EARTHQUAKES

Imperfect dominoes

Within just three years, a 2,000-km stretch of the plate boundary tracing the Indonesian archipelago slipped in four earthquakes. Studies of past and present seismic activity in the region show a complex, but organized pattern of earthquake supercycles, the latest of which has not been completed.

Roland Bürgmann

Earthquakes like company, and historic observations sometimes show sequences of large seismic events that occur unusually close in time and space. Examples of such earthquake clusters include a 1939–1999 sequence of a dozen large earthquakes that propagated, domino-style, along Turkey's North Anatolian fault[1] and a series of five great earthquakes in the mid-twentieth century that broke large sections of the plate boundaries fringing the northern Pacific Ocean[2]. Such groups of seismic events suggest some form of triggering or interaction, and have been likened by some to 'earthquake storms'[3]. Two papers by Konca *et al.*[4] and Sieh and *et al.*[5] highlight the rupture patterns in the Sunda subduction zone, where the Indian and Australian plates descend below the Indonesian archipelago at a rate of ~45 mm yr^{-1}, and a sequence of earthquakes unzip the plate boundary every 100 to 200 years to accommodate this motion.

Palaeoseismic records of earthquakes, derived from excavations across active plate boundary faults, also hint at clustered ruptures in the distant past. However, sparse exposures of geological evidence for past seismic events along continental fault zones and imprecise dating of ancient earthquakes make such inferences difficult to substantiate[6,7]. Frustrated by the difficulty of extracting meaningful and precise information about past earthquake cycles from laborious trenching studies across the San Andreas fault system in California, Kerry Sieh at Caltech turned his attention to past earthquakes and interseismic deformation along the Sunda subduction zone, where more rapid deformation rates and frequent recurrences provide a better opportunity to investigate past fault behaviour.

Here, abundant corals, which rapidly and precisely adjust their growth pattern to changing sea levels (Fig. 1, inset), record past uplift and subsidence events. The relative sea-level changes shown by the coral growth patterns result from both steady interseismic[8] and sudden earthquake[9] deformation and provide a rich record of palaeo–geodetic

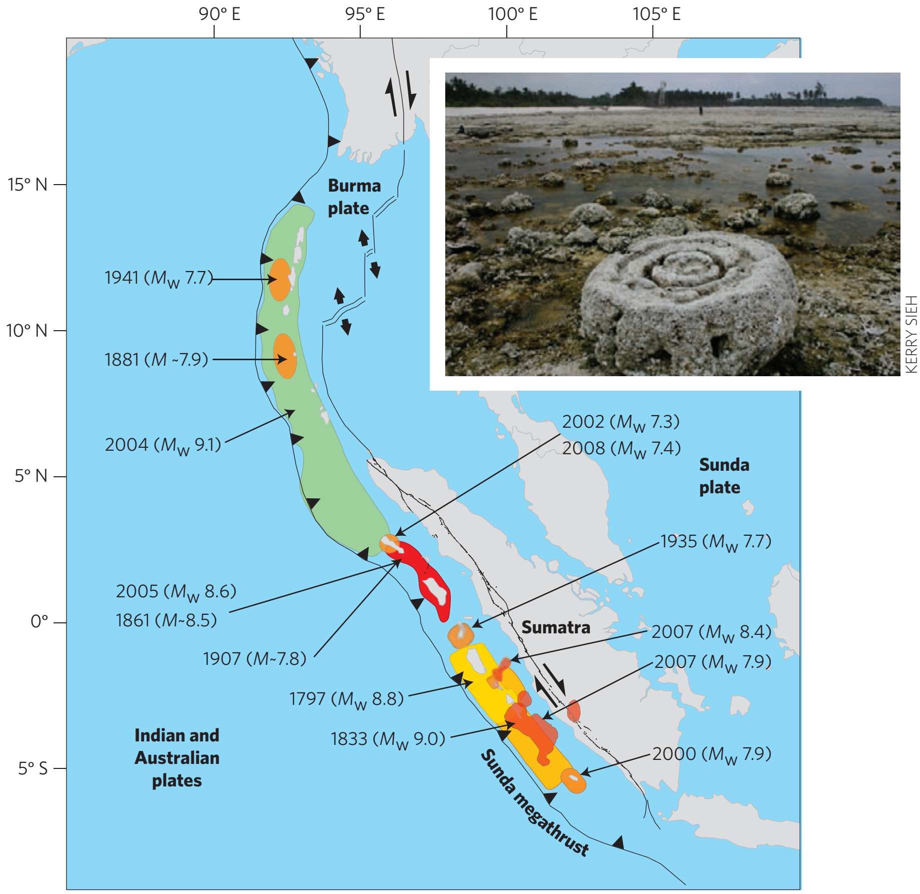

Figure 1 | Failing megathrust. Large historic earthquakes ruptured various sections along the Sunda subduction fault, where the Indian and Australian plates descend beneath the Indonesian archipelago. M is earthquake magnitude, M_W is moment magnitude. Modified with permission from ref. 4 (© 2008 NPG) and ref. 12 (© 2006 AAAS). Inset: A well-preserved fossil coral head at Tanjung Bio on the southernmost tip of South Pagai which died during an earlier earthquake, probably in 1833. In the background lies a now-sequestered beach that was raised in the 2007 earthquake.

deformation spanning the past ~700 years. Deformation events can be dated precisely, either by counting the annual coral growth bands on slabs cut from the coral heads, or by dating of coral material with the isotopic uranium–thorium dating method. During the past four years, this work suddenly gained importance as several large and deadly ruptures worked their way along the plate boundary like an imperfect sequence of toppling dominoes.

The most recent sequence of ruptures along the Sunda megathrust started with the M_w 9.1 Sumatra–Andaman earthquake in December 2004 — one of the largest global events in historic times. Given that there was no knowledge of past great megathrust ruptures along the northern half of the Sunda subduction zone, the earthquake and the resulting tsunami caught the local people and scientists by surprise. Much effort has since been made to better understand the structure, tectonics and seismic hazards of the region. One line of investigation has focused on the effects of changes in stress due to both the earthquake and subsequent relaxation mechanisms on the load of adjacent fault-zone segments[10,11]. Following the 2004 earthquake, three fault segments, spanning a distance of about 1,000 km southeast of the 2004 rupture, seemed to be well on their way towards the next failure, having last ruptured in 1861, 1797 and 1833, respectively (Fig. 1).

In fact, just three months after the 2004 calamity, the next domino fell. In March 2005, the M_w 8.6 Nias earthquake, immediately to the southeast of the 2004 rupture, turned out to be a nearly identical repeat of the 1861 rupture, based on its deformation pattern as shown by modern geodetic and coral-uplift patterns[12,13]. This event left only a 700-km-long section of the Sunda megathrust — along the Mentawai Islands — in place, which had last ruptured in 1797 (M_w 8.8) and 1833 (M_w 9.0). On 12 September 2007, two major ruptures of M_w 8.4 and M_w 7.9 occurred, continuing the chain of events.

Konca and colleagues[4] used a combination of space–geodetic, seismologic and coral-head observations to develop a detailed model of the fault slip in these events. They found that the 2007 earthquakes indeed resulted from the breaking of a portion of the 1833 rupture zone. However, the fault slip did not simply repeat the 1833 events, but instead initiated at a point far from the previous earthquakes and broke back towards the north for only a 250-km-long stretch of the megathrust. The amount of slip seems insufficient to make up for the deficit accumulated in the 200 years since the previous rupture, and no slip occurred in the 1797 rupture zone or in the northern third of the 1833 break. A large section of the plate boundary along the Mentawai Islands therefore remains intact, for now.

In the meantime, Sieh and colleagues[5] have expanded our view of the slip behaviour along the Mentawai Islands during the past ~700 years, by gleaning more evidence from coral growth patterns. Sudden drops in local sea level recorded by ancient coral heads show that in addition to the ongoing sequence of ruptures and the earthquake cluster around 1800, groups of large ruptures broke the subduction thrust around AD 1380 and AD 1650. At least two of the previous three earthquake clusters culminated with a stronger earthquake than those at the beginning of the sequence. Together with the remaining potential slip that has accumulated since 1833, these results indicate that we are not yet done with the most recent of the four earthquake 'supercycles', or sequences of earthquake clusters. An earthquake of M_w 8.8 or multiple events of smaller size are needed to complete the latest sequence. The shaking and tsunami generated by this event — imminent within the next few decades — will probably have disastrous consequences for coastal populations in western Sumatra.

Clearly, the clusters of large earthquakes along the Sunda megathrust are not coincidental. However, this is not a simple case of falling dominoes. For example, a substantial gap lies between the rupture zone of the 2005 Nias earthquake and the section of subduction thrust that broke in the 2007 sequence. To fully understand such earthquake supercycles and improve forecasts of future events, we need detailed information about the evolution of stress and slip in space and time and the mechanical processes that allow faults to communicate and trigger each other[14].

This will require more detailed observations, like those presented in the papers by Konca, Sieh and their colleagues[4,5], complemented by thorough model investigations of the underlying physical processes. Although repeated occurrences of similar event sequences hint at characteristic and thus predictable behaviour, there is also significant, poorly understood complexity in the system. For example, two relatively small earthquakes in 2002 and 2000 (see Fig. 1) may have been triggers for the 2004 and 2007 megathrust ruptures, respectively. Nonetheless, if the size and exact extent of past earthquake ruptures can be deciphered, and if the mechanisms responsible for the apparent fault-triggering can be resolved, our understanding of earthquake clusters should improve the precision of earthquake forecasts in seismically active regions of the world.

Roland Bürgmann is at the Department of Earth and Planetary Science, University of California, Berkeley, California 94720–4767, USA.
e-mail: burgmann@seismo.berkeley.edu

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ATMOSPHERIC CHEMISTRY

Wyoming winter smog

Surface ozone levels are expected to be high in polluted regions during summer months. Observations from Wyoming in February 2008 indicate that equally high concentrations of ozone can be produced during winter.

Joseph Pinto

Ozone levels of concern for human health are expected to occur near the Earth's surface mostly in the warmer months of the year. In many areas of the United States, the 'ozone season', a period during which ozone monitoring is required, lasts from May to September. During these warm months, the daily maximum ozone concentration (averaged over moving windows of 8 h) is well-correlated with the daily maximum temperature[1], because warmth and solar ultraviolet radiation facilitate the formation of ozone from its atmospheric precursors. Much lower levels of photochemical activity are expected