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Warning signs of the Iquique earthquake

An earthquake off Chile in 2014 occurred in a region where a great seismic event was expected. Two studies reveal that months of foreshocks and slow slip on the associated plate-boundary fault preceded the event.

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The most common question asked of an earthquake researcher is "When is the next Big One?" In short, the answer is "We don't know". But there is evidence that, at least in some cases, the answer could be more precise. On *Nature*'s website today, two studies[1,2] of the earthquake (magnitude 8.2) that occurred at Iquique, northern Chile, on 1 April 2014 suggest that a range of geophysical measurements collected in recent years indicated both a high overall earthquake probability and an increased short-term hazard in the region.

The Iquique event was a subduction earthquake — it occurred on the fault along which the oceanic Nazca Plate to the west thrusts itself below the South American continent at an average rate of about 7 centimetres per year. The last time a great earthquake occurred on this section of the plate boundary was in 1877, when a much larger event (magnitude 8.6–8.8) ruptured nearly 500 kilometres of the subduction thrust fault. Measurements[3,4] of deformation at Earth's surface taken by the Global Positioning System (GPS) show that much of the fault that ruptured in 1877 is currently fully coupled (locked in position, and thus building up stress and slip deficit that will be released in a future earthquake; Fig. 1). This section of the plate boundary was therefore recognized as a seismic gap, a region of an active fault that seems to be overdue for one or more great earthquakes.

The Iquique earthquake occurred within this seismic gap, but was not nearly big enough to fill it. Hayes *et al.*[1] and Schurr *et al.*[2] constrained models of the earthquake slip using seismic data from local and global stations, together with geodetic measurements of surface deformation. They report that slip of up to about 5 m occurred in a zone stretching from the earthquake's focus in the north to the Chilean coast in the southeast. Two days later, an aftershock of magnitude 7.6 expanded the rupture zone to the south for a total length of about 200 km.

Of particular note was a period that lasted for at least three months, in which foreshocks propagated towards the eventual focus of the mainshock[5]. That is, rather than snapping with no warning signs, this great earthquake was preceded by a fascinating sequence of foreshocks that, in retrospect, can be understood as part of a slow unfastening process leading up to and triggering the eventual earthquake rupture. The foreshocks occurred in a zone that had previously been recognized[3,4] as being less strongly coupled — in which the fault slips slowly without causing an earthquake (Fig. 1). It seems that the foreshocks, accompanied by slow aseismic slip in this partially locked zone, ultimately initiated a dynamic earthquake rupture, breaking the fully locked section to the southeast.

There are still some questions to resolve regarding the sequence of events leading up to the Iquique earthquake. Schurr *et al.* find that the total surface displacements produced by models of the catalogued foreshocks in the second half of March 2014 match those observed with GPS. This indicates that there was little, if any, aseismic fault slip associated with this activity. By contrast, an independent analysis[6] of GPS data suggests that aseismic slow slip in the foreshock region greatly exceeded slip associated with the foreshocks alone. Additional evidence for substantial aseismic fault creep comes from observations[5] of very small, identically repeating earthquakes among the foreshocks on the plate-boundary fault. Questions also remain about whether deformation within overlying crustal rocks contributed to the precursory activity, in addition to slip on the subduction thrust. The largest foreshock (magnitude 6.7) and several smaller events apparently occurred in the South American crust[1,2], suggesting a complicated sequence of events leading up to the mainshock.

Most large earthquakes on plate-boundary faults are preceded by foreshock activity in the weeks before the event[7]. So should researchers

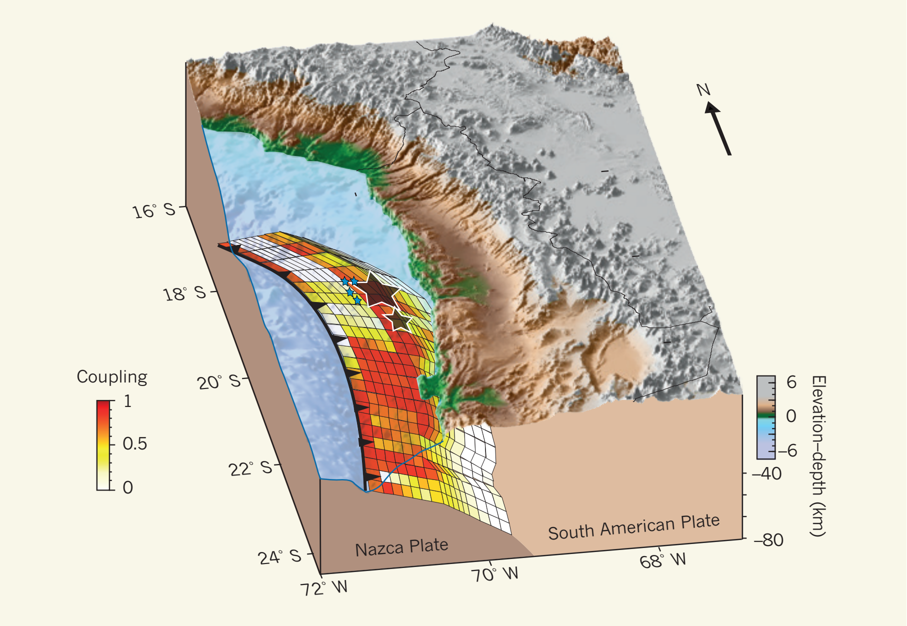

Figure 1 | Tectonic setting of the Iquique earthquake, 1 April 2014. The diagram shows the Nazca Plate thrusting eastward below South America. The colours of the rectangular fault elements indicate the degree of coupling inferred from satellite-measured surface displacements in northern Chile. A coupling value of 1 (red) means that the fault is completely locked and builds up a slip deficit until the next earthquake. A low coupling value indicates that the plate-boundary fault slips aseismically. The black stars show the approximate extent of the mainshock (magnitude 8.2, large star) and its largest aftershock (magnitude 7.6, smaller star). Blue stars indicate the area of foreshock activity near the focus of the mainshock in the months before the rupture. Two papers[1,2] suggest that geophysical data collected in recent years indicated a high overall earthquake probability and an increased short-term hazard. Figure modified from ref. 4.

have anticipated the Iquique event and provided some warning as foreshocks unfolded in early 2014? Such sequences do not yet allow for confident earthquake prediction, because there is no accepted or consistent pattern of activity before an impending large earthquake. Indeed, we still do not know how to recognize foreshocks as such when they occur. However, it seems that swarms of events that accompany transient slow slip near strongly locked sections of a fault, as apparently occurred before the Iquique earthquake, are more likely than most background earthquakes to be foreshocks of a large mainshock[8].

Hayes *et al.* argue that if we can characterize the progression of both slow and earthquake slip on a plate boundary from high-quality geophysical data, we can also model the time-dependent rise in stress on the locked sections of the fault, and therefore formally estimate the increase in earthquake probability. For example, calculations have been made[9] of the changes of stress, and of the related increase in probability of a large earthquake, associated with a flurry of small earthquakes and associated slow slip for the locked section of the Hayward fault in California in 2011 and 2012. In this case, the short-term increase of seismic hazard from the section that last ruptured in 1868 was small. Such modelling of time-dependent deformation, stress and hazard might form the basis for time-dependent, operational earthquake forecasting[10], and thus formalize the message embedded in such potentially precursory activity.

Little would have been known of the events leading up to the Iquique earthquakes if it had not been for the recent deployment of modern geodetic and seismic instrumentation in the region. Nonetheless, given that much of the activity occurred well offshore near the trench of the subduction zone, the distribution of land-based stations is sub-optimal. It is important to improve geodetic and seismic monitoring, and to include offshore sea-floor instrumentation[11], so that we can better understand unfolding plate-boundary fault activity preceding some great earthquakes.

Comparison of the detailed models of the fault slip during the Iquique sequence[1,2,6] with the extent of the fully locked portions of the subduction thrust[3,4] worryingly indicates that only a small fraction of the seismic gap ruptured. As the current studies conclude, the Big One may still be to come. ■

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