EARTHQUAKE GENERATION AND PREDICTION

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Summary

Seismic geography achieved the detailed mapping of global seismicity by the mid-1950's. On this basis, and with earthquake occurrence seen as a random process, seismic zoning was developed, and adopted in most earthquake-prone countries by the early 1960's. At that time, the prediction of individual earthquakes was generally seen as beyond the reach of science.

Plate tectonics emerged in the mid-1960's and cast new light on the global distribution of stress regimes and the associated seismicity. Support was also claimed for a view of earthquake generation which postulated a high degree of regularity in the location, magnitude, and occurrence-time of earthquakes. These features of the seismic gap hypothesis, and the proposed "seismic cycle", still attract much attention as a possible basis for earthquake prediction, but the claimed regularities and prediction results remain controversial.

Deterministic chaos has more recently raised the understanding of earthquake generation to a new level. The two main quantitative relations of seismic geography - Omori's law of 1895 and the Gutenberg-Richter relation (1954) - are now recognised as fractal, while the elements of randomness, and the fractals, are attributed to a state of self-organized criticality. The lithosphere is maintained in this state by plate motion, and regularities such as periodicity are not to be expected.

Earthquake generation can thus be understood in terms of seismic geography, plate tectonics and deterministic chaos. Within this framework, the goal of prediction can now be pursued, as in meteorology, through the study of precursory phenomena.

Introduction

The ability to predict a phenomenon is a measure of the extent to which it is understood, and prediction has been called the aim of all science. Recent earthquake disasters have confirmed that human tragedy and material destruction are largely man-made, and could have been largely mitigated, given due warning. Earthquake prediction on every possible time-scale is needed for the most effective application of countermeasures. For example, long-range prediction would focus timely attention, in the areas at risk, on the design and construction of earthquake-resistant buildings, and on the strengthening or replacement of weak ones, while short-range prediction would enable the evacuation of any weak buildings that remained.

As sources of radiated waves, earthquakes have revealed most of what is known about the Earth's internal structure, and this branch of seismology has recently developed further into seismic tomography and anisotropy mapping. The phenomenology of earthquakes has proved a more difficult study, and earthquake prediction has been slow to develop. Three major contributions to the understanding of earthquake generation can be recognised since the elastic rebound hypothesis was proposed by H.F.Reid in 1910: global seismic geography, plate tectonics and deterministic chaos. Efforts to translate these advances into predictive capacity have so far had only limited success. A level of understanding is now being reached, however, which may well support a higher form of prediction than has been possible in the past. This can best be appreciated by examining the main historical stages in the study of earthquake generation and prediction (Fig. 1).

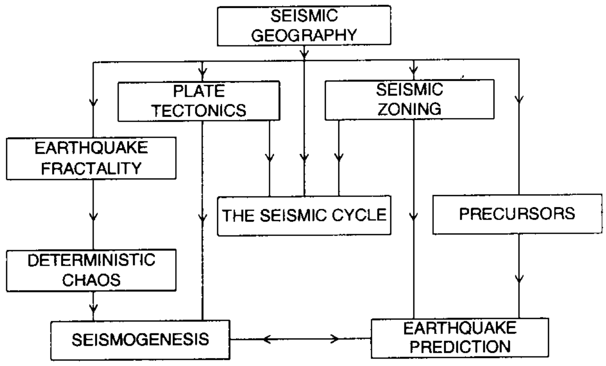

Fig.1. Development of earthquake phenomenology.

Seismic geography and associated phenomena

After Robert Mallet first attempted a world seismicity map in 1858, almost a century was to pass before the task was adequately completed. In the interim, seismographs were invented, observatory networks were set up in many countries, earthquake wave theory was formulated, the manifold recorded phases were accounted for in terms of earth structure, methods of locating hypocentres were refined, and the magnitude scale was introduced.

These many advances in seismology enabled Gutenberg and Richter to compile their "Seismicity of the Earth and Associated Phenomena" (1954), which mapped in great detail the global distribution of earthquake activity. In the plotting of epicentres, three categories of depth were distinguished, and four of magnitude. The results were referred to by Richter (1958) as "seismic geography". Arcuate and block structures were identified as the two main types of seismic environment. Several prominent phenomena were recognized as associated with arcuate structures : ocean trench, negative gravity anomaly, shallow earthquakes, positive gravity anomaly, active volcanoes, and intermediate to deep earthquakes. Narrow belts of shallow earthquakes were also identified in the Pacific, Atlantic and Indian Oceans.

Seismic geography has made four major contributions to the continuing study of earthquake generation and prediction (Fig.1). It yields evidence, as was realized only recently, that earthquakes are a fractal phenomenon, and can be understood as occurring under conditions of deterministic chaos. Earlier, it helped prepare the way for the discovery of plate tectonics (Isacks et al, 1968), and it continues to give detailed information on the associated stresses. It provides the empirical basis for a rudimentary but widely accepted form of earthquake prediction: seismic zoning. Finally, it offers a superb data-base for the study of what are intuitively the most plausible kinds of precursor: anomalies of seismicity.

The still controversial concept of the "seismic cycle" was also based on seismic geography. In the historical record, the occurrence of large earthquakes seemed, on the whole, to be random: no regular relation was apparent between successive events. For this reason, seismic zoning came to be based on an interpretation of the historical record according to the stationary Poisson model. What is predicted is the average level of future earthquake activity, not the place, time or magnitude of any individual event. Notwithstanding this general view, the seismic geography of the Kamchatka-Kuril-Eastern Japan region led Fedotov (1968) to propose a cyclical recurrence of such earthquakes in any one place, with a period of 140±60 years. He defined the seismic cycle as "the variation in the seismic regime at a given location during the time interval between two earthquakes of maximum intensity occurring at this site". Fedotov compiled evidence for the seismic cycle from events of magnitude 7.6-8.75 dating back to 1897. He acknowledged, however, that no example of a complete seismic cycle could be documented from the available data, because of the great apparent length of the cyclical period Both of these opposing views found support in subsequent major developments.

Plate tectonics

The main features of global seismicity gave support to, and were explained by, the grand scheme that emerged in the 1960's under the term plate tectonics. Linear mid-ocean activity was identified with bilateral plate creation, while the Wadati-Benioff zones of dipping activity at island arcs and asymmetric continental margins were seen to delineate subduction. Plate motion provides the main forces by which earthquake activity is generated, and details of the stress-field associated with plate motion are revealed by earthquake focal mechanisms.

Nevertheless, the relevance of plate tectonics to seismogenesis, i.e. the process by which individual earthquakes are generated, has been problematical. On the positive side, research into seismogenesis can take account of the diverse tectonic environments that are demarcated by plate tectonics, and of the associated differences in earthquake phenomenology. For example, the syle of long-term seismicity precursors is markedly different in subduction zones and regions of continental collision.

On the other hand, plate motion has been interpreted as implying a high degree of simplicity in the earthquake generating process. Regarded globally, and on a time-scale of centuries, plate motion can be assumed steady. This appeared to support the "seismic cycle" of Fedotov. For if, as the seismic gap hypothesis proposes, faults are permanently segmented, and earthquakes on a particular segment have a characteristic magnitude, then the time-interval between successive earthquakes should be constant, i.e. occurrences should be periodic. This alternative to the randomness of the stationary Poisson model has attracted much attention as a basis for long-range prediction. Its lack of success is explained by the more recent discovery that earthquakes are among the many natural phenomena that occur under conditions of deterministic chaos.

Deterministic chaos

Seismic geography yielded two quantitative empirical relations of universal scope in seismology: Omori's law of aftershock frequency as a function of time (first published in 1895), and the Gutenberg-Richter (1954) relation between earthquake frequency and magnitude. Until recently, no connection was apparent between these relations. Now they are both seen to be fractals. Other fractal relations have also been identified, such as that between fault frequency and length. With fractality thus established, earthquakes can be considered to occur in conditions of deterministic chaos.

The role of plate-motion in a lithosphere governed by deterministic chaos is analogous to that of gravity in a sand-pile: it is to maintain a state of chaos in the form of self-organized criticality. This has been described by C.H.Scholz (1991) as the normal condition of the lithosphere. Chaotic systems do not display regularities in space, size and time, of the kind proposed in the seismic gap hypothesis. Thus the "seismic cycle", which negated the earlier randomness, is in turn negated in favour of self-organized criticality, which can be regarded as a higher form of randomness.

The complexity of the seismogenic process is exemplified by the effects of changes in the static stress-field produced by an earthquake in its general neighbourhood. At shallow levels, these changes almost invariably generate aftershocks, but they rarely trigger earthquakes of comparable magnitude, and are of limited value as a means of prediction.

A feature of chaotic systems is an extreme sensitivity to initial conditions. In meteorology this is known as the "butterfly effect". In seismology it can be called the "microtremor effect": the process that culminates in a large earthquake may be initiated by a tiny earthquake, more or less remote in place and time. Meteorologists observe that a tropical cyclone is developing, and predict its future course, not from a butterfly flapping its wings, but when a tropical depression appears on the synoptic chart. Likewise, the generation process of a large earthquake may be recognised, and the earthquake predicted, when the associated conditions become sufficiently anomalous. Evidence is accumulating that this takes the form of an increase in the scale of seismicity in the future source area.

Since a fractal has no characteristic scale, the specification of scale is essential to seismicity studies, just as the scale of a geological outcrop needs to be indicated by means of a hammer or other familiar object. Scaling in seismology refers to space dimensions, time intervals, magnitude and related parameters, and a change of scale may be highly significant. On the other hand, it has been observed that, for a given mainshock, the magnitude level of the precursory seismicity is about the same as that of the aftershocks. This equivalence of scale is evidence that the precursor is also a predictor.

Earthquake prediction

The earthquake catalogues on which seismic geography is based contain an abundance of data for the study of seismogenesis. Further, hypotheses of seismogenesis can conveniently be tested against seismic zoning. For zoning is a rudimentary form of prediction, and the test of a new hypothesis is whether it can improve on zoning; a methodology for carrying out such tests has been developed by Rhoades and Evison (1993).

Plate tectonics provides the background conditions for earthquake generation. Since the nature of faulting depends on the type of stress regime, differences may also be expected in precursory phenomena. For instance, there is much evidence in the catalogues of New Zealand, Japan and Greece, that in shallow subduction zones precursory seismicity takes the form of swarms; this has been attributed to the triggering effect of pressure changes in the water entrained in subducted sediments (Evison and Rhoades, 1998).

The "seismic cycle" continues to attract interest, focussed mainly on the postulated threefold regularity: the fault segment, the characteristic magnitude, and the periodicity. Prediction based on these concepts has resulted in the failed Parkfield experiment in USA, and the still inconclusive Tokai experiment in Japan. At the same time, the well-documented aspects of the "cycle" have tended to be discounted: precursors, such as those documented by Fedotov, are claimed by some authors to be non-existent, while in seismicity studies it has become common practice to remove aftershocks from the catalogue altogether. Yet it is well known that aftershocks, treated as a set, can be predicted in terms of location, time and magnitude from the mainshock; in this sense, every mainshock is a precursor. As a means of prediction, the "seismic cycle", having formerly gained support from plate tectonics, now appears to have been bypassed by deterministic chaos (Fig. 1).

Predictability within deterministic chaos is commonplace in meteorology. The butterfly effect illustrates the chaotic, non-periodic character of hurricanes, yet the course of a hurricane can be predicted for days ahead. Likewise, the microtremor effect notwithstanding, a large earthquake can in principle be predicted for years ahead. On this time-scale, the immediate nucleation of large earthquakes by small ones is irrelevant, though it may rule out the possibility of very short-range prediction; the meteorological analogy here is not with a developing hurricane, but rather with a lightning bolt.

Predictive relations derived from the empirical study of precursors need to be accounted for in seismogenic modelling, and the new understanding of seismogenesis offers a guide to the interpretation of empirical results; this interplay is indicated in Fig. 1. The observed magnitude relation between precursory swarms and subsequent mainshocks, for example, can be modelled by means of a three-stage representation of faulting. On the other hand, scaling, as an intrinsic feature of deterministic chaos models. provides a unified view of many features of seismicity precursors (Evison and Rhoades, 1998). Early precursor studies, although they displayed a degree of scaling, as pointed out by Rikitake (1975), were carried out without the benefit of a scaling model.

Conclusion

Earthquake generation can now be understood in terms of seismic geography, plate tectonics and deterministic chaos. This understanding provides a sound basis for earthquake prediction. The means of prediction is to be sought, as in meteorology, in evidence that an event is in process of generation. The focus is thus back upon the study of precursory phenomena. Against this conceptual background, precursor studies are well placed to advance beyond the anecdotal stage, and towards the stage of operational forecasting.

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