the Garm region was later expanded to include searches for precursory phenomena associated with earthquakes.

In both the U.S.S.R. and Japan, much emphasis has been placed on trying to detect precursory phenomena. A wide variety of physical phenomena were examined, including changes in elevation of the land, in the velocity of seismic waves, in the frequency of occurrence of small earthquakes, in the electrical properties of rocks, and in earth strains and tilts. Until results emerged from these programs in the U.S.S.R. and Japan, there was considerable skepticism among scientists as to whether many of the early reports of precursory changes represented valid changes associated with earthquakes or were merely interfering effects and noise. It is largely as a result of the massive efforts in Japan and the U.S.S.R. that many geophysicists now accept the view that precursory changes do, in fact, occur before at least certain types of earthquakes. Many of the data used by U.S. and other scientists in support of the dilatancy models of precursory changes preceding earthquakes have come from measurements made in Japan and the U.S.S.R. during the past 10 years.

A number of scientists from the United States heard papers on various aspects of earthquake prediction in the U.S.S.R. at the meeting of the International Union of Geodesy and Geophysics in Moscow in 1971. Several U.S. seismologists also visited Soviet institutes working on earthquake prediction, particularly the Complex Seismological Expedition at Garm, in Central Asia. These papers and visits were instrumental in stimulating U.S. scientists to intensify their search for precursory effects of earthquakes.

A U.S.--U.S.S.R. program in earthquake prediction and earthquake-hazards reduction was one of several agreements reached at the 1972 "summit meeting" between President Nixon and Chairman Brezhnev. A detailed plan of cooperative research between scientists of the two countries was drawn up during a visit to the U.S.S.R., in October 1973, of a U.S. delegation on earthquake prediction. Several American geophysicists visited the Soviet Union, and U.S.S.R. scientists visited the United States under this program in 1974. Results of Soviet investigations at Garm were reported at a conference at Aspen, Colorado, in August 1974. U.S. seismologists installed a network of seismic instruments in the Garm region in 1974, and other U.S. projects in Garm and near the Nurek Dam, Tadjikistan, were begun in 1975.

Earthquake Prediction in the U.S.S.R.

Active field programs of earthquake prediction are under way in three areas of the Soviet Union: in the Garm region of central Asia, in the area near Tashkent in central Asia, and in Kamchatka. The first two areas are situated near the belt of moderate-to-high seismic activity that extends from the Mediterranean region across central Asia to the Himalayas and western China. Kamchatka, the most active earthquake region in the U.S.S.R., is a part of the very active seismic zone that borders the northern and western Pacific. Central Asia is generally characterized by north-south compression, which appears to be related to continental collision between India and the rest of Asia. Research in earthquake prediction in Kamchatka is made difficult by the fact that most of the large shallow earthquakes are located offshore beneath the inner wall of the Kurile-Kamchatka trench. The different tectonic environments in these three regions account for the different approaches to earthquake prediction.

Garm Region

Soviet investigators have examined possible precursory changes of a wide number of physical parameters in the Garm region of Central Asia. Among the most important of these, discovered for the first time at Garm, is the so-called t_s/t_p ratio, the ratio of the travel times of seismic shear (t_s) to compressional (t_p) waves. Soviet investigators noticed that this ratio, normally about 1.75 (a Poisson's ratio of 0.26), decreased by about 10 percent over an interval before moderate-size earthquakes. The ratio was observed then to return to normal immediately prior to the occurrence of earthquakes. The duration of this anomaly was found to be longer the larger the size of the earthquake. Soviet investigators postulate that the frequency content of seismic waves is also altered over a period of time preceding earthquakes.

Similar changes in t_s/t_p (or, alternatively, in the ratio of seismic velocities $v_p v_s$) have been observed preceding earthquakes in New York State, South Carolina, California, and Japan.

The rate of occurrence of very small earthquakes also appears to change preceding moderate and large earthquakes in Garm. The number of small earthquakes in a fault zone appears to build up very slowly with time and then to undergo a marked reduction (or quiet period) just prior to a larger earthquake. Soviet investigators have reported precursory changes in earthquake mechanisms (which reflect the types of fault motion), which they interpret as related to changes in the tectonic stresses prior to earthquakes.

An extensive series of measurements of electrical conductivity has been carried out in the Garm region since 1967. As measured over baselines a few kilometers long, electrical conductivity appears to increase by about 10 to 20 percent prior to moderate-size earthquakes. These changes have been attributed to an increase in the water content of the rocks, since dry rocks normally have very low conductivity.

A series of geodetic measurements has been made in the Garm region during the past 10 years to detect precursory changes in horizontal and vertical movements. Soviet investigators report anomalous increases in elevation of the land prior to moderate and large earthquakes.

Tashkent and Uzbek Republic

The damaging Tashkent earthquake of April 26, 1966, apparently influenced the Soviet government to give increased attention to earthquake prediction and earthquake-hazards reduction. Although this earthquake was only of moderate size (magnitude 5.3), it occurred almost directly under the major city of Tashkent and caused a great deal of damage to older structures.

The Tashkent earthquake has become well known among geophysicists since it was in connection with that event that it was recognized that geochemical indicators could be used for earthquake prediction. The content of radon and other gases in well water had been measured on a regular basis for several years prior to the 1966 earthquake, primarily in studies of the chemical properties of medicinal waters. The water that was sampled for its gas content was taken from a well that extended into what was to become the hypocentral region of the 1966 earthquake. Prior to the main shock of 1966, a marked increase was observed in the amount of an isotope of radon that has a half life of about 4 days. Similar increases were found before several of the larger aftershocks. The increase in radon prior to these earthquakes may be attributed to the openings of small cracks in the rock and to increased flow of fluids near the hypocentral region.

More than 20 wells near Tashkent and within the Fergana Basis of Uzbekistan are now being monitored for precursory changes in the radon and helium content and in temperature and fluid pressure. Marked changes in temperature and fluid flow were observed prior to the 1970 Przhevalsk earthquake, near Alma Ata in Central Asia. Changes in temperature and in the content of radon and helium are also now being monitored in several wells along the major Surkob fault zone in Tadjikistan. Few measurements of these kinds have been made in the United States. Hence, it appears that Soviet investigators are perhaps several years ahead of U.S. scientists in studying geochemical indicators that may be useful for earthquake prediction.

Kamchatka

Since the beginning of 1972, Soviet investigators in Kamchatka have been attempting to use changes in the telluric field, in seismic velocities (v_p/v_s), and in the variations of occurrence of small earthquakes for the routine prediction of earthquakes.

The earthquake regime near Kamchatka is very similar to that of southern Alaska and the Aleutians. Both are characterized by rapid underthrusting of these island arcs by the Pacific plate. This underthrust region is characterized by volcanos, very large shallow earthquakes, a deep-sea trench, and a zone of earthquakes associated with the plunging plate and dipping to great depth under the island arcs. Tectonically, the setting is also very similar to that in Japan.

Fedotov and Mogi have studied the sizes of rupture zones of very large earthquakes in the western Pacific between Kamchatka and Japan. They conclude that great earthquakes tend to fill in so-called seismic gaps, segments of active faults along which no large earthquakes have occurred for periods of tens to hundreds of years. They find that the rupture zones of these great earthquakes along a single large fault tend to abut without significant overlap. Hence, these great shallow earthquakes tend to occur with considerable spatial regularity. Fedotov has used this idea of seismic gaps to forecast those parts of the region between Kamchatka and Japan that appear to have the greatest likelihood of future great earthquakes. This technique does not provide more than a very rough estimate of the time of occurrence of future great shocks. Nevertheless, it can be used to guide more detailed studies of earthquake precursors by allowing investigators to concentrate on a few critical areas rather than spreading their attention over the entire 2,000-mile length of the plate boundary stretching from Kamchatka to Japan.

Soviet geophysicists have been carrying out a series of large underwater explosions for seismic research off the east coast of Kamchatka since 1965 to search for possible precursory changes in the velocity of compressional waves before large earthquakes. Seismic records for several explosions have been obtained each year since 1965 at several stations near the east coast of Kamchatka. The Soviet investigators reported a change in travel time of about 0.1 second over a period of a few years prior to a magnitude 7.2 earthquake that occurred at a depth of about 100 kilometers beneath the region of their experiment. It is not clear whether the change in travel time they observed was actually a precursor of the earthquake or related to uncertainties in the locations of the explosions relative to the rough topography of the ocean floor.

Soviet scientists have also been studying the natural telluric field of the earth near the east coast of Kamchatka. However, since most of the large earthquakes are located in the ocean off the east coast, it is very difficult in this region to use an active measuring technique in which a controlled current is fed into the ground and changes in the electric and magnetic fields are observed at various sites. Nevertheless, some studies have been successful, and a number of short-term variations in the telluric field observed by Soviet investigators are thought to be earthquake precursors, despite the fact that the natural telluric field is characterized by a great deal of noise related to variations in the ionosphere and changes in rainfall.

Japanese Program in Earthquake Prediction

A national program in earthquake prediction was initially launched in Japan in 1965. The funding and planning of the Japanese program have been in 5-year increments, and the program is now mid-way through the third 5-year increment. During the 11-year period 1965-1975, a total of $28 million was allocated for the program (excluding salaries), and for 1975 the amount was about $4 million. While this budget is not as large as that for the Japanese space project, it is strikingly larger than the budgets for other projects in solid-earth science in Japan.

The Japanese program of earthquake prediction places great emphasis on the collection of a wide variety of data that are seen as essential to progress in predicting earthquakes. Three new centers were set up to promote data collection and processing; the Crustal Activity Monitoring Center, for geodetic data and tide-gage data, was set up in the Geographical Survey Institute; the Seismicity Monitoring Center, under the Japan Meteorological Agency, for analyzing and recording earthquakes of magnitudes larger than 3; and the Earthquake Prediction Observation Center, for analysis of microearthquakes (of magnitudes smaller than 3), crustal deformation, magnetic data, and other data from university sources. Data from these three centers are presented to the Coordinating Committee for Earthquake Prediction (CCEP), which consists of specialists from universities and government institutions. The CCEP is actually a headquarters for earthquake prediction.

The Japanese program has established several stages of earthquake alert for scientists, government agencies, and the public. In many ways, this alert sequence is similar to the alerts issued by the Tsunami Warning System, based in Hawaii. (A tsunami is a seismic sea wave.) Whenever anomalous phenomena, such as land deformation, are observed by either nation-wide routine observations in special areas such as active faults and densely populated areas, the region of the anomaly is designated as an "area of intensified observation." If the anomaly is later suspected to be precursory to a major earthquake, the designation changes to "area of concentrated observation" and all types of observations are concentrated there. If precursory phenomena are eventually more positively identified, a warning, or prediction, of an earthquake may be issued to the public.

In his review article, Rikitake mentions that the CCEP is responsible for the judgments involved in the above procedures. However, the members of the CCEP work on a part-time basis only, and it is therefore difficult for them to examine the relevant data on a continuous basis. In addition, with respect to program activity, the CCEP is limited to coordination only. Though the CCEP cannot assign study projects to other organizations when anomalies have been observed, it can provide the available background information and suggest the kinds of observations needed.

Geodetic Surveys

Anomalous crustal uplift has been noted before several large historic earthquakes in Japan, some of them in this century, by geodetic observations. As a result, the Japanese prediction program places great emphasis on both vertical and horizontal geodetic monitoring. About 20,000 kilometers of first-order leveling lines have been established all over Japan. Plans call for the leveling to be repeated at 5-year intervals in order to maximize the probability of detecting anomalous crustal movements and to monitor strain buildup.

Some of the best observations of precursory crustal movements were made prior to the Niigata earthquake of 1964. Several leveling lines established before the earthquake were resurveyed at intervals before the earthquake and again afterward. These surveys showed that precursory uplift began about 10 years before the earthquake. These data have played a central role in developing models of the physical process in precursory phenomena, such as the dilatancy/fluid diffusion model.

A leveling survey of the Boso Peninsula, southeast of Tokyo, indicated a possible anomalous uplift there in 1969. This peninsula was uplifted in the great 1923 Kanto earthquake and had been subsiding since then. Thus, the apparent uplift in 1969 was feared to be a precursor of a large future earthquake. Therefore, the CCEP, in 1969, designated the south Kanto area as an "area of intensified observation." Leveling surveys have been repeated over the Boso and Miura Peninsulas nearly every year since 1970. It is now thought, however, that the apparent anomalous uplift in 1969 was a result of noise or errors in the geodetic observations. The late 1960's were the first time that precise leveling surveys had been carried out in this region a few years apart, but thi experience suggests that such a short period of time does not appear t be enough to obtain a reliable indication of precursory changes in vertical motion. The changes for the period 1965 to 1973 indicate a pattern that is very similar to that which has been going on since 1923. Also, the amount of strain buildup since 1923 is about one-third that released during the 1923 earthquake. Hence, the threat of a repeat of the 1923 earthquake does not now appear as imminent as it did in 1969.

Geodimeters are now being used in Japan on a regular basis for monitoring changes in horizontal distances, and the geodimeter surveys are now being integrated with previous triangulation surveys. Under their present program of earthquake prediction, the Japanese plan to establish a nation-wide network of geodimeter lines consisting of about 6,000 triangles, which they plan to remeasure every 5 years.

As of 1973, Japan had established 17 observatories for monitoring crustal movements with tiltmeters and strain meters, and some of the best data on precursory changes in tilt have come from Japan. It is planned to set up many bore-hold tiltmeters, along with other instruments, in holes several tens of meters deep, in a project to increase the number of tiltmeters and strainmeters in Japan.

Matsushiro Earthquake Swarm

The Matsushiro earthquake swarm of 1965-1977 occurred soon after the Japanese had started their first program of earthquake prediction. A wide variety of field measurements were made at Matsushiro that bear upon searches for precursory phenomena. This is one of the few times when changes both in gravity and in vertical motion were monitored. Although there is considerable debate about the scatter of the data, these observations appear to be in accord with fluid flow into a dilatant region.

One of the outstanding features of the Matsushiro swarm was the gradual enlargement with time of the fault region experiencing earthquakes. It was found that microearthquakes tended to migrate into a new region along the fault zone prior to the occurrence of moderate-size earthquakes a few months later. Based on such observations, warnings were issued that moderate-size earthquakes could be expected within a few months. One of several earthquakes predicted successfully in this way was filmed by cameramen who set up their equipment in advance.

Seismic-Activity Monitoring Programs

The Japan Meteorological Agency (JMA) now records seismic data on magnetic tape at 67 of its weather stations. The JMA network is used to locate earthquakes of magnitude larger than 3.

It is very difficult to locate precisely earthquakes that occur along the inner wall of the Japan trench off the east coast of Japan. Since the largest Japanese earthquakes occur in this offshore area, the third 5-year plan for earthquake prediction calls for the installation of several ocean-bottom seismographs for continuous monitoring of this offshore activity. This work is also under way with the JMA.

Several university groups in Japan have active programs of monitoring earthquakes smaller than magnitude 3. A great deal of research is currently under way to search for changes in the relative numbers of large and small earthquakes (the so-called b value) and for changes in the frequency of occurrence of small earthquakes. Plans are under way for telemetering of much of the data on small earthquakes to several regional centers for analysis.

To overcome problems of man-made noise in the Tokyo area, the National Research Center for Disaster Prevention installed borehole seismometers in a 3,500-meter (11,500-foot) well a few tens of kilometers north of Tokyo.

Seismic Wave Velocities

Explosions have been detonated on Oshima Island, south of Tokyo, approximately once a year since 1968 to monitor the seismic waves thus generated. No change in the velocity of the compressional (p) wave exceeding 0.1% appears to have taken place.

Ohtake has reported changes in v_p/v_s prior to 3 earthquakes in Japan, including one of the Matsushiro swarm.

Magnetic and Electrical Fields

Proton-precession magnetometers with digital recording have been set up at 12 stations in Japan. However, noise caused by local variations in the magnetic field of as much as 2 gammas between stations a few hundred kilometers apart tends to mask possible magnetic precursory signals. Also, stray electric currents from the extensive electric railways in Japan lead to large local magnetic disturbances.

Seismic Gaps

Extensive work has been done by Mogi and Utsu in identifying seismic gaps in Japan. The June 17, 1973, Nemuro-Oki earthquake, off the coast of Hokkaido occurred in one such seismic gap that had been cited as a likely place for a future earthquake. Utsu has identified five sites in central and southwestern Japan at which earthquakes with magnitudes estimated at 7 or greater occurred between 715 AD and 1325 AD as places that should be watched carefully as possible sites of future large earthquakes.

Summary

A great variety of research and data collection programs are under way in many areas in Japan to search for and monitor precursory phenomena that can be used to predict earthquakes. In addition to the geophysical disciplines mentioned above, geologists and geographers have been examining active faults, folding, and other crustal movements in rocks of the Quaternary Period (approximately the past 2 million years). Long-term rates of movement have been estimated for many faults. Also, an intensive program of laboratory studies in rock mechanics is under way to increase understanding of the physical basis of earthquake prediction.

It is quite possible that Japan will become the first country to achieve routine prediction of earthquakes. The Japanese have the experience gained from an 11-year national program of earthquake prediction, a vast number of trained scientists and technicians active in earthquake studies, and a relatively small geographic area to monitor, compared with the size of earthquake regions in the United States, the U.S.S.R., and China, for example. Also, most damaging earthquakes in Japan occur at shallow depths within the islands. These shocks generally tend to be more damaging even though they are smaller than the great earthquakes located off the east coast of Japan. Shallow earthquakes within lithospheric plates, such as those within the Japanese islands, are the sources of many of the precursory effects detected thus far. The shallow nature of the sources, and the fact that the source regions can be readily surrounded by instruments, make it much easier to monitor possible precursory changes than if the earthquakes were located off the coast.

Earthquake Prediction in China

A massive effort to detect a wide variety of precursory phenomena associated with earthquakes is under way in China. The scale of this program, and most of its results over the last few years, became known to foreign scientists when a seismology delegation from the United States visited China in October and November 1974. There has been heightened interest in the United States in earthquake prediction in China following announcements by the Chinese that they had successfully predicted a major earthquake that occurred in northeastern China on February 4, 1975. If that event was indeed predicted using acceptable scientific criteria, it is a major milestone in the history of seismology and in the forecasting of natural disasters.

Field programs to detect possible precursory phenomena have been under way for the past few years at the provincial centers of Kunming (Yunnan), Chengtu (Szechuan), and Lanchou (Kansu), within the zone of high seismic activity that crosses China from south to north, as well as in the Peking area, in the region of the damaging Hsingtai earthquakes of 1966, and near the Hsinfengking dam in Kwangtung province.

The very high level of seismic activity and the relative accessibility of many of the active regions of China to monitoring (the most active zone for earthquakes affecting the United States, by comparison, is located almost entirely offshore, along the Aleutian trench) are two factors that have led to the rapid accumulation of precursory data and can be expected to remain important for prediction of large earthquakes in China in the future. A wide variety of precursory phenomena--the existence of which have been reported previously in Japan, the U.S.S.R., and the United States--are being studied in China, largely empirically. Relatively little effort appears to have been made thus far in designing field or laboratory experiments around theories or models, such as the dilatancy/fluid-diffusion hypothesis.

Most Chinese scientists appear to be convinced that earthquakes are preceded by a wide range of precursory phenomena and that these phenomena occur in a variety of tectonic environments. Changes in the following variables have been reported prior to earthquakes and are being studied actively in extensive field programs: crustal movements, seismic velocities, frequency of occurrence of small earthquakes, seismic attenuation, the flux of radon from water in deep wells and springs, water level and temperature in wells, geomagnetic field, natural geoelectric field using telluric currents, and earth resistivity using an applied potential. Chinese scientists generally distinguish precursory phenomena as either long term (years), intermediate term (months to weeks), or short term (days to minutes).

Visiting U.S. scientists generally believe that several of the reported changes in radon flux, seismic velocity, and frequency of occurrence of small earthquakes appear to represent valid precusory phenomena. Some of the other reported anomalies may result from other causes and may have been associated in time with the earthquakes only by chance. Although precursory phenomena were observed hundreds of kilometers from the epicenters of magnitude 4-to-5 shocks, most of the anomalies with high signal-to-noise ratios did not occur at such great distances but were limited to within a few fault-rupture lengths from the epicenters. Several of the better examples of precursory phenomena have a time duration, t, that falls close to the line

$$\log t = a + cM,$$

discussed by Scholz *et al.* (1973) and Whitcomb *et al.* (1973) where a and c are constants and M is the magnitude. In addition, various short-term effects that fall well below the line defined by the equation were also observed before moderate and large earthquakes.

Among various Chinese scientists, attitudes range from acceptance of nearly all reported anomalies as valid precursors to earthquakes to the view that a large body of data should be accumulated before certain types of anomalies are chosen as the more reliable precursors. The more senior scientists generally hold the latter view.

Particularly at the provincial and county levels, where a great amount of the monitoring and data analysis is now being done, attempts are being made to use a variety of types of anomalies to predict earthquakes routinely. In addition to the February 4, 1975, earthquake, Chinese scientists claim to have predicted several other earthquakes successfully. They emphasize, however, that they have failed in some other predictions, that they have not estimated the time, place, or size very accurately in still others, and that they have made some predictions that turned out to be false alarms. They are not yet prepared to tabulate these results so as to produce a false-alarm ratio or a success-failure percentage. Most Chinese scientists believe that observations using a multiplicity of techniques, rather than reliance on a single method, are necessary for reliable prediction.

The scale of the Chinese effort to predict earthquakes is very large indeed. Some 10,000 trained workers are involved and, although figures are not available, the number of untrained volunteers working part-time is probably as large. Although the cost of this effort is difficult to convert into a U.S. monetary equivalent, it might be in the range of $50 million to $100 million a year. Although the reasons for investing such a large amount of human and economic resources in this program were not discussed during the American visit in 1974, there appear to be several fairly obvious explanations.

From a practical standpoint, the prediction of a forthcoming great earthquake is at present the only way to avoid repetition of some of the terrible calamities of the past few hundred years. The loss of 820,000 lives in the Huahsin earthquake of 1556 AD, near Sian, was due almost entirely to the collapse of houses in the densely populated valley of the Wei and Huang rivers. Housing construction in that area today, as in much of rural China in general, is undoubtedly not greatly different from that of 1556. New construction, though of brick, is generally not designed for earthquake resistance and is likewise liable to major damage in a great earthquake. To bring rural construction, which houses over 600 million Chinese, up to earthquake-resistant design standards would require an effort so immense that China's goal of industrial self-sufficiency would be drastically retarded. On the other hand, following an earthquake, reconstruction in the limited regions that will suffer great earthquakes in the next 100 years would not be a burden on the economy, *provided the inhabitants survive*. If, therefore, the great earthquakes can be predicted, the inhabitants' lives can be saved without having to resort to the draconian solution of seriously modifying or rebuilding the 30 percent or so of China's total existing housing that occupies its earthquake-prone regions.

Given the practical need for reliable prediction, then, the Chinese believe, further, that earthquakes are predictable. In their very well-documented history of large earthquakes, examples of precursory phenomena are numerous and, in particular, certain of these recur. Peculiarities in the behavior of animals and anomalous changes in the water level or water quality in wells have been reported repeatedly. Therefore, at least empirically if not theoretically, the problem seems to be a soluble one.

An extensive description of Chinese work in earthquake prediction was published in 1975 by the U.S. Delegation on Seismology that visited China in 1974.

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