EARTHQUAKE PREDICTION IN THE UNITED STATES*

By *Carl* KISSLINGER

Although the title of this lecture is Earthquake Prediction in the United States, the efforts to learn how to predict earthquakes are similar in all countries engaged in this work. There may be some differences in emphasis in different countries, but these remarks are applicable quite generally to the world effort to predict earthquakes. Scientists in the United States have benefited very much from the research done in Japan, as well as in other countries.

The prediction of earthquakes has been more a dream than a serious hope until recent years. Although earthquake scientists have discussed prediction for more than a century, only in about the last 20 years has this been the subject of systematic research on a large scale. Japan has been a world leader in this effort and now four countries have major programs; Japan, U. S. A., China and U. S. S. R. We are trying to understand the processes of earthquakes and the changes that take place within the earth before an earthquake well enough to be able to make reliable predictions of future events.

A definition of a prediction serves two useful purposes. A statement of what we understand a prediction to be also serves as a definition of the problem that we are trying to solve. Secondly, this definition provides us with a basis for judging the validity and merit of predictions that are made by various people. Seismologists have come to agree that an earthquake prediction is a statement about a future event that specifies the time, the place and the magnitude of that event, with some estimation of the errors expected in each of these parameters. We do not now know how to make such predictions. A statement about a future earthquake is not a 'prediction' in this strict sense unless all three of the parameters are given.

Two fundamental concepts guide the research on earthquake prediction: the plate tectonics theory of global geological processes and the elastic rebound theory of earthquake occurrence. Plate tectonics explains major geological processes in terms of the interaction of rigid lithospheric plates as they move over the earth's interior. Plate tectonics offers two ideas of special significance for prediction efforts; it explains why most earthquakes occur in well-defined seismic belts, so that we have an idea of where to go in order to have a high probability of observing major earthquakes, and it offers a basis for estimating the rate at which elastic strain energy accumulates along plate boundaries, an aid in estimating the likely time interval between great earthquakes on plate boundaries. Because we do not understand the origin of intraplate earthquakes in terms of any general model of geological processes, we are in a somewhat worse situation with regard to predicting these than we are for interplate events.

The elastic rebound theory states that earthquakes release energy that has accumulated slowly as elastic strain energy in deformed rocks around the fault. The earthquake occurs when the strains, or corresponding stresses, have become large enough to cause the rocks along the fault to rupture, leading to sudden slip. This model shows that if we want to predict earthquakes, we must observe indicators of

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high strain or stress in the rocks near the fault. Indicators that the rocks are in a highly strained state and that rupture is imminent are called 'precursors' of the earthquake. An ideal precursor would be some kind of behavior that always happens before an earthquake and never happens without an earthquake. No ideal precursor has yet been discovered. It is likely that a system for predicting earthquakes will be based on the use of some combination of precursors, any one of which by itself is of limited reliability, but which taken together offer a strong indication of a coming earthquake.

Many phenomena have been suggested as precursors and all of these have been investigated further and evaluated as diagnostic aids for prediction. An abundant literature on this subject exists and should be consulted for the details of various proposed precursors. Premonitory phenomena can be usefully classified as: patterns of seismicity in time and space, anomalous crustal deformation and other evidence of localized strain, changes in the level or chemistry of ground water and related changes in the composition of soil gas, and changes in the properties of rocks under high stress (electrical conductivity, wave velocities, etc.).

Seismicity patterns in time and space have emerged as very promising aids to prediction. The general global distribution of earthquakes is well-known after a century of instrumental recording and analysis of earthquake waves. The vast majority of earthquake energy is released in well-defined belts located along the boundaries between lithospheric plates. Examination of the seismicity data shows, however, that these belts are not continuously filled with great earthquakes during short time intervals and this observation has led to the important idea of seismic gaps. A seismic gap is a portion of a plate boundary in which one or more great earthquakes are known to have occurred in the past, but within which no great earthquake has happened during some number of years, the number of years to be decided by investigation. Such a gap is considered to have a high potential for a great earthquake in the near future. One group of U. S. investigators takes one hundred years as the required time to make a place a gap with high potential, and if a great earthquake has occurred more recently than 30 years, the place is considered to have low potential. The existence of a gap calls for a partial prediction, in the sense that the place is identified and the likely magnitude if a great, gap-filling earthquake occurs can be estimated from the length of the gap and the past history. No information about the time at which the earthquake will occur is provided. The existence of a gap is not a precursor in the sense defined above.

Recent research in Japan and the United States has shown that it may be possible also to predict the time to the next great event in a gap if the amount of slip that occurred in the most recent great earthquake and the long-term average rate of slip along the particular portion of plate boundary can be estimated.

Other aspects of seismicity patterns are under study as true precursors. Periods of quiescence, during which the rate of occurrence of smaller, background earthquakes decreases significantly, have been discovered before some big earthquakes. On the other hand, precursory clusters of increased activity and foreshocks have also been observed. Foreshocks offer much promise as an aid to prediction, if a way can be found to identify them as foreshocks before the main event occurs. Unfortunately, it is known that not all great earthquakes are preceded by detectable foreshocks. In our work, we have found evidence that foreshocks may be characterized by a systematic rotation of the orientation of the fault planes on which the earthquakes occur from that usually seen at the place. This behavior has been reported by other investigators, but it is not known how general this phenomenon is.

A major concern of American earthquake prediction scientists at this time is the likelihood of a great earthquake along the southern portion of the San Andreas fault, to the north and east of Los Angeles. This section of the fault, which forms the plate boundary between the Pacific and North American Plates, last broke in a great earthquake in 1857 and is clearly identified as a seismic gap. Based on geological studies, the average interval between great earthquakes seems to be about 150 years, but with a rather large deviation from this value, so that a great earthquake at this place within the next 20–30 years would not be surprising. In addition, this section of the fault has been remarkably quiet with respect to small and moderate earthquakes for many years, but the number of such events has increased recently.

The seismicity pattern, crustal deformation observations and other data indicate that a large earthquake may be imminent, but the science is not advanced far enough to allow a firm prediction. One of the interesting possible precursors that is under study here and elsewhere is the variation in radon gas in underground water or in the soil. There are reports from various earthquake zones of increases in the concentration of radon prior to an earthquake, but the relationship of the radon anomalies to the earthquakes is not at all clear. Large changes in radon concentration have been seen at a few sites in southern California recently, but the investigators are not prepared to claim that these can be interpreted as precursors.

Localized deformations of the earth's surface, either changes in elevation or changes in the distances between reference points, are indicators of accumulating strain in the earth's crust. Systematic repeated surveying of the land, with the highest available precision, is the standard method of detecting such crustal deformations. This approach is, however, very expensive in terms of manpower and time. More economical methods for gaining the same kind of information have been developed or are under study now. These included point measurements of strain (strainmeters), tilt (tiltmeters) and gravity changes as the earth's surface goes up and down. None of these methods has yet been proven capable of detecting slow deformations over many years, but they seem to have much promise as devices for monitoring short-term deformations that might precede an earthquake by a short time. Another great hope for the future is the application of space-based geodetic techniques, such as laser ranging to satellites and Very Long Baseline Interferometry measurements, to the problems of geodynamics. When the resolving power of these methods has been improved to the order of a few centimeters, they should provide fast access to large amounts of data from which localized and regional crustal deformation can be detected.

The precise measurement of distances by measurement of the transit time of electromagnetic waves offers a way of continuously monitoring crustal deformation over line lengths of a few to perhaps 10–15 km. The use of two wavelengths in a device now in use along active faults in California greatly reduces errors resulting from variations in the properties of the atmosphere, especially temperature, along the measurement path. These measurements have revealed slow movements associated with strain build-up along the fault, as well as sudden changes caused by creep events along the fault.

In addition to the scientific and technical questions that must be answered by prediction research, there are also important practical questions regarding how society should organize itself to make wise use of predictions when reliable methods are eventually developed. Serious consequences will follow if predictions are announced without proper preparation of the public and the formulation of well-designed plans of action by the administrative authorities. Japan is far ahead of the rest of the world with regard to this problem because of the enactment of Large-Scale Earthquake Countermeasures Act in 1978. This law assigns powers and responsibility to individuals and groups, from the Prime Minister down, in the event that the evidence indicates that a prediction is called for. Although there is much concern in the

United States about the social and economic impact of the predictions of damaging earthquakes, no corresponding laws or plans of action at the national level have been fully developed.

We do recognize that wise leadership and careful advance planning are needed if predictions are to be beneficial and lead to the reduction of losses of life and property caused by earthquakes. We also note that the problem is especially difficult during this time, when all attempts to make predictions are necessarily scientific experiments. However, we must make such experiments, some of which will fail and lead to public confusion, if we wish to make progress toward the development of reliable techniques for earthquake prediction.

アメリカにおける地震予知の研究*

Carl KISSLINGER

講演者の紹介と滞在中の活動

略　歴

～1970 米国 Saint Louis 大学準教授（地球物理学）
1971～ 〃 Colorado 大学環境科学研究所教授（地学）
1974～1981 同研究所長
1972～1973 米国地震学会会長
1973, 1977 日米地震予知シンポジウム米国側代表

研究業績

地震発生のメカニズム，地震予知等に関して多くの論文がある。
現在はアリューシャン列島附近の地震予知の研究に精力を注いでいる。

1982年1月31日 京都到着
2月2日 京大防災研究所訪問：地震グループと懇談討論，地震観測テレメータ・システム見学，研究所講演会出席
2月3日 京大理学部地震予知観測地域センター（高槻市阿武山）訪問，観測システム見学
2月4日 京大防災研究所訪問：地震予知問題等議論，午後特別講演（地震学）
講演題目
(1) 局地地震の発震機構決定のための地震波振幅データの利用
(2) 中部アリューシャン列島の地震テクトニクスと地震予知
2月5日 大阪にて特別講演
"アメリカにおける地震予知の研究"
2月8日 名古屋大学理学部，地球科学教室及び地震予知観測センター訪問
2月9日 気象庁地震課訪問
2月10日 東京大学地震研究所訪問，特別講演
2月12日 筑波研究学園都市訪問
建設省建築研究所国際地震工学研修センター
国立防災科学技術センター
2月14日 帰国

* 講演者の紹介は三雲　健が担当した。