debates

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Earthquake prediction: Concluding Remarks

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This debate has highlighted both a degree of consensus and a degree of continuing controversy within the thorny subject of the predictability of earthquakes. In terms of the four levels of prediction of seismicity I introduced at the start of this debate, a consensus has emerged that at least some form of time-dependent seismic hazard can be justified on both physical and observational grounds. The phenomenon of earthquake triggering leads to a transient, local increase in probability of future earthquakes, for example as aftershocks, but also sometimes in the form of subsequently larger events. In fact warnings based on such clustering are already in use in California (Michael, week 2). On the other hand, all of the contributors to this debate who expressed an opinion agree that the deterministic prediction of an individual earthquake, within sufficiently narrow limits to allow a planned evacuation programme, is an unrealistic goal.

Seismic gap hypothesis

If we examine the intermediate scenarios, we find a continuing debate on the applicability of the seismic gap hypothesis to natural seismicity (Jackson, week 4; Scholz, weeks 2, 6). This would in principle allow the calculation of longer-term conditional probabilities for time-dependent seismic hazard calculations. The root of this debate lies in the need for a consistent definition of the gap hypothesis in a form that can be objectively tested by statistical means, and the need to consider at least the possibility of a conditional probability density which may decrease with time due to the clustering properties of seismicity (Knopoff, week 3 article).

Scholz (week 6) finds it hard to believe that the gap hypothesis can fail, because of the 'weird' physics this might require. However, the gap hypothesis assumes the repetition of identical individual events, and takes no account of interactions between neighbouring faults, or the possibility of strain release by a population of smaller events. For the time being, the gap hypothesis remains open to question and future testing, preferably in prospective mode, but also in comparison with palaeseimological data, bearing in mind some of the potential pitfalls involved (Michael, week 2).

Precursors

Perhaps the greatest degree of controversy lingers in the possibility of making probabilistic forecasts of future earthquakes based on the observation of precursory phenomena. The reason for this continuing controversy is two-fold:

1. The plain practical difficulty of objectively identifying any precursory phenomena with sufficient clarity and repeatability to convince the sceptical of their general existence. Some believe that this problem will be overcome in time (Wyss, week 1; Knopoff, week 3; Biagi, week 4), although at least one feels that the effort needed will require resources comparable with those currently spent on astronomical research (Wyss, week 3). Many contributors to the debate, while acknowledging the problems, argue nevertheless that we should not rule out a priori the possibility of a level of prediction above that of earthquake clustering (Bernard, week 1; Michael, week 2; Scholz, week 2; Knopoff, week 3; Bowman & Sammis, week 4, Wu, week 5). Geller (week 4) argued that a massive investment of new resources specifically targeted at earthquake prediction would be an unwise investment without more obvious success, and Bernard (week 1) that any increase in resources

should be targeted first at a better fundamental understanding of earthquakes and crustal transients themselves. Geller (week 6) criticised the 'case study' approach inherent in the investigation of precursory phenomena, on the grounds that sample bias can lead to apparent statistical significance - the 'gambler's fallacy'. Wyss (week 6) responded by saying that this may be all we have for the foreseeable future, but this does not of itself refute Geller's argument.

2. The lack of a universally-agreed physical model for the complicated and non-linear process of seismogenesis. We may all agree that the local physics of fracture or friction play a strong role, but how do these scale from the controlled conditions of the laboratory to the field case, how do we account for changes in the boundary conditions, and how do we take into account the strong interactions between faults during earthquakes?

Self-organized criticality

In fact there is still a debate on the applicability of the current model for earthquake populations, based on the notion of self-organised criticality (Bernard, week 1; Scholz, week 2; Knopoff, week 3; Bak, week 3; Bowman & Sammis, week 4). Perhaps surprisingly to some, the contributions here have highlighted the fact that self-organised criticality itself does not preclude some degree of predictability in the statistical properties of the system. (Even a completely chaotic system has a degree of short-term predictability). In fact, there are no realistic grounds for ruling out the existence of finite fluctuations in local stress or global correlation length, which in turn may influence future probabilities of the earthquake population.

The problem may instead be that such fluctuations can be small (Bak, week 3), and hard to distinguish from the continued fluctuations inherent in a self-organised critical state, so that a 'background' level is hard to define. Finally it would be hard to devise any model which can truly account for the enormous complexity of the Earth (Knopoff, week 3; Crampin, week 5).

Knopoff (week 3) argued instead that the notion of self-organised criticality does not describe the statistical properties of the San Andreas fault in detail. However, to first order at least, this model remains the best contemporary explanation for a plethora of scaling phenomena in geology and geophysics, including earthquake and fault populations (refs 1,2; Sornette, week 7). In terms of deterministic prediction, physicists reading this article will be aware that the critical point represents the cusp between the deterministic and the random. It is this fundamental competition between order and chaos which explains the long-range correlations seen in earthquake and fault populations, as well as smaller-scale physical phenomena such as critical opalescence.

If earthquake physics similarly requires an irreducibly random element in order to explain the observed long-range correlations, and the surprising sensitivity to small perturbations in stress that we see in induced seismicity, then this goes a long way to explaining theoretically the emerging consensus on the unlikelihood of our ever being able to achieve accurate deterministic prediction.

Policy issues

The debate has also highlighted a number of issues which may come under the heading of science policy and organisation. Geller (week 5) argued that earthquake prediction should not be treated as a subject in its own right, and rather that those working in the subject area should present their results in broader fora which include those working in earthquake source physics or statistics, and requiring similar standards of objective testing. Wyss (week 6) concurred. Bernard (week 1) advocated a more fundamental approach to the observation of crustal transients, targeting the study against a range of potential applications.

A second policy issue is that of funding. Wyss (week 1) and Biagi (week 4) complained that the mere mention of 'Earthquake Prediction' in a proposal can guarantee its failure. An alternative explanation is that such proposals simply do not come over as strongly as the alternatives in a rapidly-moving and increasingly competitive world. Geller (week 6) and Jackson (week 4) highlighted the need for clear, unambiguous, and time-independent statements of individual predictions, in order to allow the objective testing of any individual prediction.

Many reviewers may also be mindful of the scientifically weak work that Wyss (week 1) highlighted. As a consequence Geller (week 4) argued that without significant progress there should be no special funding for this area, although explicitly stating that meritorious earthquake prediction research should be funded under the normal rules of peer review. Wyss (week 3) argued that without literally astronomical funding, there will be no significant progress. Those who deal with science policy in earthquake-prone countries will have to make up their own minds on the costs and potential benefits involved.

Benefits of predictions

Although we are a long way from consensus on how far we should go in terms of addressing scientific questions with potential application to earthquake prediction, many contributors nevertheless addressed the potential utility of predictions at different levels introduced at the start of the debate. Michael (week 5) pointed out that low-probability short-term forecasts, while not justifying mass evacuation of cities, may help maintain a state of preparedness beneficial in earthquake-prone areas.

Despite the continuing scientific debate on the gap hypothesis, he also pointed out (week 2) that time-dependent hazard maps already in use in California have led to significant practical benefits in terms of increased investment in aseismic building construction. However, there is also a potential downside to identifying some areas as being at high risk, in the sense that this may lead to unwarranted complacency in areas identified as being at low risk (Geller, week 3). Even if deterministic prediction could be achieved, mass evacuation programmes may not be the best option, given its own potential problems (Wyss, week 1; Michael, week 2; and Jackson, week 4).

We remain a long way from proving that any earthquake prediction scheme can succeed better than predictions based on the statistics of earthquake clustering, but this debate has highlighted in the clearest terms possible that when scientists speak of 'earthquake prediction', they do not imply the type of accurate short-term prediction that might allow public evacuations before an individual event. Instead the predictions implied come under the general category of probabilistic forecasts for a population of earthquakes. Such forecasts may instead serve as a motivation for aseismic design, and maintained vigilance by the general public and civil defence agencies.

In the end it is not earthquakes themselves which kill people, it is the collapse of man-made structures which does most of the damage. While we continue to explore the degree of predictability of earthquakes on rigorous observational, statistical and theoretical grounds, we should therefore not lose sight of the fact that the best way of preparing for the inevitable remains in the development of land use plans, and building and infrastructure design codes to mitigate their worst effects.

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