What happened and what's next?

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The huge earthquake of 26 December 2004 and ensuing tsunami were caused by a submarine rupture running from offshore Aceh, Indonesia, to the Andaman Islands. A clearer picture of events is starting to emerge.

As the human drama of the Aceh-Andaman earthquake and tsunami unfolded in the last days of 2004, laymen and scientists began scrambling to understand what had caused these gigantic disturbances of Earth's crust and seas. One of the earliest clues was the delineation, within just hours of the mainshock, of a band of large aftershocks arcing 1,300 km from northern Sumatra almost as far as Myanmar (Burma)[1]. This seemed to signal that about 25% of the Sunda megathrust, the great tectonic boundary along which the Australian and Indian plates begin their descent beneath Southeast Asia, had ruptured. In less than a day, however, analyses of seismic 'body' waves[2] were indicating that the length of the rupture was only about 400 km.

This early controversy about the length of the megathrust rupture created a gnawing ambiguity about future dangers to populations around the Bay of Bengal. If only 400 km of the great fault had ruptured, large unfailed sections might be poised to deliver another tsunami. If, on the other hand, most of the submarine fault had broken, then the chances of such a disaster were much smaller.

In this issue, Ni, Kanamori and Helmberger (page 582)[3] explain why early analyses grossly underestimated the rupture length, and they present an analysis of high-frequency

(2-4 Hz) seismic signals that clearly shows northward propagation of the rupture for a distance of about 1,200 km. Also in this issue, Stein and Okal (page 581)[4] argue that early estimates of the magnitude[1,2] were far too low. Using extremely long-period seismic 'normal mode' waves, they calculate that the earthquake's magnitude was 9.3, about three times larger than initial estimates of 9.0 (given the logarithmic nature of earthquake-magnitude scales). This much larger size is consistent with slip averaging about 13 m along a 1,200-km rupture, assuming that much of the slippage occurred too slowly to be seen in shorter-wavelength seismograms. Thus, they claim the long-versus-short rupture controversy is solved and that there is no need to worry about another giant earthquake and tsunami originating along this long section of the fault.

These two reports[3,4] are among the first published analyses of what is destined to be one of the most important earthquakes of the century. Over the next year or two, figuring out what happened will be a showcase both of what modern observations and analysis can do and of the multidisciplinary nature of modern earthquake science[5]. In the months ahead, much more will be learned about this giant event. Satellite imagery and field measurements of dramatically uplifted and submerged coastlines (Fig. 1)[6,7] and the movement of Global Positioning System geodetic stations[8],as well as tsunami records, will all add constraints on the areal extent of the rupture and the magnitude and sequencing of slip: these, in turn, will be essential to understanding the tsunami.

If all of the megathrust between northernmost Sumatra and Myanmar has produced its once-a-millennium giant earthquake, why should we have any immediate concern about another giant quake or tsunami in the Bay of Bengal? McCloskey *et al*.[9] offered one answer by estimating the stresses imposed by the giant 2004 rupture on the two big faults farther south. It seems that the section of the Sunda megathrust immediately to the south, off the coast of northern Sumatra, is now closer to failure. Likewise for the nearest portion of the great San Andreas-like Sumatran fault, which runs through Banda Aceh and down the backbone of the Sumatran mainland.

The critical question is how close to failure the 2004 rupture has moved these two big faults. This will be moot until more is known about the history of their past ruptures. It will be necessary to learn how the Sumatran parts of the megathrust are segmented structurally, and how they have behaved in the past. Immediately south of the 2004 rupture, for example, it appears from the historical record that there were very large earthquakes in 1861 and 1907[10]. Where on the megathrust were these ruptures, and how often and how regularly do they recur? Palaeoseismic data are available only for a 700-km-long section farther away, from about 1° to 5° south of the Equator. Giant earthquakes and tsunamis occur there about every 200-230 years, sometimes as a single giant earthquake, sometimes as two in relatively quick succession, as happened in 1797 and 1833[11,12].

Big faults on the northern flank of the 2004 rupture also pose a hazard; the northern extension of the 2004 rupture continues for another 1,000 km, up the west coast of Myanmar, well past Bangladesh to the eastern end of the Himalayas. Too little is known of its long-term history to provide a meaningful assessment of its future behaviour. Moreover, long sections of the enormous thrust fault along which India is diving down beneath the Himalayas have not failed for centuries and are only one to three fault-lengths away from the 2004 rupture.

It is sobering to realize that big earthquakes sometimes occur in clusters (for example, seven of the ten giant earthquakes of the twentieth century occurred between 1950 and 1965, and five of these occurred around the northern Pacific margin)[13]. Because many of the giant faults in the Aceh–Andaman neighbourhood have been dormant for a very long time, it is quite plausible that the recent giant earthquake and tsunami may not be the only disastrous twenty-first-century manifestation of the Indian plate’s unsteady tectonic journey northward.

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Fig. 1 Evidence of uplift – here about 1.5 m. This aerial photo shows new land that emerged on the southwest coast of Simeulue island, above the southern edge of the megathrust rupture that caused the Aceh–Andaman earthquake. The wide strip of land consists of a former fringing coral reef; what was previously a beach (far left) has been left high and dry. Inset, a field of fire-coral heads on a neighbouring coral reef that rose about a metre during the earthquake.

Fig. 1