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, the convergence direction varies along the rupture zone and becomes strike–slip at the north end of the rupture, presumably

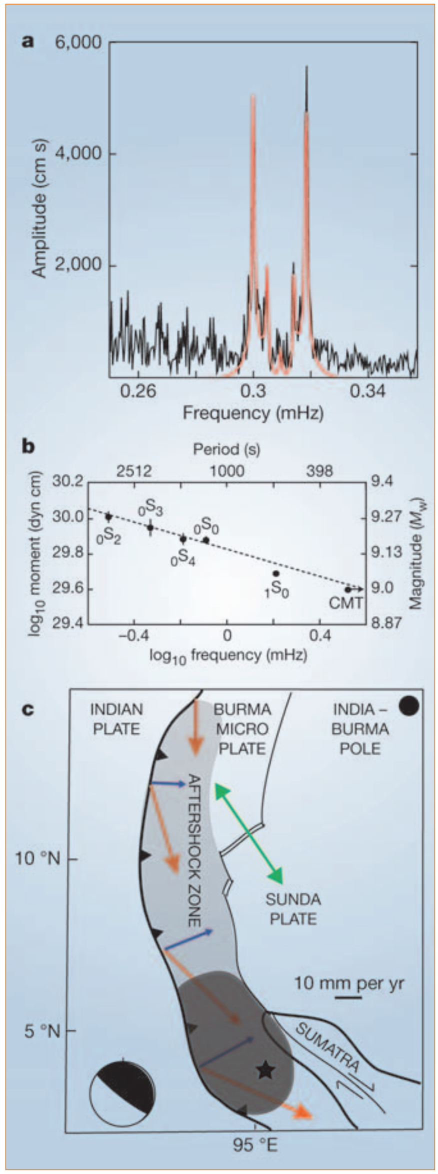

Figure 1 Features of the 2004 Sumatra–Andaman earthquake. **a,** Observed (black) and predicted (red) amplitude spectrum for a $_0S_2$ multiplet, showing the best-fitting seismic moment (1.0×10^{30} dyn cm). **b,** Variation in seismic moment and moment magnitude, M_w, with period. CMT (for Centroid-Moment 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.

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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Seismology

Energy radiation from the Sumatra earthquake

We determined the duration of high-frequency energy radiation from Indonesia's great Sumatra–Andaman earthquake (26 December 2004) to be about 500 seconds. This duration can be translated into a rupture length of about 1,200 km, which is more than twice as long as that inferred from body-wave analyses performed soon after the event. Our analysis was able rapidly to define the extent of rupture, thereby aiding the assessment of seismic hazard in the immediate future.

Soon after the Sumatra–Andaman earthquake, seismic body-wave studies in the period range of 10 to 50 s indicated that there had been a slip distribution over a 400-km segment[1–3] (Fig. 1a). These methods for rapid assessment of major earthquakes rely on the extended P-wave train to deduce the source rupture pattern. But when an event lasts longer than the period between the later-phase PP and P waves, a problem arises in determining the source duration.

Figure 1b shows the observed displacement seismogram for a seismic event of magnitude 7.1 (which occurred near the epicentre of the 26 December earthquake (Fig. 1a, red star) on 2 November 2002). The phases PP and PPP are apparent, but are seen to disappear at high frequency (in the range 2 to 4 Hz) because of attenuation in the Earth's mantle[4]. We therefore analysed high-frequency radiation from the Sumatra earthquake by determining amplitude–time envelopes and smoothing them as described[4] (see supplementary information). Comparison of the smoothed envelopes for the main shock of this event with three smaller fore- and aftershocks shows that the amplitude and duration of the main shock are much larger (Fig. 1c).

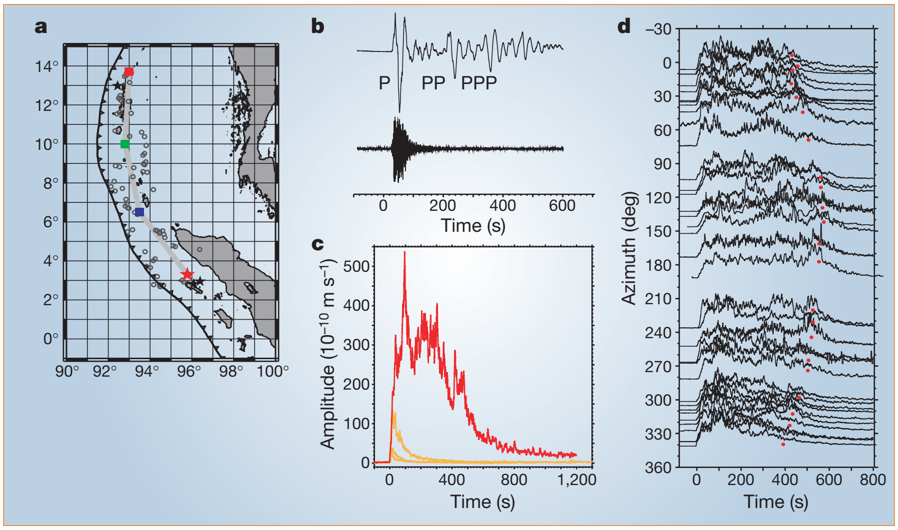

Figure 1 Frequency of radiation from the 2004 Sumatra–Andaman earthquake. **a,** Rupture-termination points of the earthquake estimated from body-wave inversion (blue square) and from high-frequency radiation (red square) calculations; green square, candidate for termination point (see supplementary information). Red star, earthquake epicentre; circles, aftershock locations; black stars, locations of large foreshocks and aftershocks. **b,** Typical teleseismic seismograms (broadband) showing P waves before (top) and after (bottom) high-bandpass (2–4 Hz) filtering; later phases are removed by attenuation. D = 64 degrees. **c,** Enveloped high-frequency seismogram comparing the main shock (red) with smaller events (orange) at the same station. **d,** Smoothed envelopes (2–4-Hz bandpassed) of the main shock as a function of azimuth (horizontal angle): shorter wave trains are evident in the direction of rupture (azimuth about 340°). Red dots, estimated end of the source duration.

Figure 1d plots the envelopes for the main shock as a function of azimuth (angular distance from the horizon). Each envelope shows a short rise time, then a relatively flat, sustained portion, which is followed by rapid decay. The envelope duration (red dots in Fig. 1d) reveals a clear azimuthal pattern of 400 s in the direction of rupture (at about 340°) to 590 s in the opposite direction. We assume that these high-frequency signals are derived mostly from the rupture front[5]. From the range of the azimuthal variation in duration (190 s), we determine the rupture length to be 1,200 km — the longest ever recorded. Then, from the average duration (about 500 s), we can derive the average rupture speed as 2.5 km s^{-1}.

The rupture length is comparable to the length of the aftershock distribution (Fig. 1a). The rupture was substantially longer than that of the 1960 great Chilean earthquake[6] (340 s), and had a larger magnitude of 9.5, but the tectonic setting at Sumatra is very different from that at Chile. In Chile, the age of the subducting plate is young (15 million years old) and the plate convergence is nearly normal to the trench, whereas in Sumatra the subducting plate is older (more than 60 million years old) and the plate convergence is oblique, especially in the north. This difference could be responsible for the difference in slip behaviour between the two events, and hence the disparities in rupture length and magnitude.

The high-frequency radiation reflects only the propagation of the rupture front, so it alone cannot uniquely determine the slip distribution. Modelling of long-period surface waves and normal modes will eventually constrain the spatiotemporal distribution of slip. Despite such uncertainty, our simple analysis at high frequency provides an accurate and rapid determination of the duration and rupture length of this earthquake, which are important for rapid assessment of immediate seismic hazard in the area.

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