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On the existence of earthquake precursors

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Abstract
Earthquake prediction based on precursors can aim to provide fully quantified, time-varying, synoptic forecasts, which do not depart from physical and geological principles, and are amenable to formal testing. These features are in contrast to the traditional occultist or soothsayer style of prediction. The recently-advanced, pre-emptive hypothesis that earthquakes are intrinsically unpredictable, and precursors non-existent, is also amenable to testing: it is refuted by the well-known relations between mainshocks and aftershocks. These relations show that a set of aftershocks is to a high degree predictable from the mainshock, so that, as a matter of principle, the mainshock is a precursor to its aftershocks. This result is compatible with the power-law property of seismicity, on which the unpredictability hypothesis is based. Empirical research on most precursors is difficult because of the scarcity of data, and is still largely at the anecdotal stage. Additional difficulties at the experimental stage are exemplified by the failure of the Tokai and Parkfield experiments to advance the study of precursors as planned. A comparative abundance of data is available on seismicity anomalies, and research on this type of precursor is progressing towards the operational stage.

Key words *earthquake prediction – precursors*

1. Introduction

Research on earthquake precursors has recently been joined in the literature by a succession of articles, opinion pieces, technical comments, and reports of small gatherings, in which the hypothesis is being promoted that earthquakes are unpredictable, and precursors non-existent. The arguments given, including some definitions of prediction, contain matters extraneous to seismology. As a seismological statement, however, the hypothesis is capable of being tested, and this represents progress. For, as Geller *et al.* (1997) have pointed out, a fundamental flaw in the optimism about earthquake prediction in the 1970's was that the prediction scenarios were not stated as testable hypotheses.

Prediction is ubiquitous in science as a test of understanding: to the extent that a phenomenon is understood, it can be predicted, and *vice versa.* If earthquakes were unpredictable, seismogenesis would be a closed book, research would be futile, and the earthquake would remain, in the words of Alexander McKay (1902), «a visitation and a mystery». On the practical side, moreover, earthquake hazard estimation would remain static, as in seismic zoning, allowing no opportunity for the time of occurrence of future earthquakes to be taken into account, as well as the location and size, in the design and deployment of countermeasures.

The evidence being put forward for this pessimistic view of the future of seismology deserves careful study.

2. Earthquake prediction

Earthquake precursors are phenomena which precede earthquakes and enable them to be predicted. The discussion of precursors thus requires an understanding of what is meant by

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prediction. Three types of definition of earthquake prediction are in current use, although two of them are now outmoded.

The prediction of earthquakes, as of other events, has traditionally been the province of occultists and soothsayers, whose claims, although well-intentioned, are characterized on the one hand by vagueness, and on the other by unwarranted precision. This style of prediction has been cited by Geller (1996), with the following quotation from Richter (1958): «At present there is no possibility of earthquake prediction in the popular sense, that is, no one can justifiably say that an earthquake of consequence will affect a named locality on a specified future date». The definition contained in this statement combines the ill-defined («an earthquake of consequence») with the absurdly precise («specified future date»). It is the only style of earthquake prediction to which the public had been much exposed before 1958. In the 1920's, the eminent U.S.A. geologist Bailey Willis had predicted a severe earthquake in Southern California, but this was premature, considering the state of seismology at that time, and the incident had the effect of widely discrediting such attempts (Geschwind, 1997).

Richter's dismissal of earthquake prediction was clearly aimed at occultists and soothsayers, and at their style of statement. To cite him as an authority on earthquake prediction is now anachronistic. A quarter of a century after Richter (1958), it was acknowledged, by an international panel of seismologists, that the most informative way to convey an earthquake prediction, including the uncertainties, is by means of probability distributions in the space-time-magnitude domain (IUGG, 1984). Such is the style appropriate to modern empirical seismology.

A vestige of the occultist's style lingers on in the scientific literature. For example, Geller *et al.* (1997) begin as follows: «Earthquake prediction is usually defined as the specification of the time, location and magnitude of a future earthquake within stated limits». Apart from the question of what such limits are supposed to be, this «window» type of specification is no more justifiable, in terms of physics, than the «specified future date» quoted above. A result which lies just outside the «window» is almost as good as one which lies just inside, but the «window» allows only for success or failure. This is sometimes defended on the ground that it is what the public understand and expect. Yet even a shooting target provides for four different levels of success, and a dartboard provides for 43. The public are well able both to understand a continuously variable type of specification, such as that represented by the barometric contours on synoptic weather maps, and to appreciate that it is the most informative.

The second outmoded style of earthquake prediction perpetuates a confusion between seismological matters and those involving economics, politics, etc. This has been resolved (UNEP, 1980) by the equation

$$\text{Hazard} \times \text{Vulnerability} = \text{Risk}$$

where hazard (*i.e.* the probability of occurrence of future earthquakes) is the seismological factor in earthquake risk. Elements of the vulnerability factor have been invoked by Geller (1996), Main (1996), and Geller *et al.* (1997), and have been included in various meanings which have been attributed to the term prediction. Thus, Main (1996) adopts (in his glossary) a definition which requires the parameters and probability of the earthquake to be specified «with sufficient precision that actions to minimize loss of life and reduce damage to property are possible». Geller *et al.* (1997), on the other hand, state that «prediction would have to be reliable ... and accurate ... to justify the cost of response». Such matters will require much attention from the relevant experts when the operational stage of earthquake prediction is reached, and they have already been extensively analysed. In one international symposium (Unesco, 1984), for example, sessions were held on the economics of earthquake prediction, on individual and group response to earthquake warnings, on the role of institutions, and on the communication of predictions and warnings, as well as three sessions on seismological themes. Speakers included specialists in sociology, economics, engineering, law, political science and civil defence. The various elements of vulnerability, although of crucial importance to earthquake risk, lie outside the seismological province of hazard, and of whether earthquakes are predictable and precursors exist.

Confusion also arises over the time-scale to which prediction is meant to apply. This has been variously stated. Geller (1996) restricts himself to short-term prediction. Main (1996) is principally concerned with the intermediate term, but also states that accurate long-term prediction is potentially difficult or impossible. Because of this and the above vaguenesses, it could be said that a fundamental flaw of the present pessimism about earthquake prediction is that most of the unpredictability scenarios have not been stated as testable hypotheses; for it has been well said (Geller *et al.*, 1997) that hypothesis-testing is what separates speculation from science.

What, then, is meant by the statement «earthquakes cannot be predicted», as used for a title by Geller *et al.* (1997)? It will be read by some as merely describing the present situation. This meaning, however, would make much of the content of that paper redundant, and also those of Main (1996) and Geller (1996), since they all give detailed theoretical and empirical reasons for unpredictability, as well as characterizing it, on occasion, as inherent or intrinsic. Again, the statement, as a title, might have been shorn of important provisos for the sake of brevity. But, as already discussed, the elaborations offered in these and the other texts are many, varied, and unquantified.

3. The unpredictability hypothesis

The theoretical case against the existence of precursors is that earthquakes are intrinsically unpredictable. In the interests of testability, this is the sense in which the statement «earthquakes cannot be predicted» will be read here. Such a universal statement is in the same class as «swans cannot be black». A logical connotation of such statements is that one contrary example refutes.

The unpredictability hypothesis, a corollary of which is that no prior event can be a predictor, is based on evidence that earthquakes belong to the class of natural phenomena which display the condition of self-organized criticality, a prominent feature of which is unpredictability. Aftershock sequences, for example, follow power laws relating frequency of occurrence to time and earthquake moment, and such self-similar laws are a characteristic of the criticality condition (Ito and Matsuzaki, 1990).

Let us accept the proposition that power-laws connote unpredictability. In this light, let us examine the well-known properties of aftershocks and their relations with mainshocks. These, including the two power laws mentioned above, are as follows:

Location

1) Aftershocks are located in a space surrounding the mainshock.

2) Aftershock epicentres occupy an area A (km^2) given by

$$\log_{10} A \approx M_m - 4$$

where M_m is the mainshock magnitude (Utsu, 1961).

Time

1) Aftershocks begin at the time of the mainshock.

2) The frequency of occurrence $n(t)$ of aftershocks, as a function of time t, is given by

$$n(t) = a(c+t)^{-p} \qquad \text{(Omori's law)}$$

where $t \geq 0$ is the time after the mainshock, and a, c, and p (> 1) are numerical parameters.

Magnitude and moment

1) The largest aftershock magnitude M_1 is given by

$$M_1 \approx M_m - 1.2 \qquad \text{(Båth's law)}$$

2) The frequency of occurrence $n(m)$ of aftershocks, as a function of moment m, is given by

$$N(m) = A\, m^{-B} \quad \text{(Gutenberg-Richter relation)}$$

where $N(m)$ is the number of aftershocks of moment m and greater, and A and B ($\approx 2/3$) are numerical parameters.

Some of these relations are subject to rather wide uncertainties. As a whole, however, they show that the location, time and magnitude of a set of aftershocks can be estimated, to a high degree, from the parameters of the preceding mainshock. In other words, the mainshock is a precursor, and the aftershocks, as a set, are predicted.

This result is compatible with earthquakes having properties associated with self-organized criticality. While the Gutenberg-Richter power law applies to aftershock sequences, Båth's law implies that the mainshock does not belong to the Gutenberg-Richter set; for if it did, the right-hand-side of Båth's law would be about 0.3 instead of 1.2. Similarly, the Omori power law includes the parameter c because the time of the mainshock ($t = 0$) is a singularity. We thus have an earthquake set which, although following power-law distributions, is intrinsically predictable by means of an earthquake outside the set. Conversely, given only the set of aftershocks, one could estimate to a high degree the location, time and magnitude of the mainshock. It follows that, as a matter of principle, a mainshock might itself be predictable by means of prior earthquakes, including a power-law set which did not include the mainshock as a member; an example of this is referred to below.

Power laws display self-similarity and exemplify the principle of scaling, including that numbers of power laws can coexist on a hierarchy of scales. A set of aftershocks, for example, which follow a power law appropriate to their own scale, may also belong to a power law on a much larger scale, and the larger power law may include the mainshock, and other earthquakes of like magnitude and greater. The set of aftershocks, although predictable on their own scale, by means of their own mainshock, may be unpredictable otherwise. Predictability on any scale, however, is sufficient to refute the hypothesis that earthquakes are intrinsically unpredictable, and its corollary that precursors are non-existent. In the context of the mainshock/aftershock phenomenon, mainshocks are precursors.

4. Empirical research: the anecdotal stage

The empirical case against the existence of precursors is that after much research the goal of prediction has not been achieved. How much research is needed to solve any problem depends on the difficulty of the task. As yet, the theory of seismogenesis has little to offer on the subject of possible precursors. How, then, should one proceed with the empirical study of minor anomalies which may be precursory to major earthquakes? The first stage is to record case histories, as a guide to more systematic studies. Rikitake (1975) was able to compile a list of 112 case histories, involving 13 suggested precursory phenomena; later the number of case histories was increased to 391, and the phenomena to 19 (Rikitake, 1979). These were thorough compendia, as Scholz (1990) remarked, and further examples have been published in recent years. And while any individual case history, being anecdotal, might involve mere coincidence, or faulty observation, Rikitake showed that most of the data displayed a linear correlation between the mainshock magnitude and the logarithm of the precursor time (*i.e.* the time between precursor and mainshock). This correlation, although not predictive, served to advance the study of precursors somewhat beyond the anecdotal stage. But the typical number of case histories for any one suggested precursor is still small. Considering also that the data have been collected under a variety of conditions, one could not expect, for most precursors, that predictive correlations would have yet emerged.

In a small number of studies, precursors have failed to appear in circumstances where they might have been expected from previous case histories (*e.g.* Boore *et al.*, 1975; Mogi, 1985). These negative results have been widely cited. It should be noted, however, that they, too, are anecdotal in character. There has been no systematic attempt to demonstrate that any particular type of precursor is non-existent.

The following reasons have been given by Geller *et al.* (1997) for doubting that precursors exist:

1) In general, the phenomena have been claimed as precursors only after the earthquakes occurred.

2) The pattern of alleged precursors tends to vary greatly from one earthquake to the next.

3) The alleged anomalies are frequently observed at only one point, rather than throughout the epicentral region.

4) There are no objective definitions of «anomalies».

5) No quantitative physical mechanism links the alleged precursors to earthquakes.

6) Statistical evidence for a correlation is lacking.

7) Natural or artificial causes unrelated to earthquakes have not been compellingly excluded.

8) In other fields, threshold signals have often been erroneously claimed as important physical effects; most if not all «precursors» are probably misinterpreted as well.

9) Each new claim brings a new set of proposed conditions, so that hypothesis testing is nearly impossible.

These strictures provide a penetrating critique of the anecdotal stage of precursor research. If there were no sign of their being overcome, one could conclude, with Geller *et al.* (1997), that prediction is very difficult, if not impossible, and that the anecdotal stage might persist for a long time ahead. Some attempts to advance to the experimental stage have encountered even more difficulties. In favourable circumstances, on the other hand, experimental results have also been obtained to which most of the above strictures do not apply.

5. The experimental stage

Two large field experiments which were designed with a view to a more systematic study of earthquake precursors have been in progress for many years. These are the Tokai experiment in Southern Japan and the Parkfield experiment in California. The purpose has been to observe precursors to major earthquakes at these localities, which, according to the seismic gap hypothesis, are favourable localities for the early occurrence of such earthquakes. Limitations inherent in the experiments are that the seismic gap hypothesis was accepted untested, and that any results would be specific to the particular localities and earthquakes, and would be of unknown generality.

The Tokai and Parkfield experiments were set up with the capacity to record a wide variety of precursors before the occurrence of the expected earthquakes. In neither case has the earthquake so far occurred, however, so that the opportunity to identify precursors has not arisen. As time goes by, this can be seen as evidence against the seismic gap hypothesis, but little has been learnt about precursors. Thus the two major experiments in precursor research have not so far produced any advance beyond the anecdotal stage, nor any information on whether precursors exist or not.

The alternative strategy available for the deployment of experimental resources would be to rely on the stationary Poisson model of future seismicity. As the model of least information, this is the simplest, and is entitled to be accepted, as in seismic zoning, until some more elaborate model can be shown to be superior. Under this strategy, instrumentation would be widely deployed in the seismically active region. As a result, every sufficiently large earthquake should provide some data, if only on a proportion of the deployed instruments. Whichever strategy is adopted, the collection of data on possible precursors (excepting those involving seismicity anomalies) is difficult, expensive and time-consuming.

Anomalies of seismicity or of ground deformation are intuitively the most appealing phenomena to be closely related to major earthquakes. Of these, seismicity anomalies are much the easiest to study because of the large quantity of data available in earthquake catalogues. It is noteworthy that the mainshock/aftershock relations which form such a prominent part of empirical seismology were derived from standard seismograph network data, without the need for special instrumentation. Much information is likewise available on the phenomena of foreshocks (Abercrombie and Mori, 1996), quiescence (Wyss and Habermann, 1988) and swarms (Evison and Rhoades, 1997), and on patterns such as «M8» (Kossobokov *et al.*, 1990). With these advantages, seismicity anomalies might be expected by now to have overcome some of the above-listed deficiencies of the anecdotal stage. The nine deficiencies are well-specified, and call for a specific response.

To begin with, seismicity anomalies are exempt from two of the deficiencies listed above, *i.e.* (3) and (7). Another, (8), does not apply to such an anomaly as the swarm, which is not a threshold signal, and is easy to recognize in advance. Thus, of the most favourable class of proposed precursors, the swarm is one of the easiest to study. Published accounts of the swarm precursor show that the other listed deficiencies, with the exception of (5), do not apply either. This can be demonstrated by reference to Evison and Rhoades (1993). Quantitative criteria are there given for the recognition of swarms, thus answering point (4). Also given is a list of all New Zealand swarms from 1962 to 1990. These include a cluster of five located east off East Cape (swarms 14, 16, 19, 21 and 22) which, together with a small subsequent swarm, predicted to a high degree the East Cape earthquake (M_L 7.0) of 5 February 1995 (UT) (Evison and Rhoades, 1997). Thus point (1) is answered. Moreover, the East Cape swarm earthquakes constitute a power-law set, of which the mainshock is too large to be a member, so the prediction does not contradict any theoretical unpredictability associated with such sets.

Statistical correlations between the parameters of swarm precursors and the related mainshocks are also given by Evison and Rhoades (1993), bringing up to date those first published by Evison (1977), and thus answering point (6). As with many earthquake phenomena, the predicted parameters are functions of magnitude (point (2)). The precursory swarm hypothesis is being subjected to a series of rigorous tests (point (9)), for which the methodology has been published by Rhoades and Evison (1979, 1993). As to point (5), this is hardly a deficiency, since in science it is not unusual for empirical studies to precede, and lead on to, theoretical understanding.

Systematic studies of the precursory swarm hypothesis (with clustering), on New Zealand and Japan data, have led to the formulation of a statistical model (Rhoades and Evison, 1993), which quantifies the swarm-related hazard in space, time, and magnitude. The model is now supported by 17 precursory sequences, comprising 36 swarms correlated with 29 major earthquakes (Evison and Rhoades, 1997). Despite the advantages mentioned above, this degree of progress has required a long-term effort. Whether swarms can be used to improve upon the stationary Poisson model for estimating future earthquake activity is the subject of a continuing series of formal tests. In the meantime, with the difficulties of the anecdotal stage largely overcome, the quantity of correlated data in these systematic studies may be considered *a priori* evidence that the swarm precursor exists.

Most proposed precursors are shorter-term than the swarm. This can be seen by comparing the precursor times for swarms with those for precursors generally. For swarms, the precursor time T_p (days) as a function of earthquake magnitude (M_m) has been calculated from the data given for the predictive regressions (Evison and Rhoades, 1997); for precursors generally, the same function has been given by Rikitake (1979). The equations are as follows:

Swarms $\log_{10} T_p = 0.54\, M_m - 0.14$

All precursors $\log_{10} T_p = 0.60\, M_m - 1.01.$

While these relations have slopes which are not greatly different, the constant terms result in a large difference in precursor time. At $M_m = 6.5$, for example, the value of T_p for all precursors is about one-third of that for swarms. The evidence that swarms are precursors, with power-law restrictions not operating during the time between swarm and mainshock, suggests that other types of precursor may also exist, whether in the long, intermediate or short term.

6. The operational stage

Looking ahead to the final stage of precursor research, such precursors as survive the experimental stage can be considered for operational prediction. With this in mind, certain operational desiderata can be usefully taken into account at the earlier stage. The precursor needs not only to exist, but also to be a better estimator of future earthquakes than the current method, *i.e.* the method used in the production of seismic zoning maps. Further advantage is gained if several such precursors can be combined in estimating the hazard (Aki, 1981; Rhoades, 1989).

The principal seismological factor in seismic zoning, as mentioned above, is the stationary Poisson model as applied to historical seismicity. This model has no memory; the estimated hazard is constant with time. No one is happy with such a model. Yet seismic zoning has been incorporated in the building codes of earthquake-prone countries since the 1960's. Any substantial improvement on the stationary Poisson model would have great practical value. This is a task for earthquake prediction. A meteorological analogy was pointed out by Y.V. Riznichenko (quoted by Evison, 1984): seismic zoning is concerned with the earthquake «climate», and prediction with the «weather». The challenge has two aspects which are often overlooked in definitions of earthquake prediction. Seismic zoning is a regional or country-wide estimation of earthquake hazard. Thus the prediction of individual earthquakes might not, of itself, bring an overall improvement. Reverting to the meteorological analogy, what is needed is synoptic forecasting, *i.e.* the country-wide, and eventually world-wide, mapping of time-varying earthquake hazard.

Secondly, the Poisson model expresses the hazard as probability distributions, and is thus superior to the archaic «window» style of prediction. Presenting synoptic forecasts, in like manner to the Poisson model, puts forecasting on the same footing, in this respect, as the best seismic zoning maps. Forecasts can then be compared directly with the Poisson-based estimates, and the performance of a forecasting hypothesis can be monitored in terms of hazard refinement (Rhoades and Evison, 1979, 1993). In this methodology, past earthquakes which have occurred unrelated to swarms, and *vice versa* (sometimes referred to as past failures and false alarms) are incorporated as an integral element of the hazard.

These desiderata can be conveniently prepared for at the stage of hypothesis formulation, and they lead to a format very different from what could have been envisaged early in the study of earthquake precursors. Richter's (1958) textbook is an encyclopaedic authority on the seismology of the time, but even seismic zoning was then in its infancy, and Richter makes no mention of the Poisson model. Since the early 1960's, great advances have been made in the theory and practice of earthquake hazard estimation, and this is now the context of prediction research.

7. Conclusions

The search for precursors among anomalies of seismicity can be assisted by taking due account of the properties of power-law distributions, such as the Gutenberg-Richter relation and Omori's law. The conditions under which seismicity precursors occur can provide, in turn, a guide to the study of other types, on which data are comparatively scarce.

For most proposed precursors, the anecdotal stage of empirical research is necessarily protracted. Progress to the experimental stage can be assisted by acknowledging that the practical objective is to improve on the existing Poisson model of hazard estimation, especially by showing how the hazard varies with time. This also leads to hazard formats which are appropriate to the operational stage. Research can proceed from stage to stage on the basis that earthquakes are not intrinsically unpredictable, and that, despite the difficulties confronting experimentation in this field, there is growing empirical evidence that precursors exist.

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