Where prediction is not possible

For those — such as Californians — who live at plate boundaries, earthquakes are a fact of life. Others, who may count themselves lucky, should think again.

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READERS elsewhere may be forgiven for not knowing that last week Britain had what may have been its biggest earthquake this century. No one was injured, and the reported structural damage was limited to ruptured gas mains, cracked masonry and collapsed chimneys. With a magnitude of about 5, the event on the Anglo-Welsh border was only one-hundredth the size of last October's earthquake on the San Andreas fault; indeed, California has a few earthquakes this size each year.

The difference is that the San Andreas fault marks the boundary between two crustal plates, whereas Britain sits well within the borders of a plate that stretches from the Mid-Atlantic Ridge to Japan, and from the Arctic Ocean to the Mediterranean. The plate boundaries are where almost all the action is: plot the world's earthquakes and active volcanoes on a map and the plates emerge, as in a game of connect-the-dots.

But what of the stray dots in the middle — the intraplate earthquakes? They signal the failure of the simplifying assumption of plate tectonics, that the plates are rigid monoliths which deform only at their edges. And whereas plate tectonics provides a framework in which to understand — and perhaps ultimately to predict — plate-boundary earthquakes, there is as yet no analogous theory for earthquakes in 'stable' continental crust. No seismologist can say, even after the fact, why last week's earthquake occurred where or when it did, or why it was the size it was.

Of course, these questions cannot be answered with certainty for any earthquake, but at least at plate boundaries one can see (and measure) the direct cause of the activity. For example, the Pacific plate is moving northwards with respect to North America at about five centimetres a year. If, instead of sliding smoothly by one another, the two plates are locked together by friction on the fault, then stress will accumulate at the boundary. When the fault does slip, it does so catastrophically, in an earthquake whose size depends, in part, on the amount of slip.

Experience with the San Andreas has led to the definition of several fault segments with different behaviour: some creep aseismically; others slip frequently in small earthquakes; still others seem to store up energy for longer times and rupture in great earthquakes. Although this idea of 'characteristic earthquakes' is not universally accepted (and may not apply to all faults), at least one can say how much of a 'slip deficit' is likely to have accumulated at various parts of a plate-boundary fault, and put an upper limit on the size of earthquake that may occur.

Away from plate boundaries, life for seismologists is more difficult. Most intraplate earthquakes cannot be assigned to an identifiable fault zone, in part because most are too small to rupture the Earth's surface, but also because the low level of intraplate seismicity makes it difficult to identify 'active' zones. Most continental interiors are characterized by a rather uniform state of stress, arising from forces acting on the edges and base of the plate (see M. L. Zoback *et al. Nature* **341**, 291–298; 1989). Typically, the deformation rate that results is only one-thousandth of that at a plate boundary such as the San Andreas; to generate large earthquakes the strain must somehow be concentrated.

Arch Johnston, of Memphis State University, has pointed out that the largest intraplate earthquakes are associated with areas of continental crust that have been weakened by an episode of stretching and thinning, during the formation of a rift or a new ocean basin. (This is bad news for the heavily populated eastern seaboard of the United States, which was stretched during the early stages of the opening of the Atlantic Ocean.) But the correlation breaks down at smaller, yet still damaging, magnitudes; notably, some of Australia's largest onshore earthquakes have occurred in very old, unrifted crust.

If all intraplate earthquakes were as benign as last week's event in Britain, the failure to understand them would represent an intellectual challenge and no more. But historical records show that past intraplate earthquakes have been as powerful as the great San Francisco earthquake of 1906. In New Madrid, Missouri, three magnitude 8 earthquakes occurred in a three-month period in 1811–12, damaging structures 1,500 km away on the Atlantic seaboard. And, given modern population densities, even a modest earthquake in an urban area can be devastating: last December's magnitude 5.5 event in Newcastle, Australia, killed 12 people and caused A$1,500 million worth of damage.

Seismologists are fond of saying, "Earthquakes don't kill people; buildings do". The long gaps between large intraplate earthquakes — for example, 500–1,000 years for the recurrence of a magnitude 7 earthquake on the New Madrid zone — have bred complacency about seismic protection east of the Rocky Mountains. In fact, residents of the eastern United States are only now beginning to realize that their seismic risk (a term that takes into account not just intrinsic earthquake hazard, but factors such as population concentration, soil conditions and building codes) is comparable with that of Californians. As a result, Memphis (the largest city near the New Madrid zone) has just adopted seismic resistance requirements, and New York City is about to follow suit.

The buzz of regulatory activity may give the impression that the intraplate earthquake problem is in hand, at least in principle; that what we lack in predictive skills can be made up for by engineering. But there is a worrying loose end, which calls into question the ability to estimate the seismic hazard of an intraplate region: intraplate seismicity seems to be inherently patchy in time and space, and more so than can be explained simply by the statistics of small numbers.

A particularly striking example, only recently recognized, is the Meers fault in southwestern Oklahoma. A conspicuous fault scarp, 30 km long, bears witness to a faulting event about 1,200 years ago (A. J. Crone & K. V. Luza *Geol. Soc. Am. Bull.* **102**, 1–17;1989). If the event was accompanied by an earthquake (which must be confirmed by showing that the fault extends downwards several kilometres into the crust), the earthquake would have had a magnitude of about 7. Yet today, unlike the New Madrid zone, the area surrounding the Meers fault is essentially aseismic. In the New Madrid zone, the likelihood of a major earthquake is estimated by extrapolation from the frequency of smaller earthquakes, but how does one estimate the seismic hazard of the Meers fault?

A further obstacle to understanding is thrown up by the observation that, before the event 1,200 years ago, the Meers fault had not moved for at least 100,000 years. If recurrence times can be as long as 100,000 years (and if there can be no seismicity in the meantime), there must be areas of the continents capable of significant seismic activity about which we know nothing at all. Frustrating for seismologists, perhaps, but there should be plenty of work for structural engineers.

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