Appendix E: On TSUNAMI HAZARD IN WESTERN AUSTRALIA

The recent occurrence of two massive earthquakes off the coast of Sumatra in December 2004 and March 2005 has greatly heightened the awareness of the tsunami hazard among the Australian public, especially in Western Australia. The following is a brief summary of tsunami hazard for the Perth region, which emphasizes the hazard due to subduction zone earthquakes off Sumatra.

Tsunami Source Zones and Tsunami Hazard for Perth

Tsunami are usually generated by earthquakes in subduction zones, where one of the rigid, tectonic plates which comprise the earth's surface dives beneath another. The subduction zone which lies offshore Indonesia to the northwest of Australia, where the Australian plate subducts beneath the Eurasian plate, is the one which presents the most direct tsunami hazard to Australia. In the recent past earthquakes off Java have caused large tsunami which have reached heights of 4 to 6 metres on Australia's northwest coast (due to the 1994 Java and 1977 Sumbawa earthquakes, respectively). Although these events have hitherto caused little damage and taken no lives, the rapid increase in population of northwest Australia suggests that these tsunami are potentially an important hazard that merit further consideration. This is especially true when the substantial investment in oil and gas infrastructure along the Northwest Shelf is considered. Since this infrastructure supports much of Western Australia's economy, a tsunami affecting production facilities on the Northwest Shelf may have a severe economic impact. These tsunami appear capable of having a significant impact on the northwest coast, but do not typically generate significant wave heights in the Perth area.

The occurrence of the 26 December, 2004 Sumatra-Andaman earthquake, however, established that the tsunami source zone which poses a greater hazard for the Perth area lies off the coast of Sumatra, to the west of Java. It is now widely recognized that this subduction zone can produce some of the largest earthquakes in the world and the associated tsunami are massive enough to affect the entire Indian Ocean Basin. These tsunami have the potential to affect the coastline near Perth.

Historical Earthquakes and Tsunami Off Sumatra

As pointed out in the Sept. 2004 edition of Geoscience Australia's AusGeo News (Cummins and Burbidge, 2004), great thrust earthquakes have occurred off Sumatra in historic times, prior to the events of 26 December 2004 and 28 March 2005. Newcomb and McCann (1987) document the occurrence of these earthquakes in 1833 (Mw=8.7-8.8) and 1861 (Mw= 8.3-8.5), which occurred before widespread European settlement in WA. Zachariasen et al (1999) have recently used the growth ring record of coral microatolls to estimate the uplift associated with the 1833 earthquake, and estimate that its moment magnitude may have been as high as 9.2, a truly massive earthquake which may affect the entire Indian Ocean basin, including the Perth area. However, until archival evidence of the 1833 tsunami was discovered in the Seychelles by a Canadian team during a post-tsunami survey of the Boxing Day Tsunami, no known historical evidence existed to suggest that the tsunami associated with the 1833 earthquake affected the Indian Ocean beyond Sumatra. In particular, no observations of tsunami were made in WA, but there was only sparse European settlement in 1833 (the first settlement on the Swan River was established in 1829).

Results of modelling of the open-ocean propagation of the tsunami associated with the 1833 Sumatra earthquake are illustrated in Figure 2 (Cummins and Burbidge, 2004). This modelling is accurate only for tsunami propagation in deep water, and does not account for actual run-up of the tsunami onto the shoreline, where its amplitude will usually increase several fold. What the numerical simulation shows is that, although the waves are large enough to affect the entire Indian Ocean basin, the pattern of radiated tsunami energy is highly directional (Fig. 2c), with most of the energy concentrated in the southwest direction, away from Sumatra and into the open Indian Ocean. This pattern is determined by the strike of the Sumatra subduction thrust fault. Unlike tsunami generated off Java, which direct most of their energy towards a limited section of Australia's northwest coast, tsunami from massive earthquakes off Sumatra spread considerable energy throughout the Indian Ocean. Such tsunami can affect a much wider stretch of Australia's coastline, extending from the northwest coast to the Perth area and even as far south as Tasmania. In the numerical simulation of the 1833 tsunami, open-ocean tsunami wave heights all along the WA coast are 15-25 cm, and the run-up from these may be as high as 1 metre or more. Thus, these tsunami events are a concern for the entire western coast of Australia, including the Perth area.

The Great 26 December 2004 Sumatra-Andaman Earthquake and Tsunami

The Great Sumatra-Andaman Islands earthquake of 26 December 2004, which initial was ascribed a magnitude of 9.0, was the largest earthquake since the 1964 Alaskan earthquake (M9.2) and is among the five largest earthquakes in the past century. Subsequent analysis has shown that a more accurate estimate of the magnitude is 9.3, making it the 2nd largest earthquake ever recorded (after the 1960 Chile earthquake, magnitude 9.6). The ‘Boxing Day Tsunami’ generated by this earthquake caused over 290,000 deaths and widespread destruction, mainly in Indonesia, but also in Sri Lanka, India, Thailand, and even on the east coast of Africa.

Like the 1833 earthquake, the effects of the tsunami in Sumatra were catastrophic. Tsunami run-up exceeding 30 m has been measured in Sumatra, where people had little time to escape, and whole villages have been razed. Unlike the 1833 event, fault rupture extended well north of Sumatra into the Nicobar and Andaman Islands, which resulted in waves of 5-10 m in height hitting Thailand and Sri Lanka approximately 1½-2 hours after the earthquake occurred. As is typical for a subduction zone earthquake, the seafloor was uplifted near the plate boundary and subsided 100-200 km landward of the plate boundary. In the case of the Boxing Day Tsunami, this resulted in a wave travelling to the east whose leading edge was receding, corresponding to withdrawal of the sea, while to the west the leading edge resulted in inundation. Thus, people who first encountered the wave in Thailand were given some warning by the sudden withdrawal of the sea, and in some cases lives were saved when this warning was recognized and acted upon. In many cases, however, this natural warning was not understood and the subsequent sudden inundation claimed many lives. In Sri Lanka the first effect of the wave was inundation, and people had little or no warning. This would also have been the case in most areas impacted by the 1833 tsunami.

The Great 28 March 2005 Sumatra Earthquake: No Indian Ocean-wide Tsunami

On 28 March 2005, another great subduction zone earthquake occurred off Sumatra. Although this earthquake was not as large as the 26 December 2004 event, at a magnitude of 8.7 it was still the 7th largest earthquake to have occurred worldwide since 1900, a massive earthquake by any standard. Like almost all other earthquakes of similar size, and in particular like the 26 December event, it had a shallow thrust faulting mechanism and would therefore normally be expected to generate a tsunami. In the hours following the occurrence of this event, most seismologists worldwide expected another large tsunami to be generated, and were surprised when only a minor tsunami was subsequently observed in the Indian Ocean. Although eventually reports were received of a 3-metre wave causing considerable damage on the island of Simeulue, the tsunami caused by the 28 March earthquake was in general not as large as had been expected. How could an earthquake which was in many respects similar to the 26 December earthquake behave so differently in its ability to generate a tsunami?

While the 28 March earthquake was considerably smaller than the 26 December one (magnitudes 8.7 and 9.3, respectively), the main reason the former failed to cause a large Indian Ocean-wide tsunami is likely related to the different way in which the fault slip for each earthquake was distributed over the fault surface. The epicentre is generally associated with the point at which the fault slip that causes an earthquake first occurs, but this initial slip subsequently spreads over some finite area of the fault surface. For great subduction zone earthquakes such as the Sumatra events of 26 December 2004 and 28 March 2005, this area can extend for up to 500-1000 km along the strike of the subduction zone, and 100-200 km down dip. The usual pattern is for rupture to initiate near the deepest part of the fault plane, and then spread along strike and to more shallow depths. It is fault slip at shallow depth that is most effective in displacing the large mass of water required to generate a tsunami, because it occurs closer to the sea floor and therefore displaces it more than slip at greater depth, resulting in greater displacement of water above the sea floor.

The effectiveness of fault slip at shallow depth in exciting a tsunami is important when considering different tsunami excitation associated with the 26 December 2004 and 28 March 2005 earthquakes. While the slip distribution, estimated from observed seismic waveforms, for the former earthquake features a localized concentration of slip near about 15 km depth, much of the slip is distributed over the fault plane, with a large zone of 5-8 m slip occurring at shallow depth near the trench axis. As discussed in (a) above, it is this latter slip which dominates the vertical seafloor displacement, and this occurs near the trench access where it displaces a deep column of water, resulting in a large tsunami. The slip for the 28 March 2005 earthquake, on the other hand, was highly concentrated near the epicentre at 30 km depth. In this case only two small patches of seafloor were vertically displaced 2 m in the deep water near the trough axis, while the largest vertical displacement of 3 m occurred about 100 km landward of the trough axis near the island of Nias, where the water is less than 1 km deep. Therefore, we can tentatively conclude that the 28 March 2005 earthquake was not effective in displacing the large mass of water required to generate a large, Indian Ocean-wide tsunami due to the unusual character of its fault slip, although evidently a sufficient mass of water was displaced to produce a 3 m local tsunami on the island of Simeulue.

Stress Triggering and the Potential for Further Earthquakes and Tsunami along the Sunda Arc

The occurrence of two great earthquakes rupturing adjacent segments of the Sumatra subduction zone within 3 months strongly suggests a causal connection between the two events. The most plausible candidate for this connection was elucidated in a paper by McClosky et al. (2005) a few weeks prior to the occurrence of the 28 March earthquake. Subduction zone earthquakes occur in response to stress which accumulates due to the frictional contact between the tectonic plates as one slides beneath the other (in this case the Indian/Australian plate sliding beneath Sumatra). When the fault slips during an earthquake, this accumulated stress on the plate boundary in the area of rupture will be wholly or partially relieved. The fault slip will also change the stress field in the region surrounding the rupture area, and this stress change almost always adds to the stress accumulating on the adjacent segments of the fault as a result of relative plate motion. If these adjacent segments have not experienced a major earthquake for a time long enough for stress to have increased to a level close to the frictional strength of the interplate contact, the additional stress due to a nearby large earthquake may be enough to initiate a new earthquake in the adjacent segment. This mechanism is called 'stress triggering', and has been inferred to be responsible for earthquake sequences in Turkey, Japan, and California.

The Great 28 March 2005 Sumatra earthquake ruptured the segment of the Sumatra subduction zone immediately to the southeast of the rupture area of the 26 December 2004 earthquake, with the epicentres of the two earthquakes separated by only 200 km. Since the rupture of the 26 December 2004 earthquake spread to the northwest of its epicentre, this event relieved stress on the plate boundary only off northern Sumatra and in the Nicobar and Andaman Islands region, but added to the stress accumulating on the plate boundary southeast of its epicentre, off central and southern Sumatra. As described above, we know that the most recent large earthquakes occurred on these segments of the subduction zone in 1861 and 1833 respectively, so that stress has been accumulating on this section of the plate boundary for over 100 years, and it seems likely that the level of stress is approaching the strength of the interplate contact in this area. It thus seems reasonable to conclude that the additional stress caused by the 26 December 2004 earthquake on the plate boundary to the southeast of its epicentre was sufficient to trigger the 28 March 2005 earthquake, which occurred in roughly the same area as the 1861 earthquake and had similar magnitude (8.7 for the 2005 vs. 8.3-8.5 for the 1861 earthquake).

Will this stress-triggering mechanism be effective in triggering further earthquakes along the Sumatra subduction zone, and if so what will be the impact on the West Australian coast and the Perth area? The next segment along the Sumatran subduction zone, immediately to the southeast of the 1861 and 28 March 2005 rupture areas, corresponds to the rupture area of the Great 1833 Sumatra Earthquake. Newcomb and McCann (1987) estimated a magnitude for this earthquake of 8.8 based on historical accounts, but more recent estimates based on evidence from coral microatolls on the Sumatran coast (Zachariasen et al., 2000) suggest a magnitude of 9.2. This latter estimate would mean that the size of the 1833 earthquake rivals that of the 26 December 2004 earthquake (magnitude 9.3, Stein et al., 2005). Although there are at present still no well-documented historical accounts of an Indian Ocean-wide tsunami following the occurrence of the 1833 earthquake, reports from a Canadian team conducting a post-event survey of the 26 December 2004 tsunami in the Seychelles indicate that there is archival evidence that a tsunami occurred there in 1833 of similar size to the 2004 event. Thus, a recurrence of the 1833 earthquake would seem likely to produce another Indian Ocean-wide tsunami. Since this segment of the subduction zone has been accumulating stress for over 180 years, it is likely close to failure and therefore seems a possible candidate for stress triggering.

Because the amount of stress involved in earthquake stress triggering is typically only a very small fraction of that required to cause an earthquake, and because the failure strength of the interplate contact and variations thereof are poorly understood, it is unfortunately impossible to predict just when and where the next earthquake on the Sumatra subduction zone will occur. A recurrence of the 1833 Great Sumatra Earthquake seems likely within the next 50 years based simply on the accumulation of stress in this part of the subduction zone, but a consideration of stress triggering due to the recent large earthquakes in the Sumatra subduction zone suggests there is heightened possibility of another large earthquake within the next few years. A tsunami caused by such an earthquake would direct more energy southward towards Australia than was the case for the 26 December 2004 event, but preliminary modelling suggests that, while the impact would be larger, it would not be dramatically so. Further work is required to quantify just how large the tsunami impact in the Perth area would from a recurrence of the 1833 event.

Other Tsunami Sources that May Affect the Perth Area

As described above, while large earthquakes off Java can generate large tsunami that may affect Australia's northwest coast, these events typically do not generate the type of Indian Ocean-wide tsunami that may be a threat to the Perth area. Other large earthquakes have occurred in the Indian Ocean in historic times, but with the exception of Sumatra there are no other sources of massive subduction zone earthquakes that could pose a serious threat to Perth. Sources of tsunami other than subduction zone earthquakes off Indonesia are both rare and difficult to quantify.

Another type of tsunamigenic event which might threaten the Perth area are volcanic eruptions in Indonesia. Active volcanoes are numerous and include two catastrophic eruptions in the 1800’s, Tambora in 1815 and Krakatoa in 1833. The Krakatoa eruption produced a devastating tsunami, whose runup on the coast of WA was in the range 0.5-2 m (Allport & Blong, 1995). This tsunami was even observed on the coast of New South Wales, where its height was typically about 10 cm. While generally regarded as rare, Indonesia is one of the most volcanically active regions in the world, and the hazard from such events cannot be discounted but is difficult to assess.

The remaining two types of tsunamigenic events are asteroid impacts and submarine landslides. The former are exceedingly rare, and the only well-studied but still controversial example of a large tsunami generated from an asteroid impact is that if the Chixulub impact which is thought to have resulted in the extinction of the dinosaurs 65 million years ago (Stinnesbeck et al., l993). Compared to asteroid impacts, the hazard from submarine landslides, including the possibility of massive flank collapses of volcanoes such as Heard Island, are more likely but, like volcanic eruptions, difficult to assess. Finally, the hazard from local tsunami generated by landslides off the West Australian coast, possibly associated with unstable accumulations of sediments, is unknown.

Conclusion

Thus, although the tsunami hazard for Australia is probably highest along the northwest coast, the tsunami hazard along the WA coast near Perth may be higher than recent historical experience suggests. Massive events such as the 1833 Sumatra earthquake and the 1883 eruption of Krakatoa may not be well represented in the historical record because of the historical differences in population trends on the west vs. east coast of Australia. The potential for such tsunami to cause harm is compounded by the lack of a formal tsunami warning system in place for the Indian Ocean. Currently, preparations are under way to establish such a system, which is proposed to be operated jointly by the Bureau of Meteorology, Geoscience Australia and Emergency Management Australia.

In any case, further research into tsunami hazard for the West Australian coast seems warranted. One important step forward would be a systematic study of tsunami deposits along the western coast. A first step towards this has been made by Nott and Bryant (2003), but a more systematic approach would require a reliable method for distinguishing between tsunami and storm deposits. Another important area of research is to search for and collate historical accounts of the tsunami associated with the 1833 earthquake; although there may be no Australian accounts, there are many Indonesian ones, and there should also be evidence in historical documents from elsewhere in the Indian Ocean. More accurate tsunami run-up calculations are also needed, to identify the particular hot spots along the coast where tsunami energy may be focused (this would also be useful to narrow down the search for tsunami deposits). Finally, some effort should be made to establish an operational warning capability by using tide gauges on Cocos and Christmas Islands, which can provide several hours advance warning for a tsunami generated off Sumatra.

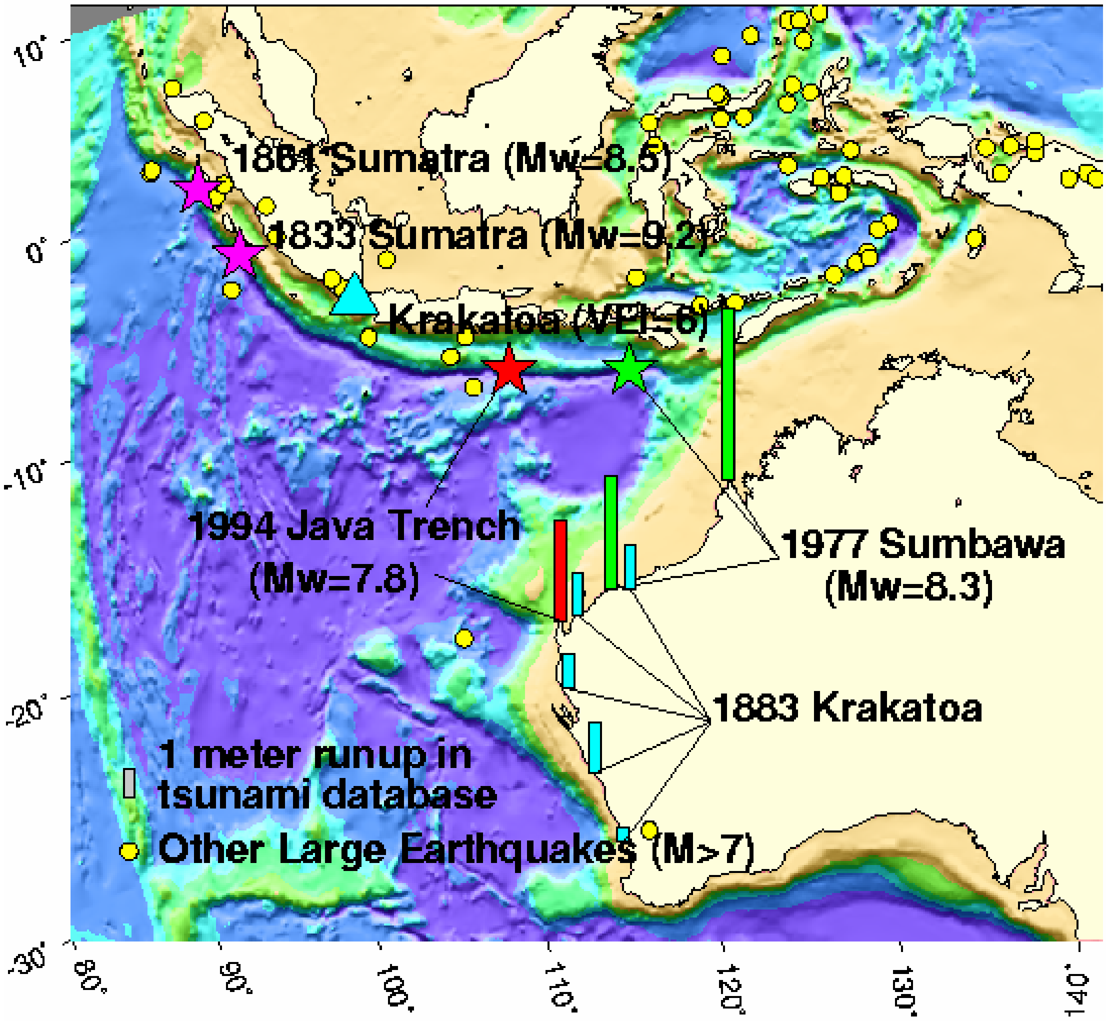

Figure 1. WA Tsunami run-up observations and the corresponding tsunamigenic events, with events color-coded to match the runup observations. Mw is a logarithmic measure of earthquake size, similar to the Richter scale but better suited to very large events, while VEI is the Volcanic Explosivity Index, with 6 for Krakatoa being one of the largest in recorded history. There are no recorded observations in Australia of the tsunami events of 1833 and 1861.

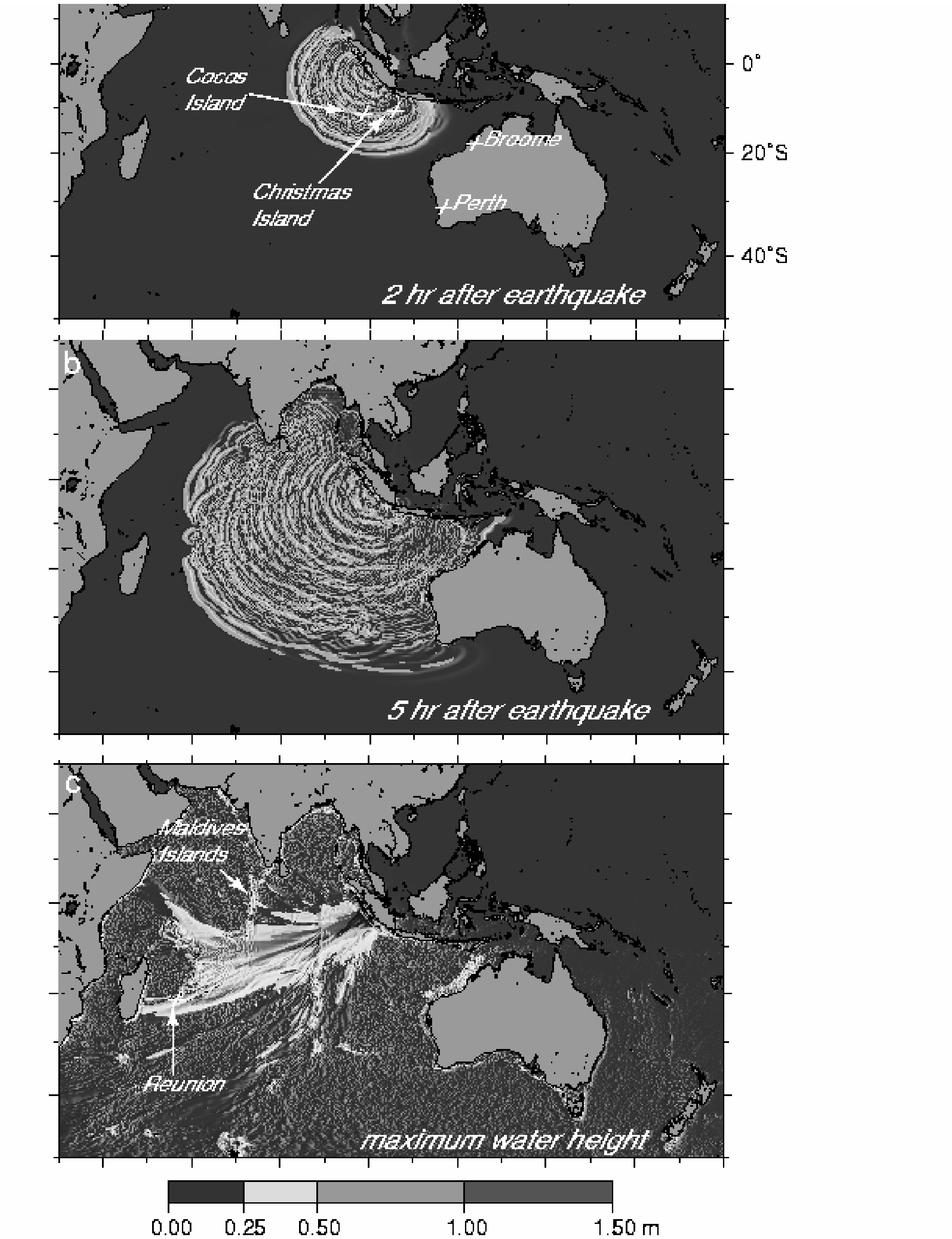

Figure 2. Numerical modelling results of the propagation of the tsunami associated with the 1833 Sumatra earthquake throughout the Indian Ocean. Note that the tsunami's early arrival at Cocos and Christmas Islands may provide a basis for warning more distant affected areas.

References

Abercrombie, R. E., Antolik, M., Flezer, K. and Ekstrom G., (2001). The 1994 Java tsunami earthquake: Slip over a subducting seamount, *J. Geophys. Res. , No. B4 , p. 6595.*

Allport, J.K. and Blong, R., 1995. The Australian Tsunami Database.

Cummins, P., and Burbidge, D., (2004). Small threat, but warning sounded for tsunami research, AusGeo News, 75, p.4-7, http://www.ga.gov.au/image_cache/GA5018.pdf

McCloskey J., Nalbant S. S. & Steacy S, (2005). Earthquake risk from co-seismic stress Nature, 434. 291.

Newcomb, K.R. and McCann, W. R., (1987). Seismic history and seismotectonics of the Sunda Arc, *1987. Jou. Geophys. Res.*, 92, 421-439.

Nott, J. and E. Bryant, Extreme Marine Inundations (Tsunamis?) of Coastal Western Australia, *Jou. Geology*, 11, 691-706.

Stein, S., and Okal, E. A., (2005). Speed and size of the Sumatra earthquake, *Nature*, 434, 581-582. Stinnesbeck W. et al. l993. Deposition of near K/T boundary clastic sediments in NE Mexico: Impact or turbidite deposits? Geology 21: 797-800.

Yoshida, Y., Satake, K. and Abe, K., (1992). The large normal-faulting earthquake of April 5, 1990 in uncoupled subduction zone, *Geophys. Res. Lett.*, 19, 297-300.

Zachariasen, M., Sieh, K., Taylor, F. W., Edwards, R. L. & Hantoro, W. S. (1999). Submergence and uplift associated with the giant 1833 Sumatran subduction earthquake: evidence from coral microatolls. *J. Geophys. Res.*, 104, 895-919.