

Seismic evidence for broken oceanic crust in the 2004 Sumatra earthquake epicentral region

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The great Sumatra earthquake of 26 December 2004 was the third largest event to occur in a subduction zone in the past 50 years. The rupture initiated at 30–40 km depth northwest of Simeulue Island¹ and propagated for ~1,300 km to the northern Andaman Islands². The earthquake was caused by sudden slip along the plate interface between the subducting Indo-Australian plate and the overriding Sunda plate^{3,4}. Although detailed knowledge of the structure of the subduction interface is important to define potential sources of large megathrust earthquakes, available data^{5–8} have not provided such information so far. Here we present a high-quality seismic section of the focal region, from the abyssal plain down to 40 km depth below the fore-arc. The seismic data reveal that the subducting crust and oceanic Moho—the crust–mantle boundary—are broken and displaced by landward-dipping thrust ramps, suggesting that the megathrust now lies in the oceanic mantle. We image active thrust faults at the front of the accretionary wedge, consistent with thrust aftershocks on steeply dipping planes. Our observations imply that very strong coupling leading to brittle failure of mantle rocks accounts for the initiation of such an exceptionally large earthquake.

Plate interface geometries of the northern Sumatra subduction zone have been determined by fitting simple curves along hypocentres of aftershock recordings of the main event^{6–8}. To gain structural knowledge, seismic refraction methods are commonly used, but the resolution is of the scale of kilometres⁹. Seismic reflection is capable of providing much higher resolution images; however, the combination of poor penetration through strongly deformed wedge sediments, seafloor scattering and severe water-bottom multiples hampers imaging below ~10 km with conventional techniques¹⁰.

To improve on surveys^{5,6} hitherto insufficient to image the plate boundary configuration at depth, we acquired deep marine reflection data aboard WesternGeco's marine seismic vessel *Geco Searcher* (Tsunami Survey) (see Supplementary Information, Method). Seismic profile WG1 was shot at a right angle to the margin, as close as possible (54 km northwest) to the epicentre of the 2004 earthquake (Fig. 1). It is 243 km in length and terminates ~60 km off the coast of northwest Sumatra.

On the Indo-Australian plate, the highly reflective top of the basalt is capped by a thin layer of pelagic sediment, in turn covered by a thick, landward-thickening (2.1–3.16 s) turbidite sequence (Fig. 2, Supplementary Information, Fig. S1). The oceanic Moho is clearly imaged, which provides a crustal thickness estimate of ~4.5 km (~1.4 s) assuming an average P-wave velocity of 6.3 km s⁻¹ (ref. 11). Seaward of the accretionary wedge front, the oceanic crust and pelagic deposits are cut and offset by two landward-dipping thrust ramps (CMP 25700 and 28200). At the tip of these thrusts, minor faulting is observed in the turbidites with possible folding of the lower horizons (Fig. 3). A shallow northeast-dipping reflector, which could be a thrust décollement within the oceanic crust, links the outer (R1) with the inner (R2) thrust fault. The latter clearly offsets the oceanic Moho, and penetrates into the mantle (Fig. 3, Supplementary Information, Fig. S2), suggestive of incipient thrust imbrication of oceanic crust slices. Offshore southern Sumatra, landward-dipping reflectors have been observed within the oceanic crust beneath the trench and interpreted as crustal faults⁹.

As reported for the Middle America trench¹², plate bending at subduction zones generates trench-parallel conjugate normal faults that dissect the entire sedimentary column and penetrate into the basement, producing seafloor and basement offsets of 100–500 m.

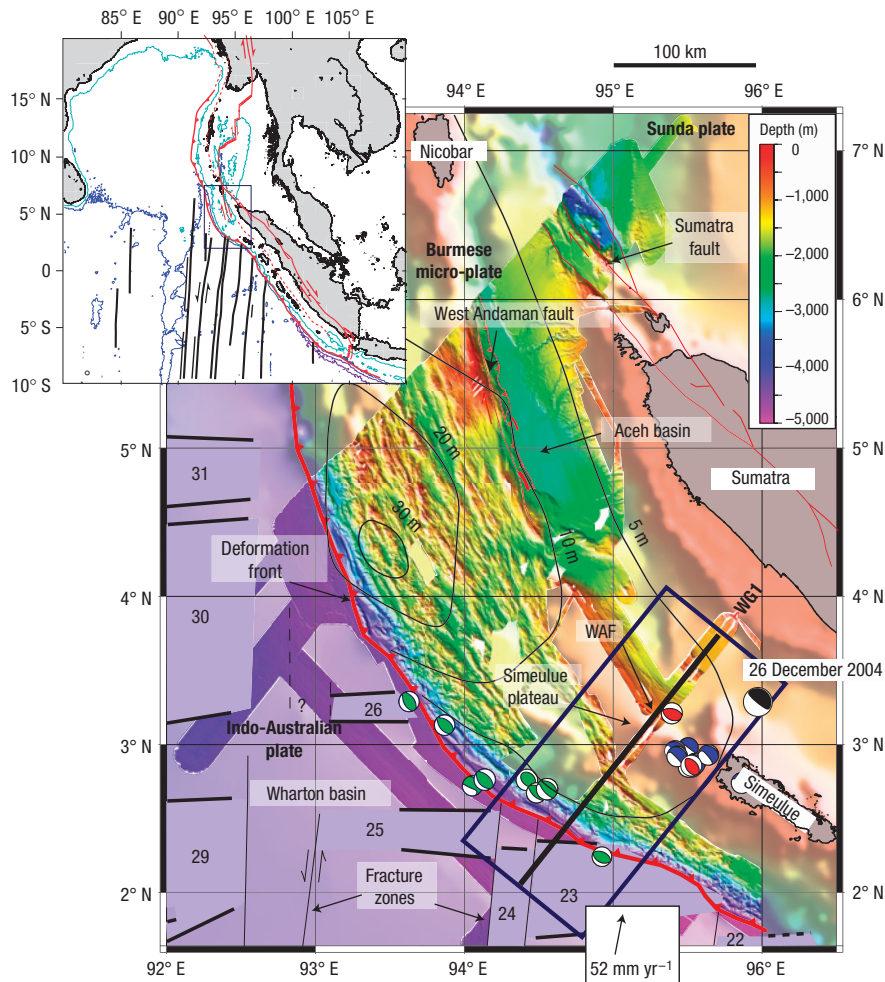


Figure 1 Study area. Location of seismic reflection profile WG1 superimposed on recently acquired bathymetric data^{5,6,15}. Oceanic north–south fracture zones and magnetic anomalies¹¹ (numbers) are marked. Black contours indicate co-seismic slip³ of the 26 December 2004 earthquake. Other focal mechanisms correspond to $M_w \geq 5.4$ aftershocks: frontal thrust earthquakes in green, thrust events below the Simeulue plateau in blue, steep thrust events in red (see Supplementary Information, Tables S1,S2). Hypocentre locations are from Engdahl *et al.*⁸ and fault plane solutions from the Harvard Centroid Moment Tensor catalogue. The rectangle delineates aftershocks projected onto the depth cross-section in Fig. 4. WAF: west Andaman fault. The regional tectonic setting is shown in the inset.

On profiles collected 65–175 km south of WG1, Franke *et al.*¹³ interpret minor faulting within the sediments as originating from bending-related extension. Minor faulting within the turbidites is also observed on profile WG1 (Fig. 3), but the absence of normal fault scarps at the sea floor and the geometry of the offsets associated with R1 and R2 at the top and base of the oceanic crust suggest that these deep crustal faults are not bending-related normal faults. Furthermore, seafloor mapping¹⁴ and seismological studies¹⁵ on the Indo-Australian plate indicate the presence of reactivated fracture zones oriented N5° E, with dominantly left-lateral slip¹⁵, active since ~ 7.5 Myr ago. Their shallow expressions have been imaged on both northwest–southeast and southwest–northeast trending 3.5 kHz mud penetrator profiles¹⁶, and seismic data reveals they can be followed from the sea floor down to the basement¹¹. The interpreted deep faults ahead of the wedge front have dips of 10°–30°; hence, a projection in the direction perpendicular to the strike of the fracture zones would yield dips of 30°–50°—very small for strike-slip faults. Therefore, these are unlikely to be reactivated fracture zones. Because of their small dip-slip component (15–30 m vertical throw at the sea floor,

with eastern block downthrown), the reactivated fracture zones may accommodate bending-related deformation.

A clear landward-dipping thrust (MT), marked by high-amplitude reflections, reaches the sea floor at the base of the main continental slope (Figs 2,3). Both the strong signature and the 1-km-high, steep (30°) wedge front that extends for at least 300 km northwards (Fig. 1) suggest that most of the relative plate motion is taken up by this ‘main thrust’. The ~ 100 m cumulative vertical offset of the sea floor and underlying turbidite beds confirms that MT is active and indicates it might have been the principal emergent dislocation of the 26 December 2004 earthquake. This thrust steepens downdip from $\sim 15^\circ$ – 20° to $\sim 30^\circ$ – 40° at ~ 10 km depth. It is difficult to identify any associated vertical offset at the top of the oceanic crust, but MT is aligned with a deeper reflector that penetrates into the oceanic mantle, and which we interpret as a deep-penetrating thrust ramp (R4). Two other splays in the accreted sediments (T1 and T2) merge onto a similar reflector at depth (Fig. 3).

Beneath the frontal part of the wedge, two steeply dipping (31°, 35°) thrust aftershocks occurred at 17.5 km depth⁸, falling

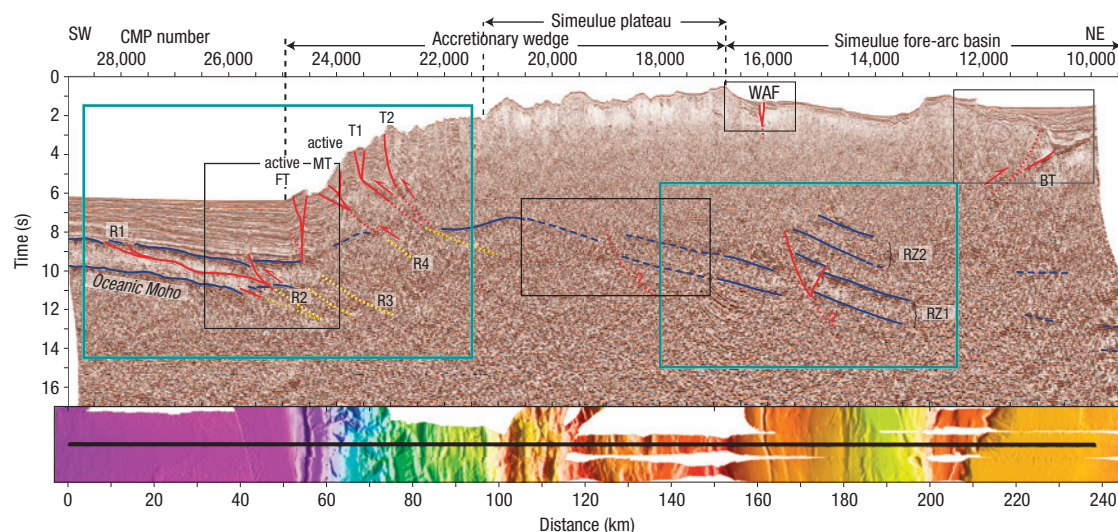


Figure 2 Seismic profile WG1. Interpreted seismic reflection image as a function of two-way travel time, plotted using a time-varying automatic gain control. Vertical exaggeration is 1:6 at 1.5 km s^{-1} . R1–R4: thrust ramps cutting through the oceanic crust. FT: frontal thrust, MT: main thrust, T1 and T2: near-surface wedge thrusts, R1 and R2: pairs of reflectors bounding less reflective zones in the outer fore-arc, WAF: west Andaman fault, BT: backthrust. Solid red lines: interpreted thrust faults; dashed red lines: faults where less certain; dashed yellow lines: deep-penetrating reflectors interpreted as thrust faults within igneous oceanic crust or mantle. Blue and black boxes indicate locations of images shown in Fig. 3 and Supplementary Information, Fig. S2, respectively. The lower panel shows a 17-km-wide strip of bathymetry along the profile.

close to the oceanic Moho (Fig. 4) (refs 7,8). Two other deep thrust events (16, 22 km depth) with steep dips (33° , 41°) were reported in this area, and at least four more occurred farther northwestwards (depths 17–20 km; dips 34° – 44°) (Fig. 1, Supplementary Information, Table S1). An aftershock study⁶ using ocean-bottom seismometers also located deep earthquakes near the trench. The presence of such events further confirms the existence of thrust ramps in the oceanic crust/mantle next to or seaward of the wedge toe, as indicated by the seismic image. Although the exact value is poorly constrained¹⁷, a significant amount (5–30 m) of co-seismic slip in the frontal part of the wedge has been inferred for the 26 December 2004 earthquake³ (Fig. 1).

The top and bottom of the subducted crust can be followed along significant portions of the profile (Fig. 2). At a more detailed level, these reflectors are discontinuous, as if broken up and offset by faults (Fig. 2). Beneath the outer fore-arc basin (CMP 13500–16000), a pair of strong reflectors (RZ2), separated by a less reflective zone, can be seen between 7 and 10 s, above the subducted crust (Figs 3,4). A band of reflectivity was observed at similar depths beneath Vancouver Island above the Cascadia subduction megathrust¹⁸. Calvert *et al.*¹⁸ suggest that these features are the result of either tectonic underplating of oceanic crustal material in a duplex in the fore-arc continental lower crust, or crustal erosion of the fore-arc continental crust followed by downward transportation with the subducting plate. The evidence from WG1, summarized in the schematic section of Fig. 4, supports an oceanic crustal underplating model for these reflectors. The presence of an ophiolite associated with a pronounced gravity anomaly on Simeulue Island¹⁹ further supports this hypothesis.

The hypocentre of the December 2004 main shock projects below CMP 11572 on profile WG1, ~ 155 and ~ 165 km to the northeast of seafloor traces of MT and FT, respectively (Fig. 4). Although poorly constrained, the focal depth of the event is estimated to be 36 ± 5 km (ref. 7). Under the most sedimented part of the Simeulue fore-arc basin, a landward-verging reflector (BT) is observed, possibly marking the position of the continental backstop

of the wedge, that is, of Sumatran continental crust. This inference is corroborated by the presence of sub-horizontal reflectors at ~ 9 s, where the continental Moho would be anticipated²⁰ (Figs 2,4). Therefore, the hypocentre seems to lie below the continental Moho, either at the continental mantle/subducted crust interface or in the oceanic mantle (Fig. 4).

Subduction megathrusts are generally thought to lie near the top of the subducting basaltic layer or in the overlying sediments²¹. Here there is no evidence for a reflector in the sediments that could be interpreted as a décollement, which suggests a plate interface at or below the top of the igneous crust. Although the subduction interface must have been along the basalt/sediment contact in the past—because subducted oceanic crust is imaged down to 40 km depth, not stacked in the wedge—its irregular (saw-toothed) geometry broken by crustal thrust ramps suggests it no longer is. Indeed, the development and persistence of significant irregularities, which would otherwise get abraded by repeated slip, suggests the location of the plate interface has changed. Moreover, stress release on active thrust faults cutting through the oceanic crust would hinder building, at the basalt–sediment interface, the amount of stress required to produce a very large earthquake. Fracturing and slicing of the oceanic crust along landward-dipping thrust faults can be accounted for by a décollement level mostly lying in the upper mantle of the downgoing plate, possibly just below the Moho (Fig. 4).

Assuming a quasi-planar geometry between the hypocentre and the ‘roots’ of the active frontal thrust faults (R2–R4) would yield an approximately 165-km-wide locked zone with a dip of 10 – 12° , consistent with most seismological and geodetic estimates^{17,22,23}. In the vicinity of profile WG1, the presence of a set of six aftershocks (in blue on Figs 1 and 4; Supplementary Information, Table S2) with 13° – 18° dips, projecting at distances of 145–165 km and located at 25–28 km depth—hence in the lower plate—suggests active thrust faulting within and at the base of the subducting plate. Figure 1 shows that these aftershocks lie in the region of co-seismic slip^{3,17}. In Japan, intra-slab earthquakes are found to

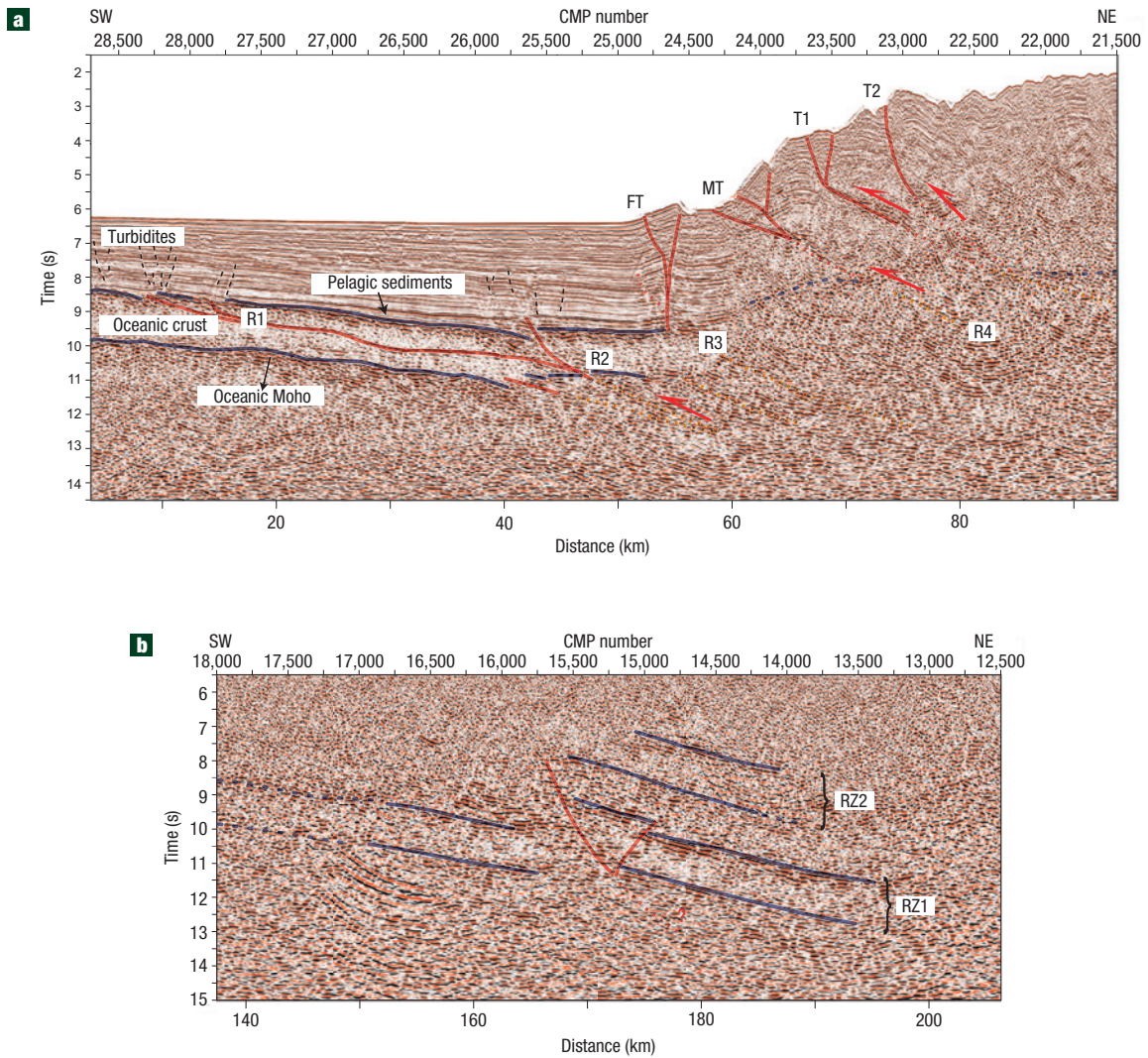


Figure 3 Detailed seismic images. **a,b**, Blow-ups of the frontal part of the accretionary wedge (**a**) and the deep outer fore-arc structure (**b**). The vertical exaggeration is 1:4 at 1.5 km s⁻¹. See Fig. 2 for location and nomenclature. Thin dashed lines highlight minor faulting in the sediments above the thrust ramps.

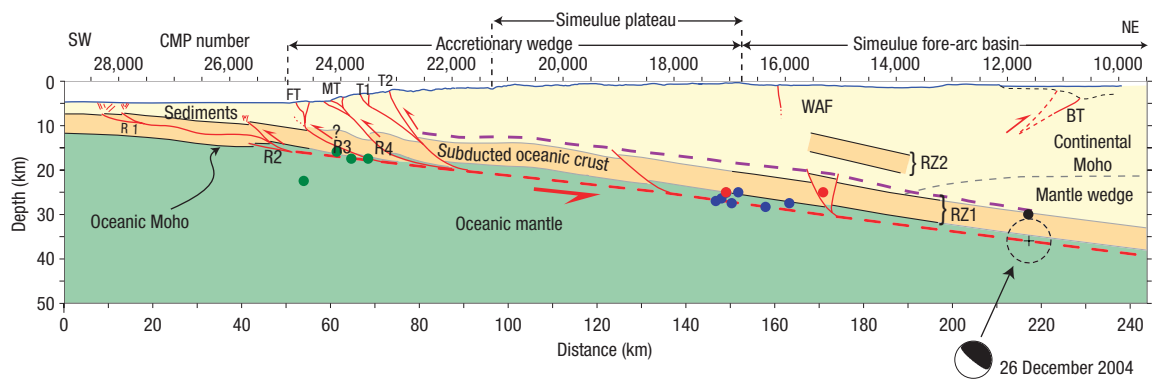


Figure 4 Schematic depth cross-section at 1:1 scale. Projected location of the 26 December 2004 hypocentre at 36 km depth, with the dashed circle representing 5 km depth error. The small black circle above denotes the default depth of 30 km. Aftershocks from within the black rectangle in Fig. 1 are projected onto the profile: steep frontal thrust events (green), thrust events below the Simeulue plateau (blue) and steep thrusts (red). The standard position of the megathrust is marked as a purple dashed line, and our proposed upper mantle location as a red dashed line (note the alignment of the four aftershocks in blue and three in green).

closely follow the oceanic Moho over more than 150 km (ref. 24). Although unconventional, the mantle megathrust model shown in Fig. 4 is compatible with most of the different lines of evidence in the Simeulue focal region. The December 2004 main shock rupture would have nucleated beneath the continental mantle and propagated upward to the sea floor by way of the crustal thrust faults MT/R4 and FT/R3 at the front of the wedge.

The upper and lower limits of locked subduction interfaces are usually thought to correspond to temperatures of 150 and 350 °C, respectively²⁵, the former coinciding with the dehydration transition from clay (stable sliding) to illite–chlorite (stick–slip), and the latter with the onset of plastic flow in crustal rocks. For a mantle megathrust however, such inferences ought to be reconsidered, with the upper limit lying farther upwards, including at the sea floor, and the lower one, farther downwards (for example, 40–50 km depth) as suggested by geodetic studies^{23,26} and the occurrence of a deep (45 km) earthquake in September 2007. In any event, seismic coupling in mantle rocks, which fail brittly at temperatures as high as ~600 °C (ref. 27), ought to be stronger than between accreted sedimentary material and oceanic basalt²⁸. This might account for the exceptional magnitude and long return period of the 26 December 2004 event, (> 500 yrs, possibly 1000 yrs or more), longer than usually observed for $M \sim 8$ earthquakes on fast subduction zone segments, including in central Sumatra²⁹. If the mantle megathrust geometry is correct, models of accretionary wedge mechanics³⁰ should be revisited.

Perhaps the 2004 Sumatran event should be considered an example of a novel class of exceptionally large and infrequent megathrust earthquakes ('Mantle Megaquakes': $M_w > 9$), typical of subduction zones and great collision ranges such as the Himalayas³¹, rupturing deep mantle interfaces with a mechanical strength much greater than that of thrusts in the crust. The common occurrence of slices of mantle peridotites attached to oceanic crust in ophiolite complexes along most suture zones implies that such giant quakes, although fortunately rare, may be the rule rather than the exception along convergent plate boundaries.

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