Speed and size of the Sumatra earthquake

We now have a clearer picture of the seismic features of last year's gigantic event.

Our seismological results reveal that Indonesia's devastating Sumatra–Andaman earthquake on 26 December 2004 was 2.5 times larger than initial reports suggested — second only to the 1960 Chilean earthquake in recorded magnitude. They indicate that it slowly released its energy by slip along a 1,200-km fault, generating a long rupture that contributed to the subsequent tsunami. Now that the entire rupture zone has slipped, the strain accumulated from the subduction of the Indian plate beneath the Burma microplate has been released, and there is no immediate danger of a similar tsunami being generated on this part of the plate boundary, although large earthquakes on segments to the south still present a threat.

Our results come from an analysis of the Earth's normal modes $_0S_2$, $_0S_3$ and $_0S_4$. These consist of singlets or split peaks that have distinct periods, or eigenfrequencies, owing to the planet's rotation and ellipticity. Great earthquakes excite these modes, which can be observed by Fourier analysis of long seismograms (Fig. 1a). Singlet amplitudes depend on the location of the earthquake and seismic station, earthquake depth, focal mechanism and seismic moment[1]. The decay of energy with time owing to inelastic processes in the Earth, which is equivalent to the width of the spectral peak, depends on the mode's attenuation, or quality factor Q.

Using the focal mechanism and depth reported by the Harvard Centroid-Moment Tensor (CMT) project (see project website, www.seismology.harvard.edu/projects/CMT) and singlet eigenfrequencies[2], we obtained consistent estimates of seismic moment and Q by two methods: fitting amplitude spectra (Fig. 1a) and fitting the decay of narrow-band filtered singlets[3] (results not shown). The estimates of Q for $_0S_2$, $_0S_3$ and $_0S_4$ are 525, 405 and 380, respectively, and are consistent with previously reported values[4].

As well as the longest-period normal-mode multiplets $_0S_2$, $_0S_3$ and $_0S_4$, we analysed radial modes $_0S_0$ and $_1S_0$ to obtain estimates of seismic moment and moment magnitude (Fig. 1b). Moment values take into account the inclusion in the seismograms of both ground motion and changes in the gravity field[5]. From the normal modes, we estimate that the seismic moment was as large as 1.0×10^{30} dyn cm (moment magnitude $M_w = 9.3$).

There was also a systematic increase in seismic moment with period (Fig. 1b), which explains why conventional methods used to assess earthquake size dramatically underestimated it. The $_0S_2$ moment is about 2.5 times larger than indicated by the CMT solution, which was based on surface waves with periods below 300 s and which gave a value for the moment magnitude of 9.0. Assuming that other events' reported moments do not also underestimate their true size, this makes the Indonesian earthquake the second largest ever to be instrumentally recorded.

The larger moment we obtain presumably reflects slow slip that was not detectable from the surface waves. The systematic increase in moment with increasing period, reflecting the spectrum of the source time function, is consistent with this idea. A moment still increasing at these very long periods has not been previously observed for other earthquakes, raising issues about the physics of faulting — for example, at what period the moment ultimately stabilizes and reaches its static value.

The slow slip probably occurred over the northern part of the 1,200-km length of the rupture zone indicated by aftershocks (Fig. 1c). The larger moment can be fitted by 11 m of slip on a fault 1,200 km long and 200 km wide (down-dip dimension). This is a larger area than is implied by body-wave inversions, which find rapid slip on the southern part[6]. A larger rupture area is consistent with the fact that split modes are better fitted by a source with centroid at 7 °N than by one at the epicentre at 3 °N, where rupture started and propagated northward[6]. Another analysis using normal mode $_0S_0$ also favours a long rupture[7]. Tsunami run-up, which is the water's highest elevation at the point of maximum horizontal penetration, was 25–30 m in the near field on Sumatra. This implies about 12–15 m of slip, because run-up typically does not exceed twice the fault slip[8].

It seems that the slow slip helped to excite the tsunami, as suggested by successful modelling of the wave from sea levels detected by the Jason satellite, using a source that includes the northern segment[9]. Large tsunami amplitudes in Sri Lanka and India also support rupture on the northern, north-trending segment, because tsunami amplitudes are largest when perpendicular to the fault.

The picture emerging from the normal modes is consistent with the regional tectonics. Although the plate geometry and motions are not precisely known, the Burma microplate is a sliver between the larger Indian and Sunda plates. Combining the motions of India[10] and Sunda[11] with respect to Eurasia, which are known from global-positioning satellite data, with estimates of Burma's motion with respect to Sunda, inferred from back-arc spreading[12,13], yields India's motion with respect to Burma (Fig. 1c). Because the India–Burma pole is nearby,

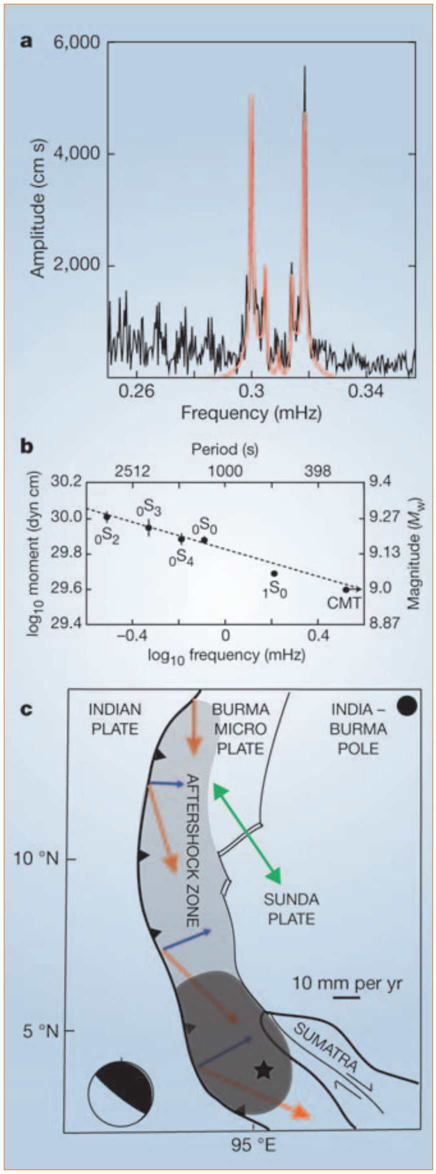

Figure 1 Features of the 2004 Sumatra–Andaman earthquake. **a,** Observed (black) and predicted (red) amplitude spectrum for a $_0S_2$ multiplet, showing the best-fitting seismic moment (1.0×10^{30} dyn cm). **b,** Variation in seismic moment and moment magnitude, M_w, with period. CMT (for Centroid-Moment Tensor project) represents the result from surface waves with periods below 300 s. **c,** Comparison of aftershock zone (greys) with minimum area of fast slip (dark grey; corresponding to one-third of rupture area), estimated from body waves, and the possible area of slow slip (light grey; corresponding to the northern part of the fault area) inferred from normal modes. Star, earthquake epicentre. Arrows: total (red) and orthogonal (blue) convergence for an India–Burma euler vector of (14.8 °N, 99.8 °N) 1.55° per million years; green, back-arc spreading; scale bar, 10 mm per year. Black and white disc, CMT focal mechanism.

the convergence direction varies along the rupture zone and becomes strike–slip at the north end of the rupture, presumably explaining why rupture ceased. The CMT focal mechanism reflects the arc-normal component of convergence: 15–25 mm per yr.

If the entire aftershock zone slipped, then strain accumulated on the northern part of the rupture has been released. There is therefore no immediate threat of an oceanwide tsunami being generated by slip on this segment of the plate boundary, because such earthquakes should be at least 400 years apart. However, the danger of a large tsunami resulting from a great earthquake on segments to the south remains.

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