debates
18 March 1999

The status of earthquake prediction

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What is it?

Earthquake prediction invites debate partly because it resists definition. To Ian Main's very helpful definitions I would add that an earthquake forecast implies substantially elevated probability. For deterministic prediction, that probability is so high that it justifies exceptional response (although not necessarily evacuation as Ian Main suggests; evacuation is not generally envisaged as a response to earthquake warnings, and it would probably be counter-productive even if future earthquakes could be predicted accurately.). Thus prediction demands high certainty.

Forecasting and predicting earthquakes must involve probabilities. We can predict thunder after lightning without talking of probabilities because the sequence is so repeatable. But earthquakes are more complex: we need probabilities both to express our degree of confidence and to test that our forecasting is skilful (better than an extrapolation of past seismicity).

What we can do

We can estimate relative time-independent hazard well (Japan is more hazardous than Germany) but our precision is limited (Is Japan more hazardous than New Zealand?). Hazard statements are quantitative, but even after 30 years none of the models has been prospectively tested (for agreement with later earthquakes). We can estimate well the long-term seismic moment rate (a measure of displacement rate integrated over fault area) but to estimate earthquake rates we need to know their size distribution. There are very different ideas about how to do this[1,2] but none has been tested scientifically.

What we cannot do

We cannot specify time-dependent hazard well at all: in fact, we have two antithetical paradigms. Clustering models predict that earthquake probability is enhanced immediately after a large event. Aftershocks provide a familiar example, but large main-shocks also cluster[3]. The seismic gap theory asserts that large, quasi-periodic 'characteristic earthquakes' deplete stress energy, preventing future earthquakes nearby until the stress is restored[4]. How could these antithetical models coexist? It is easy: there are many examples of each behaviour in the earthquake record. So far, the seismic gap model has failed every prospective test. The 'Parkfield earthquake'[5] has been overdue since 1993, and a 1989 forecast[6] for 98 circum-Pacific zones predicted that nine characteristic earthquakes should have happened by 1994; only two occurred.

Our attempts at earthquake forecasting, as Ian Main defines it[7], have failed. (Note that 'earthquake forecasting' is often defined differently. Nishenko[4] defined it to mean estimation of time-dependent earthquake probability, possibly on a decade time scale, and not necessarily involving precursors.) Most studies of earthquake forecasting assumed that precursors would be so obvious that estimates of background (unconditional) and anomalous (conditional) probabilities were unnecessary. Hundreds of anomalous observations have been identified retrospectively and nominated as likely precursors, but none has been shown to lead to skill in forecasting[7]. Given the bleak record in earthquake forecasting, there is no prospect of deterministic earthquake prediction in the foreseeable future.

What is the difficulty?

In principle, earthquakes might be predicted by one of two strategies: detecting precursors, or detailed modelling of earthquake physics. For precursors, confidence would come from empirical observations; understanding mechanisms would be desirable but not necessary. Earthquake physics involves modelling strain, stress and strength, for example, in some detail.

The precursor strategy will not work because earthquakes are too complicated and too infrequent. Even if precursors existed, a few observations would not lead to prediction, because their signature would vary with place and time. This problem cannot be overcome simply by monitoring more phenomena such as electric, magnetic or gravity fields, or geochemical concentrations. Each phenomenon has its own non-seismic natural variations. Monitoring these phenomena without complete understanding is courting trouble. Monitoring them properly is a huge effort with only a remote connection to earthquakes. Such studies would certainly unearth more examples of anomalies that might be interpreted as precursors, but establishing a precursory connection would require observations of many earthquakes in the same place.

Earthquake physics is an interesting and worthwhile study in its own right, but short-term earthquake prediction is not a reasonable expectation. One idea is that high stresses throughout the impending rupture area might induce recognizable inelastic processes, such as creep or stress weakening. Even if these phenomena occur they will not lead to earthquake prediction, for several reasons. Earthquakes start small, becoming big ones by dynamic rupture. The critically high stress needed to start rupture is not required to keep it going. The telltale signs, if they were to exist, need affect only the nucleation point (several kilometres deep), not the eventual rupture area. Even very large earthquakes cluster[8], indicating that seismogenic areas are almost always ready. Earthquakes clearly respond to stress changes from past earthquakes[9], but the response is complex. For example, most aftershocks occur on planes for which the shear stress should have been reduced by the main shock. Monitoring strain accumulation and deducing the boundary conditions and mechanical properties of the crust will tell a lot about earthquakes and perhaps allow us to predict some properties. To forecast better than purely statistical approaches would be in itself a solid accomplishment, which must come long before deterministic prediction.

Part of our difficulty is a lack of rigour in Earth sciences. We examine past data for patterns (as we should) but we pay very little attention to validating these patterns. Many of the patterns conflict: some contend that seismicity increases before large earthquakes[10], others that it generally decreases[11]. We generally explain exceptions retrospectively rather than describe the patterns, rules and limitations precisely enough to test hypotheses.

What is possible?

Some argue that earthquakes possess a property known as self-organized criticality (SOC), so earthquakes cannot be predicted because seismogenic regions are always in a critical state. But SOC would not preclude precursors. For example, if lightning were governed by SOC, we could still predict thunder with a short warning time. Nothing discussed above makes earthquake prediction either possible or impossible.

Others argue that SOC comes and goes and that outward signs of SOC (such as frequent moderate earthquakes) provide the clue that a big earthquake is due. If SOC comes and goes, it is not clear how to recognize it. To be useful, it must apply to big events only, and we would need many (rare) examples to learn how big they must be. SOC would presumably appear gradually, so at any one time it might give at best a modest probability gain.

The important question is not whether earthquake prediction is possible but whether it is easy. Otherwise it is not a realistic goal now, because we must learn earthquake behaviour from large earthquakes themselves, which visit too infrequently to teach us.

What should be done?

Earthquake hazard estimation is the most effective way for Earth scientists to reduce earthquake losses. Many outstanding scientific questions need answers: the most important is how to determine the magnitude distribution for large earthquakes, which is needed to estimate their frequencies. Time-dependent hazard is worth pursuing, but prospective tests are needed to identify the models that work. These tests should cover large areas of the globe, so that we need not wait too long for earthquakes. For global tests we need global data, especially on earthquakes, active faults and geodetic deformation.

Basic earthquake science is a sound investment for many reasons. Progress will lead to advancements in understanding tectonics, Earth history, materials and complexity, to name just a few. Results will also benefit hazard estimation. Wholesale measurements of phenomena such as electric fields with no clear relationship to earthquakes will not help.

For real progress we need a methodical approach and a better strategy for testing hypotheses. We have good reason to expect wonderful discoveries, but not deterministic prediction.

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