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THE BOXING DAY 2004 TSUNAMI —A REPEAT OF 1833?

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An article in the September 2004 issue of *AusGeo News* discussed how massive earthquakes in the Sumatra subduction zone have the potential to cause tsunamis large enough to affect the entire Indian Ocean basin.

This potential was demonstrated three months later when a magnitude 9 earthquake off northern Sumatra triggered the Boxing Day tsunami. Over 200 000 died amid widespread destruction in Indonesia, Sri Lanka, India, and Thailand and on the east coast of Africa.

Despite this major event, the danger of tsunamis in the Indian Ocean has not passed. A regional tsunami warning system could help to prevent further tragic loss of life.

Figure 1. Great earthquakes in the Sumatran subduction zone. Note that other large earthquakes occurred in the Andaman and Nicobar Islands in 1881 and 1941.

The magnitude 9.0 Sumatra–Andaman Islands earthquake of 26 December 2004, which caused the most destructive tsunami in recent history, was the largest earthquake since the magnitude 9.2 Alaskan earthquake of 1964, and was among the five largest earthquakes in the past century. Such massive earthquakes only occur in subduction zones where two of the rigid tectonic plates that comprise the earth's surface are converging, and one plate, usually composed of heavier oceanic material, dives beneath another, usually composed of lighter continental material. The Boxing Day earthquake occurred in the Sunda subduction zone, where the Indo-Australian plate is sliding beneath Sumatra.

The locations of this and other major earthquakes along the Sumatra subduction zone are shown in figure 1. The great 1833 earthquake ruptured a segment of the subduction zone about 1000 kilometres southeast of the rupture area of the 2004 shock. Like the 2004 tsunami, the one following the 1833 earthquake devastated the adjacent coastal area of Sumatra. However—as shown in figure 2—most of the energy of the 1833 tsunami was directed into the open Indian Ocean. While the tsunami may have had an impact on Sri Lanka, the Maldives and other islands in the Indian Ocean, its origin further southeast along the zone prevented it from causing much damage in the Bay of Bengal, and there would have been little effect on Thailand. The wave height on the Australian coast may have been somewhat larger than during the 2004 tsunami, but Australia would still have been spared the main plume of energy radiated into the Indian Ocean.

Like the 1833 event, the effects of the 2004 tsunami in Sumatra were catastrophic. Tsunami run-up exceeded 30 metres in some places in Sumatra, where people had little time to escape and whole villages were razed. The 1833 event would not have produced the waves, 5–10 metres high, that hit Thailand and Sri Lanka last year about one to two hours after the earthquake.

As is typical in a subduction zone earthquake, on Boxing Day the seafloor rose near the plate boundary and subsided 100–200 kilometres landward of the boundary (see figure 1 of the September 2004 article). This resulted in a wave travelling to the east whose leading edge was receding, causing the sea to withdraw, while to the west the leading edge inundated the coast.

Thus, people in Thailand were given some warning by the sudden withdrawal of the sea, and in some cases lives were saved when this warning was recognised and acted on. In many cases, however, people did not understand the phenomenon and the subsequent sudden inundation killed many. In Sri Lanka, the first effect of the wave was inundation, giving people little or no warning. This would also have been the case in most areas hit by the 1833 tsunami.

Could victims of the 2004 tsunami in Sri Lanka and Thailand have been warned in time? The September 2004 *AusGeo News* article pointed out that tide gauges on Christmas Island and the Cocos Islands could provide effective warning of tsunamis caused by Sumatran earthquakes such as the one of 1833. The 1833 earthquake occurred off southern Sumatra, much closer to the Cocos Islands than was the 2004 earthquake.

While a tsunami like that of 1833 would arrive at the Cocos Island within about 20 minutes of the earthquake occurring, this was unfortunately not the case with the Boxing Day tsunami, whose source zone was closer to Thailand and Sri Lanka than to the Cocos Islands. A plot of the 2004 tsunami travel times (figure 3) shows that the tsunami had already passed Thailand and Sri Lanka by the time it reached the Cocos Islands. Clearly, a tsunami warning system will require more instrumentation in this region if it is to deliver effective warnings to those countries.

The extent of rupture along the arc and potential for future events

Earthquake ruptures relieve stress on the subduction zone plate boundary, so a zone segment that ruptures during a major earthquake might not be expected to rupture again for some time. In assessing the risk of future earthquakes and tsunamis in the region, the crucial question is: how much of the subduction zone ruptured during the 2004 earthquake?

As shown in figure 1, this earthquake did not rupture the segments of the subduction zone that ruptured during the 1833 and 1861 earthquakes. These segments can be expected to have been accumulating strain energy for 172 and 144 years, respectively, and so they have to be considered at risk for future earthquakes.

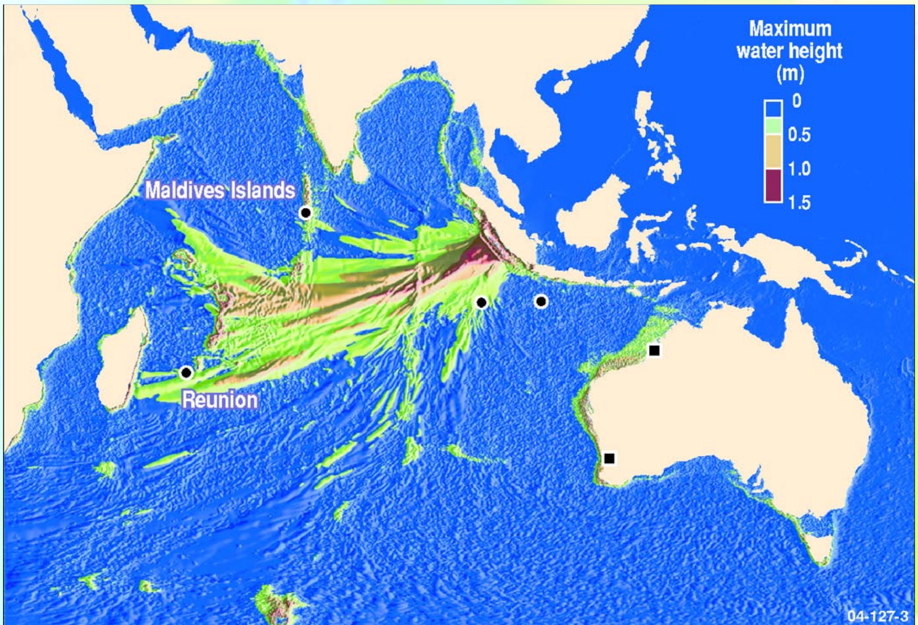
The 2004 earthquake did, on the other hand, rupture a substantial length of the subduction zone north of the rupture areas of the 1833 and 1861 shocks. While aftershocks appear to be active over a 1300-kilometre section of the zone stretching from the Andaman Islands in the north to the earthquake epicentre below the northern tip of Sumatra, the seismic waveform data appears to indicate that only a 450-kilometre length of the subduction zone off northern Sumatra ruptured (figure 4).

Has the stress on the plate boundary north of Sumatra been released or is it still accumulating, to be released in a future earthquake, perhaps generating another large tsunami? This is especially important for assessing the potential for further tsunami impact in Thailand, Sri Lanka and the Bay of Bengal.

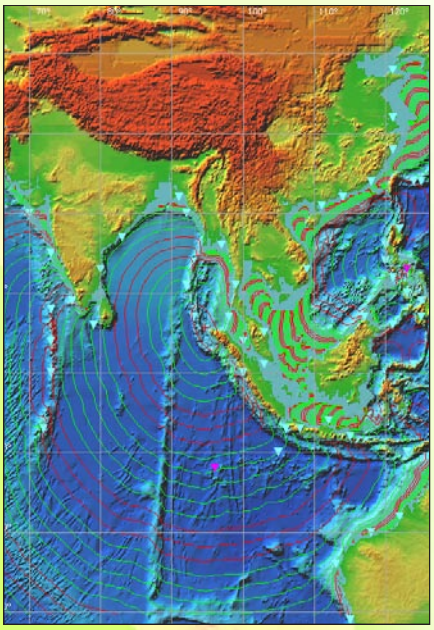
Seismic waves will be generated efficiently only if the entire fault slips as a unit at essentially the same time (that is, within few minutes). Rupture over a longer time interval will not be as efficient, but tsunami waves may still be generated as long as the rupture occurs within 10–20 minutes. The arrival time of the tsunami in the Bay of Bengal—in particular at the tide gauge at Vishakapatnam, where it arrived two hours and 36 minutes after the earthquake occurred—suggests that the northern tip of the rupture that generated the tsunami is in the northern Nicobar Islands (i.e. between the northern boundary of the rupture area inferred from seismic waves and that inferred from aftershocks).

Finally, there are reports of widespread uplift and subsidence in the Andaman Islands, consistent with fault movement.

All these observations are consistent with a rupture offshore from Sumatra with rapid, coherent slip that generated seismic waves. As the rupture propagated northwards, the fault slip may have been less sudden, and therefore progressively less efficient at generating first seismic and finally tsunami waves. The suggestion is that stress was relieved on the plate boundary along the entire extent of the aftershock zone, but whether the stress was totally or only partially relieved has yet to be determined.



▲ **Figure 2.** Calculated maximum amplitude of the tsunami caused by 1833 Sumatra earthquake. Most tsunami energy was directed into the open Indian Ocean, away from the Bay of Bengal. (Numerical modelling performed by David Burbidge of Geoscience Australia.)



▲ **Figure 3.** Travel-time contours for the Boxing Day tsunami. The source zone is roughly constrained by the tsunami arrival times at the Vishakapatnam and Cocos Islands tide gauges. (the latter is indicated by the magenta inverted triangle southwest of Indonesia). Contours are at 15-minute intervals, and alternate colour every hour. (Figure generated using software provided with the Integrated Tsunami Database for the Pacific, by Slava Gusiakov.)

Need for a tsunami warning system in the Indian Ocean

The tragic events of Boxing Day 2004 make starkly evident the importance of establishing a tsunami warning system for the Indian Ocean. More and better instrumentation, and a long-term program to educate people about the dangers of tsunamis, are clearly needed.

The short one to two hour lead time (figure 3) between an earthquake in the Nicobar–Andaman Islands region and the arrival of a tsunami in Thailand or Sri Lanka places stringent requirements on the operation of the technical component of such a warning system.

There is a far shorter lead time for tsunami impact on Sumatra itself. While the shaking due to the earthquake and the first, receding wave of the tsunami are likely to provide some warning, an extensive and long-term public education program is needed if the local population is to recognise these signs and be aware of evacuation routes.

As the September 2004 *AusGeo News* article surmised, the greatest tsunami threat in the Indian Ocean appears to be posed by great subduction zone earthquakes off Sumatra. It seems likely that the 2004 earthquake has relieved stress on the plate boundary from northern Sumatra to the Andaman Islands, so that great earthquakes are less likely to occur there in the near future. However, the possibility cannot be discounted that enough stress remains to cause an earthquake that might lead to another large tsunami in the Bay of Bengal.

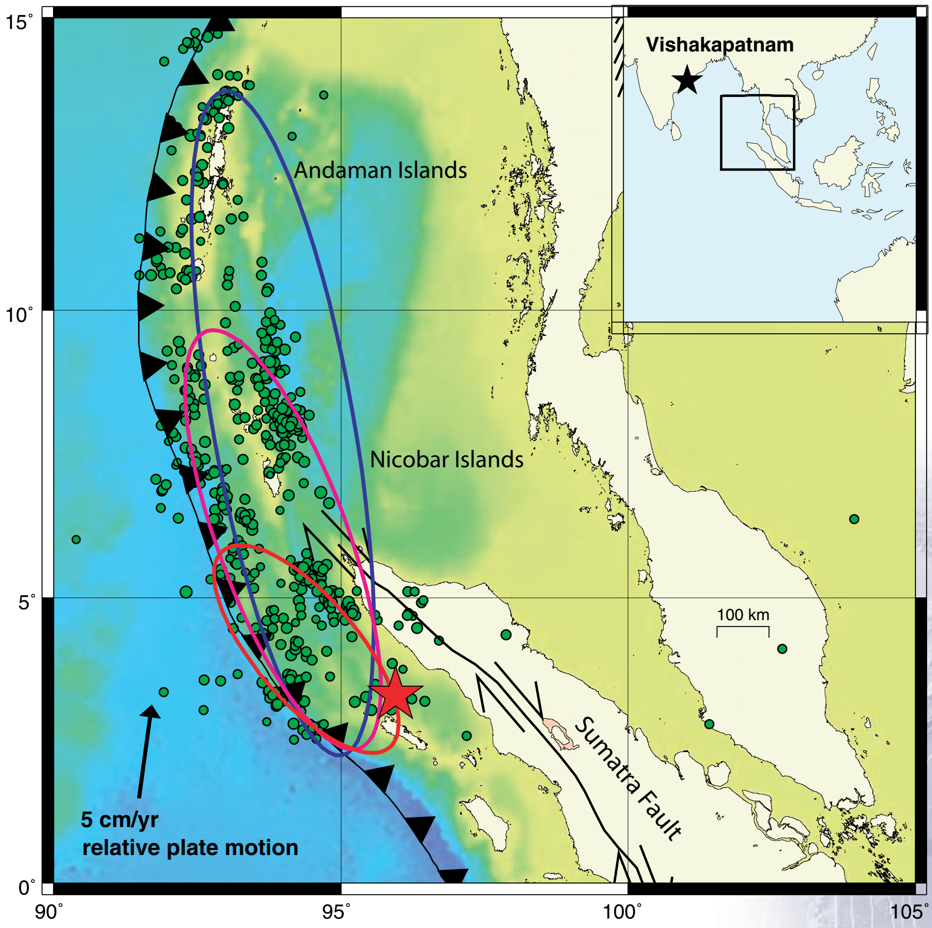
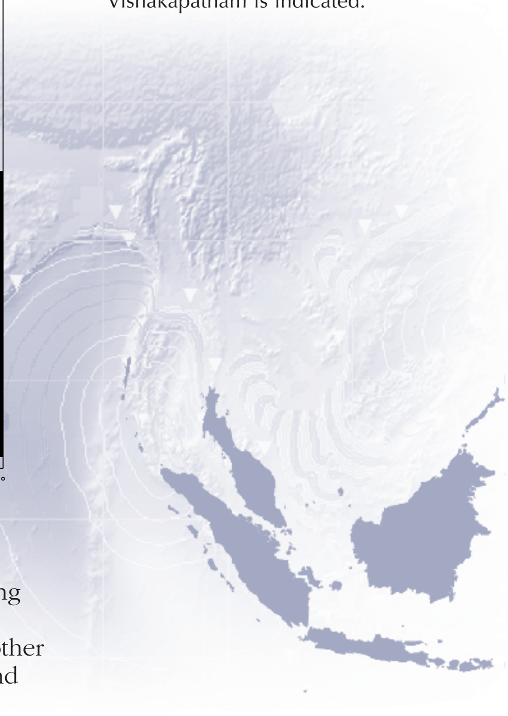


Figure 4. The 26 December 2004 Sumatra–Andaman Islands Earthquake. The red star indicates the epicentre of the main shock, and green circles those of aftershocks, estimated by the US Geological Survey. The red, magenta, and blue ellipses indicate respectively the area of seismic wave generation (from a model by Chen Ji of California Institute of Technology), tsunami generation (from travel time computations by Kenji Satake and Eric Geist), and crustal deformation (from information supplied by Roger Bilham of the Cooperative Institute for Research in Environmental Sciences). The position of the tide gauge at Vishakapatnam is indicated.



Further south, the plate boundary off central and southern Sumatra has not ruptured since the mid-1800s, so we know that these areas have accumulated considerable strain energy that could be released in a massive earthquake resulting in another ocean-wide tsunami.

Finally, the Makran subduction zone off the coast of Iran and Pakistan is another source zone for large tsunamis, as we know from the magnitude 8 earthquake and tsunami that occurred there in 1945.

The Indian Ocean countries, including Australia, cannot ignore the potential for future destructive earthquakes and tsunamis. The need for an Indian Ocean tsunami warning system is as urgent as ever.

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