EARTHQUAKE PREDICTION

TSUNEJI RIKITAKE

DEVELOPMENTS IN SOLID EARTH GEOPHYSICS

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PREFACE

Academic as well as social attention has recently been drawn to earthquake prediction especially in countries like Japan, the U.S.A., the U.S.S.R., the People's Republic of China and so on which have been suffering from destructive earthquakes from time to time. Intensive work on earthquake prediction study in these countries has brought out some clues that enable us to believe that prediction of some earthquakes, if not all, will be put into practice in the foreseeable future.

The present author, who has been working in the Earthquake Research Institute (ERI), University of Tokyo for over 30 years has become involved in the national program on earthquake prediction in Japan although he was originally a geomagnetician. As one of the senior members of the ERI, which is one of the most powerful agencies of earthquake research in Japan, it was natural to take part in such a nationwide program.

As international interest in earthquake prediction grew in the 1960s, the author was also asked to organize a number of international symposia on earthquake prediction and has been working as the secretary of the International Commission on Earthquake Prediction attached to the International Association of Seismology and the Physics of the Earth's Interior.

All through his activity mentioned in the above, he began to feel that a textbook on earthquake prediction is needed not only by students who want to study prediction-oriented seismology but also by non-professional people who are concerned with the present status of scientific earthquake prediction. It would also be a matter of utmost importance to let administrative and legislative people know about the feasibility of earthquake prediction.

This is the reason why the author has undertaken the writing of a book on earthquake prediction. A number of friends of his said that it would not be the right time to write a book on the subject because earthquake prediction study is rapidly developing and relevant data are accumulating with an immense speed at the moment. The author agrees with them. But he still thinks that it might be worthwhile writing a book on the subject because it would doubtless stimulate further study. In order to have a variety of readers, the author tried not to use much mathematics. Although some mathematics will be found in a few chapters of this book, the author hopes that what he writes can be understood even if those mathematical expressions are skipped.

Many earthquake prediction studies have appeared in classical documents as well as current journals and books written in Japanese which are too difficult for people outside Japan to read. As there is no doubt that Japan has played the leading part in promoting earthquake prediction study, what the author writes about Japanese work in this book may be of some help to overseas readers.

A number of Chinese achievements are also included in this book although the author reads Chinese writings very poorly. As for literature written in Russian, only translations either in Japanese or English can be referred to because the author does not read Russian. The author fears, therefore, that important literature written in Russian might be missing. He sincerely hopes that a similar book on earthquake prediction would be published in a popular language such as English by someone who can extensively refer to literature written in Russian.

At this point the author would like to pay a tribute to Professor T. Hagiwara, the Chairman of the Coordinating Committee of Earthquake Prediction in Japan and the Ex-chairman of the International Commission on Earthquake Prediction for his vigor in promoting earthquake prediction study. The author was stimulated very much by discussions almost every day with Professor Hagiwara while he was working at the ERI. The author has also been inspired in many respects of geophysics by Professor Takesi Nagata, now the Director of the National Institute of Polar Research in Japan. The author is very thankful to these senior colleagues. The author has also been influenced by many colleagues in the ERI. Among them, he should like to extend his thanks especially to Professors I. Tsubokawa, K. Mogi and Y. Hagiwara whose geodetic and laboratory work has been most important in developing a theory of earthquake prediction.

Drs. Y. Harada, T. Dambara, M. Tazima, N. Fujita and other members of the Geographical Survey Institute also inspired the author through personal talks. The author would like to thank them. Many data were supplied to the author by observers and researchers who are working at the frontier of earthquake prediction study in Japan. The author is particularly indebted to Drs. T. Matsuda and K. Nakamura at the ERI for geological information, Drs. T. Mikumo and K. Oike at the Kyoto University for microseismic data, and Drs. Y. Tanaka and T. Tanaka at the Kyoto University for crustal movement data.

Dr. Y. Yamazaki at the ERI performed a unique observation of resistivity change at the author's suggestion. He also assisted the author in many ways in promoting earthquake prediction study. The author sincerely thanks Dr. Yamazaki for his help.

Turning to the support given by overseas colleagues to the author's work, he should first of all like to thank the members of the Cooperative Institute for Research in Environmental Sciences (CIRES) operated by the University of Colorado and the National Oceanic and Atmospheric Administration (NOAA). The author is especially grateful for many inspiring discussions with Professor C. Kisslinger, the Director of the CIRES. Chinese literature, which he brought back from China as one of the members of the U.S. seismology delegation sent to China in 1974, was of great help to the author.

Dr. E.R. Engdahl critically read the manuscript and Mrs. J. Trebing kindly checked the English. Dr. T. Chan helped the author in reading Chinese

literature. The author would like to extend his sincere thanks to them. Substantial portions of this book were completed while the author was holding a Senior Visiting Fellowship at the CIRES in 1974 and 1975.

Some of crustal movement data were supplied to the author by Dr. G.J. Lensen of the New Zealand Geological Survey and Dr. S.R. Holdahl of the National Ocean Survey, NOAA. The author is very grateful to them.

In conclusion the author should like to thank Drs. F.W.B. van Eysinga of Elsevier Scientific Publishing Company who urged the author to write this book and constantly encouraged him in the course of writing.

T. RIKITAKE

CONTENTS

Chapter 1

INTRODUCTORY REMARKS

Predicting an earthquake is certainly a matter of deep concern for seismologists as well as the general public. In a highly seismic country like Japan, where people have long suffered from earthquake disasters, the desire to foretell an earthquake was so strong that people were tempted to rely on superstitious fortune-telling in earlier years. It is only recently that earthquake prediction on a scientific basis became known as one of the branches of earth science. A nationwide program on earthquake prediction started only in the early 1960s in Japan. Intensive studies on the subject seem to have started in the U.S.S.R., the People's Republic of China, the U.S.A. and other countries some time later.

Although many papers on earthquake prediction came out in recent years, not very many reviews, by which we can see the overall development of the subject, have so far been published. It is perhaps better to draw up a list of them in the following so that those who want to trace the progress of earthquake prediction study may refer to them:

1962: Hagiwara, T., Earthquake prediction (in Japanese).
Tsuboi, C. et al., *Prediction of Earthquakes — Progress to Date and Plans for further Development* (Report of the Earthquake Prediction Research Group in Japan).

1964: Oliver, J., Earthquake prediction.

1965: Press, F., Earthquake prediction: a challenge to geophysicists.
Press, F. et al., *Earthquake Prediction: a Proposal for a Ten Year Program of Research.*

1966: Båth, M., Earthquake prediction.
Lomnitz, C., Statistical prediction of earthquakes.
Press, F. and Brace, W.F., Earthquake prediction.
Rikitake, T., A five-year plan for earthquake prediction research in Japan.

1967: Hagiwara, T. and Rikitake, T., Japanese program on earthquake prediction.

1968: Press, F., A strategy for an earthquake prediction research program.
Rikitake, T., Earthquake prediction.
Savarensky, E.F., On the prediction of earthquakes.

1969: Hagiwara, T., Prediction of earthquakes.
Hagiwara, T. and Rikitake, T., La previsione dei terremoti.
Hagiwara, T. and Rikitake, T., Neue Entwicklungen in der Erdbebenprognose.
Pakiser, L.C. et al., Earthquake prediction and control.

1970: Kanamori, H., Recent developments in earthquake prediction research in Japan.
Nersesov, I.L., Earthquake prognostication in the Soviet Union.
Oliver, J., Recent earthquake prediction research in the U.S.A.
Rikitake, T., Prévision des tremblements de terre.

1971: Coe, R.S., Earthquake prediction program in the People's Republic of China.
Pakiser, L.C. and Healy, J.H., Prédiction et contrôle des tremblements de terre.

1972: Healy, J.H. et al., Prospects for earthquake prediction and control.
Rikitake, T., Earthquake prediction studies in Japan.
Rikitake, T., Problems of predicting earthquakes.
Rikitake, T., An earthquake prediction operation in an area south of Tokyo.
Sadovsky, M.A. et al., The processes preceding strong earthquakes in some regions of Middle Asia.
Savarensky, E.F. et al., Geophysical principles for studying forerunners of earthquakes.

1973: Hagiwara, T., The development of earthquake prediction research (in Japanese).

1974: Bolt, B.A., Earthquake studies in the People's Republic of China.
Johnston, M.J.S. et al., Earthquakes — can they be predicted or controlled?
Kisslinger, C., Earthquake prediction.
Rikitake, T., Japanese national program on earthquake prediction.
Sadovsky, M.A. and Nersesov, I.L., Forecasts of earthquakes on the basis of complex geophysical features.
Savarensky, E.F., Introductory remarks and Soviet national program on earthquake prediction.

1975: Press, F., Earthquake prediction.

Complete references of the above reviews will be found in the bibliography toward the end of this book. Perhaps there are other review papers which were overlooked by the author. Schmidt (1971, 1973) published comprehensive lists of earthquake prediction-oriented papers including those written in Russian. As the author does not read Russian, it is likely that he missed review papers written in Russian. It is also regrettable that many papers published in China are at the moment inaccessible to the author, so that it is possible that there are important reviews in Chinese that have not come to the author's attention.

On the basis of those reviews and numerous individual papers, the author tried to summarize the most up-to-date knowledge about earthquake prediction study in this book. Emphasis will especially be put on Japanese work, much of which has not been known outside Japan because of linguistic difficulties. The author is convinced that data taken in Japan play an important role in promoting earthquake prediction study because seismicity is high there and a well-organized program on earthquake prediction is underway.

First of all, many of the legends about non-scientific prediction of earthquakes will be presented in Chapter 2 mostly on the basis of Japanese sources. Being picked up from historical documents, most of these legends are hard to believe. However, what is written in this chapter might be of some interest especially for non-Japanese readers because Japanese classical writings are quite inaccessible to most overseas people. At any rate, what is written in this chapter demonstrates how strong the longing of mankind to have the ability to forecast a disastrous earthquake was even in medieval time.

The science of earthquakes in early years was developed mostly in Japan after its new civilization about 100 years ago. Chapter 3 is devoted to describing how prediction-oriented earthquake science developed in Japan. It is rather surprising that no strong appeal for earthquake prediction study was proposed until about 15 years ago in spite of many disastrous earthquakes occurring in Japan. As a matter of fact, it used to be a taboo for a seismologist to talk about earthquake prediction some 30 years ago when the author was a student. A seismologist was supposed to work on less ambitious subjects and write papers.

However, data relevant to earthquake prediction have been accumulating over a period of scores of years. As will be mentioned in Chapter 4, a research group for earthquake prediction was formed in Japan around 1960. Japanese seismologists have now started to discuss ambitiously a possible approach to earthquake prediction at many meetings. The outcome of the group's discussion was published as a now-famous report named *Prediction of Earthquakes — Progress to Date and Plans for further Development* (Tsuboi et al., 1962). Being called the "blueprint" of earthquake prediction research, the report became a milestone of earthquake prediction study in later years.

It appears to the author that no remarkable effort toward earthquake prediction was made in the U.S.A. until a U.S.—Japan conference on earthquake prediction was held in Tokyo and Kyoto in 1964. Soon after the conference, a highly destructive earthquake of magnitude 8.4 hit Alaska giving rise to much damage there. In the following years, earthquake prediction has become one of the important subjects of earth science in the U.S.A. Although no nationwide program was set up until 1974, much money funded by the National Science Foundation (NSF) and the U.S. Geological Survey (USGS) was spent in promoting earthquake prediction study in the U.S.A.; some of the American work such as microearthquake monitoring became more advanced than that in Japan despite the fact that the project started only recently.

On the other hand, it becomes apparent that intensive earthquake prediction studies are progressing in Central Asia and Kamchatka, the U.S.S.R. (Rikitake, 1968b, 1970b; Savarensky, 1974; Savarensky and Rikitake, 1972). Coe (1971) and Bolt (1974) reported on intensive work on earthquake prediction that is in progress in the People's Republic of China.

Programs on earthquake prediction in these countries will be given in a summarized form in Chapter 4 although only limited knowledge about the programs in the U.S.S.R. and China was available to the author.

From Chapter 5 on, the author reports on various geophysical elements that are thought to have something to do with earthquake prediction. One of the most outstanding discoveries by Japanese workers, who vigorously took up intensive studies of earthquake phenomena after the great Kanto earthquake of 1923, was certainly the crustal deformation that occurs in association with a large earthquake. Although it has been known in Japan since A.D. 679 that a crustal deformation is accompanied by a strong earthquake, the precise characteristics of earthquake-associated crustal movement have become clear only by repetition of geodetic surveys.

In Chapter 5 are summarized almost all reported examples of land deformation associated with an earthquake as revealed by repetition of triangulation, levelling and geodimeter surveys in an encyclopedic manner. These studies have an important bearing on estimating the ultimate strain of the earth's crust. Even a number of precursory land deformations forerunning an earthquake have been found by the geodetic method.

A few classic reports on anomalous sea retreats are reproduced in Chapter 6. Curiously enough, only a very few examples of precursory land uplift or subsidence relative to sea level have been found through modern tide-gauge observations.

In order to supplement geodetic work, that is essentially intermittent, continuous observations of crustal movement have long been made by making use of tiltmeters and strainmeters of various models as readers will see in Chapter 7. General agreement between crustal deformations as revealed by geodetic surveys and those observed by water-tube tiltmeters have been reported in Japan. Although quite a few precursory effects have been reported by tiltmeter and strainmeter observations, it seems likely that signals observed by horizontal pendulum tiltmeters as well as highly sensitive strainmeters are often contaminated with noise as the statistics in Chapter 15 indicate. However, water-tube and borehole tiltmeters seem fairly reliable.

Chapter 8 is reserved for seismicity research, which plays one of the most fundamental roles in earthquake prediction. Current theory on plate tectonics had a strong impact on the basic idea of earthquake prediction. Extremely large earthquakes occurring in front of an island arc are interpreted as the result of crustal rebound following a tremendous compression or shearing by plate motion. Although no detailed mechanism of medium or small earthquakes beneath an island arc has been worked out, there is no doubt about the importance of monitoring strain accumulation in the earth's crust for earthquake prediction. The implication of plate tectonics on earthquake prediction will be reviewed in the first section of Chapter 8.

Present status and recent achievements of intensive microearthquake observation in Japan and the U.S.A. is also dealt with in Chapter 8. Several characteristics of foreshock activities, i.e. decreases in b-value and seismicity, reorientation of the axis of compression for small shocks prior to a main shock and the like will be described along with the concept of seismicity gaps which plays an important role in determining probable locations of large earthquake in the near future. Brief mention will be made about deep-well observations of microearthquakes, which seem to be the only way to obtain highly sensitive observations in a noisy city such as Tokyo, and submarine seismology, too.

It is still hard to say that much about foreshock activities is well understood. In some cases many microearthquakes forerun a moderately large earthquake as observed a number of times during the 1965—1967 Matsushiro earthquake swarm in Japan. On the contrary, it is believed, according to the concept of a seismicity gap, that areas of very low seismicity at present, such as the San Francisco and the South Kanto (a district to the south of Tokyo) areas, would become the seat of a large earthquake some day. Such apparently conflicting views must be understood by taking different conditions in the earth's crust of respective zones into account.

Quite an exciting discovery pertinent to earthquake prediction was reported from studies of seismic wave velocities in the Garm area, Middle Asia, U.S.S.R. It was found that the ratio of P-wave velocity V_p to S-wave velocity V_s of small earthquakes in an area considerably decreases before a moderately large earthquake that occurs in the same area. As will be seen in Chapter 9, it was really hard for the present author to believe that V_p changes by 15% or so when he was first informed by Professor E.F. Savarensky (1968) who talked about Soviet discoveries at a symposium in Zurich in 1967. It was ascertained, however, by the later work in the U.S.S.R. and the U.S.A. that the V_p/V_s ratio drops and recovers prior to an earthquake in many cases. The length of anomalous period of the V_p/V_s ratio seems to be closely correlated with the magnitude of the coming earthquake. As similar findings were later reported from Japan and China, changes in the V_p/V_s ratio or V_p itself have become one of the most powerful elements of earthquake prediction. Intensive study of the physical mechanism for such a change led us to a dilatancy model as will be seen in later chapters.

Changes in the geomagnetic field and earth currents, which are reviewed in Chapter 10, have long been supposed to have something to do with earthquake occurrence. Modern studies made it clear, however, that most of the data in earlier years are spurious because of inadequate measuring and noise-elimination techniques. It seems now established that a seismomagnetic effect hardly exceeds the order of 10 gammas (about 1/500 of the intensity of the earth's magnetic field). A precursory geomagnetic change may well be a little smaller. According to a recent development in the measuring technique of the geomagnetic field, however, it is not quite hopeless to monitor a magnetic forerunner in a low-noise circumstance. In spite of many reports of anomalous changes in earth currents associated with an earthquake, no clear-cut overall character of precursory signals in earth-currents has been brought to light. Remarkable changes in electric resistivity forerunning an earthquake have been reported first in the Garm region followed by a similar observation on the San Andreas fault, California, U.S.A. On the other hand, precursory and coseismic changes in earth resistivity associated with large earthquakes at a teleseismic distance have been observed by an unusually high-sensitivity