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The 2011 Tohoku-Oki earthquake that shook Japan was the latest in a string of surprising megaquakes.

Why giant earthquakes keep catching us out

A spate of huge earthquakes in the past seven years has provided humbling lessons, says Thorne Lay.

If you are under the impression that there have been an unusual number of horrific earthquakes of late, often contradicting scientific expectations, you are correct. The rate of occurrence of ‘great’ earthquakes — those of magnitude 8 or larger — since December 2004 is about 2.5 times the average rate over the preceding century. Five quakes of magnitude 8.5 or greater have struck since the magnitude-9.2 Sumatra–Andaman earthquake on 26 December 2004, which produced a devastating tsunami that took more than 230,000 lives around the Indian Ocean. One year ago this month, the magnitude-9 Tohoku-Oki earthquake and tsunami in Japan caused massive devastation.

This activity is not unprecedented in the long term: from 1950 to 1965, Earth was wracked by seven earthquakes of magnitude 8.5 or greater, including the largest yet recorded — magnitude 9.5 in Chile in 1960. Where the recent batch of quakes differs from historical ones is in seismologists’ ability to quantify the rupture processes. Modern instruments for recording ground motions, and the analytical methods for extracting information, were developed mostly between 1970 and 2000 — a quiet interval with few great earthquakes and none over 8.5. In effect, the geophysical community became ready to study great earthquakes just in time for the recent batch.

Almost all the recent events have violated some theories of where and when great earthquakes can occur and what their consequences can be. This is perhaps unsurprising, given the short time over which detailed data on such events have been available.

The recent great earthquakes have all hit near subduction zones: regions in which oceanic plates are diving under other plates. Here, friction causes sticking and slipping of the rocks that results in intermittent earthquakes. Geophysicists thought that in certain regions of these plate boundaries, warm rock or slippery sediments should prevent the build up of friction enough to avoid a large quake. We thought that regions that had ruptured recently wouldn’t rupture again for years, and that segments where a long time had passed since the last big event were most likely to slip in the near future. We underestimated the extent to which one earthquake can trigger another. Our analysis procedures had been developed to handle faulting that lasts seconds rather than the minutes seen in some recent quakes.

Researchers have long tried to make rational decisions about which fault zones should provoke the most concern, to focus limited resources for earthquake preparedness. But having only a century’s worth of detailed earthquake history, we have sometimes been lured into ignoring areas that were harbouring potential for giant slip. It is essential that geophysicists learn as much as possible, as quickly as possible, from the recent events. Population growth means that more people are now, and will be, exposed to earthquake hazards than during 1950–65.

Trigger Points

A common question is whether the recent great earthquakes are directly related to each other. The record over the past 110 years suggests that such spates of activity may be a statistical fluctuation. Indeed, there is no corresponding spate of increased occurrence of smaller events such as the devastating magnitude-7 Haiti earthquake of 12 January 2010. But great earthquakes can interact on a regional scale. The 2004 Sumatra–Andaman earthquake, for example, is thought to have triggered further great quakes along the same plate boundary in 2005 and 2007 (see ‘Surprise scenarios’). A stretch of the Sumatra plate boundary between these quakes has not ruptured since 1797 and seems to be stuck, accumulating strain — an area of concern for a future great earthquake.

Whether a large earthquake can have a wider reach, triggering activity on the other side of the planet that leads to another great earthquake years later, is controversial. So far, seismic waves from a major quake have been seen to directly trigger only small events at a great distance. However, it is conceivable that dynamically triggered events in a far-off region could induce a great earthquake there sooner than would otherwise have been the case.

We still have much to learn about earthquake triggering. On 15 November 2006, for example, the plate boundary between the sinking Pacific plate and the overriding plate along the Kuril Islands (which run between the Kamchatka Peninsula and Japan) ruptured in a magnitude-8.4 earthquake. This triggered small earthquakes 100 kilometres offshore in the Pacific plate — a common occurrence. But two months later, a magnitude-8.1 earthquake shook the same plate boundary in 2005 and 2007 (see ‘Surprise scenarios’). A stretch of the Sumatra plate boundary between these quakes has not ruptured since 1797 and seems to be stuck, accumulating strain — an area of concern for a future great earthquake.

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lessons about our ability to issue early warnings. Some researchers have argued that quakes grow from an initial rupture that has some kind of signature indicating how large the final rupture will be. Recent earthquakes have undermined that hope. Great events in Peru in 2007 (magnitude 8.0) and 2001 (magnitude 8.4) both seem to have started with magnitude-7.7 ruptures that, after a pause, triggered adjacent regions to fail with larger energy release. The 2011 Tohoku-Oki earthquake (magnitude 9.0) seems to have begun as a tiny magnitude-4.9 event. Early预警 efforts are challenged by these erratic growth patterns.

Rupture Mechanics

The first surprising megaquake of the past decade, the 2004 Sumatra–Andaman event, ruptured along an unexpected 1,300-kilometre stretch of the plate boundary, extending into an area where seismologists had thought that the plates would shear horizontally rather than subduct. It was extraordinarily long lasting; fault sliding continued for more than 7.5 minutes. Most procedures for determining earthquake slip had been developed using smaller events, lasting perhaps 30 seconds, for which remote seismographs record two distinct signals: primary (P) waves followed several minutes later by secondary (S) waves. In the Sumatra event, P waves were still coming in as the S waves from the start of the rupture arrived, muddling the two. Yet it took only a few weeks for research groups to modify their algorithms. Such updated programs are now widely used, allowing researchers and government agencies to analyse the faulting of even the largest earthquake within minutes to a few hours of an event.

The magnitude-8.1 earthquake on the plate boundary in the Solomon Islands on 1 April 2007 (2 April local time) ruptured an unexpected location, at which an oceanic rift system — a ridge where new ocean crust is being formed — intersected the subduction zone. Convention held that rift-zone rocks, being hot and deformable, would not accumulate enough frictional strain for a large quake. However, analysis of seismic waves showed that the two sinking plates slipped under the overriding Pacific plate in different directions; the rupture spread right across the ‘triple-junction’ at which the three plates came together. Re-evaluation of risk assessments for other areas where ridges are subducting, from Peru to Tonga to Vanuatu, is under way.

The magnitude-8.8 earthquake on 27 February 2010 in Chile struck a section of the plate boundary that last ruptured in 1835 (Charles Darwin experienced the shaking). Basing our ideas of where large earthquakes will occur on historical events has fostered the concept that plate boundaries are strongly segmented, with isolated regions repeatedly experiencing comparably sized events. This is not always the case. Although the 2010 earthquake initiated in the central region of the 1835 rupture zone, where large slip was expected, the main sliding was located to the north, where the plate boundary had ruptured as recently as 1928.

A magnitude-7.8 earthquake off the coast of Sumatra on 25 October 2010 was surprising in that it ruptured the shallowest portion of the subduction zone, creating a huge tsunami. The low-strength, easily deformed sediments on the plate boundary at shallow depth in the fault should, it was thought, prevent the accumulation of elastic strain and thus stop large slip. They did not. We must now consider this type of event in risk assessments, because it shows that large tsunami-generating events could happen nearer to the ocean trench than previously thought.

Similarly, the 11 March 2011 Tohoku-Oki event occurred on a plate boundary that historically had experienced much smaller events. The shallow portion of the fault was not expected to accumulate a large amount of elastic strain. Surprisingly, the event had huge slip of 40–80 metres at shallow depth, and also drove slip in adjacent fault segments that had ruptured as recently as 2005, increasing the total size of the event and producing a larger tsunami than had been prepared for.

Bitter Lessons

Unfortunately, we often advance our understanding of earthquakes through bitter experience. But progress is being made.

We are improving our ability to anticipate risk in specific regions. Geodetic observations of strain accumulation were already mapping out regions with potential for large earthquakes in Sumatra, Chile and Japan before recent great earthquakes struck there. Sea-floor measurements off Japan were on the verge of defining the potential for the large, shallow fault displacements that occurred in 2011. Given more time to observe where strain was accumulating, the size of the earthquake and tsunami might not have been a surprise. Even as things were, rapid analysis of data from regional seismic networks in Japan enabled early warnings; warnings that can be improved (see page 144).

Part of the solution is a wider spread of instrumentation. The dense coverage of seismometers and Global Positioning System instruments in Japan has helped immensely in monitoring activity and in understanding the recent great event. Other regions need to be better instrumented, especially offshore. A major effort is under way to improve our understanding of great-earthquake risk off the coasts of Oregon and Washington in the United States, where a magnitude-9 earthquake last struck in 1700.

Although individual great earthquakes are still sure to surprise us, the most important shift in our thinking has already occurred: we must allow for the possibility of larger earthquakes in regions where we thought that potential did not exist. That is one difficult lesson that we can consider learned. ■

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