# Chapter 3
# 2004 Sumatra–Andaman Earthquake and Tsunami

**Abstract** The December 26, 2004 Sumatra earthquake of Mw 9.1 caused wide spread damage in South and South-East Asian countries. The resultant tsunami claimed an estimated 230,000 human lives, the largest ever loss of human lives in a tsunami. Extensive damage and loss of human lives occurred in Indonesia, Thailand, Sri Lanka, India and many other countries. This chapter includes an introduction to the earthquake and an in-depth description of the tsunami.

## 3.1 Introduction

In the previous chapter we discussed the 1755 Lisbon tsunami and the birth of the science of earthquakes (seismology). A lot of new discoveries were made in the next 200 years, the most significant among them being the development of traveltime tables of waves generated by earthquakes and the structure of the Earth deduced from the observation of earthquake waves traveling through and around the Earth. A major development was the setting up of the World Wide Standard Seismograph Network during 1963–1964, where over 100 seismic stations equipped with three-component short-period Benioff seismographs and three-component long-period Press Ewing seismographs were set up, providing for the first time a global coverage of earthquake recordings using similar instruments. This also led to the development of the plate tectonics hypothesis during the late 1960s and early 1970s. Seismological networks further expanded tremendously during the last three decades of the twentieth century. Seismological arrays were installed in Europe, Japan and America. Crustal deformation studies using GPS measurements provided impetus to our knowledge about plate motion and crustal deformation due to earthquake occurrence processes. It appeared as if the seismologists were just getting ready to study great earthquakes that were to occur over the next decadal years after a general lull of mega earthquakes (Mw 9) since the great 1964 Alaska earthquake of Mw 9.4. This lull was broken by the mega Andaman–Sumatra earthquake on 26 December 2004, on Boxing Day, the day after Christmas. Various estimates of its magnitude range from 9.0 to 9.3, however, a magnitude estimate of 9.1 is considered as the most robust. The region of its occurrence was not considered to produce such a large earthquake and hence the tsunami caused by this earthquake devastated a large area around the source region. Thus

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this earthquake and the tsunami took people by surprise. In the known history of the coastal region around the Bay of Bengal and even around the Indian Ocean, the tsunami caused by this earthquake was the most devastating, killing about 230 thousand people. Nobody expected it to have that far a reach, killing people more than 5000 km away in Somalia. Maximum damage was in Sumatra, Indonesia, India's Andaman and Nicobar Islands and east coastal region and Sri Lanka.

## 3.2 Tectonics and Earthquake History in the Sunda Arc

The Sumatra–Andaman subduction zone marks the eastern boundary of the Indian plate where it subducts under the Sunda plate (Fig. 3.1). The 26 December 2004 giant Sumatra–Andaman earthquake occurred in this subduction

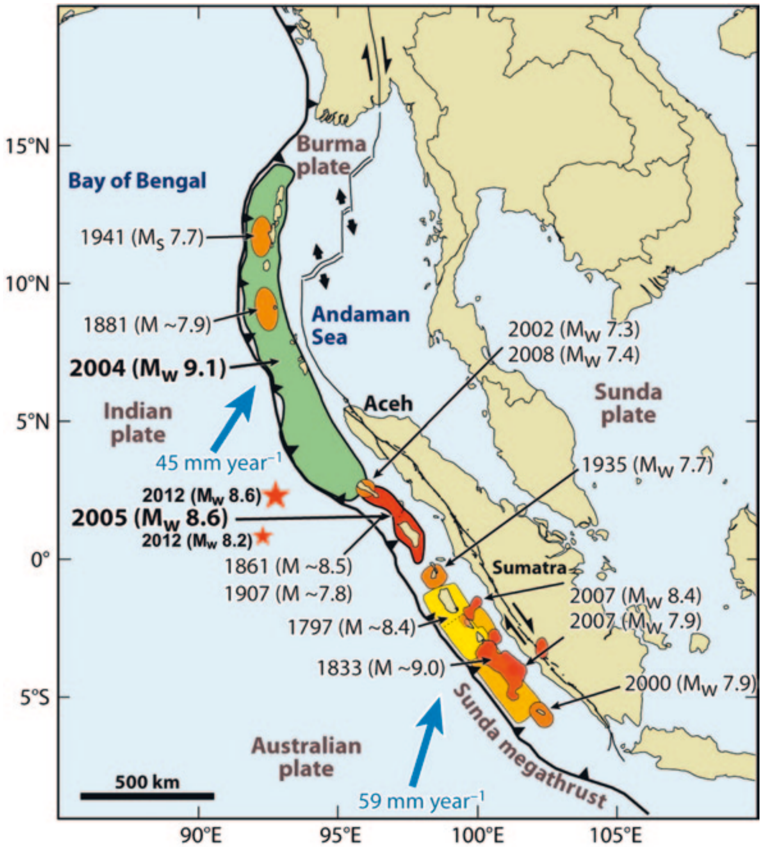


**Fig. 3.1** Earthquake ruptures in the Sumatra–Andaman subduction zone. The inferred magnitudes for the historical earthquakes are denoted by M. Ms is the estimated surface wave magnitude whereas Mw is the moment of magnitude estimated for recent earthquakes. The blue arrows indicate the rate and orientation of plate motions relative to the Sunda plate (modified from Shearer and Burgmann 2010)

zone. No great earthquake (M $\geq$ 8) has been reported from the Andaman–Nicobar and northern Sumatra regions, though major events in 1847 (M 7.5), 1868 (M 7.6), 1881 (M 7.9) and 1941 (M 7.7) occurred in the regions. Great earthquakes in 1797, 1861, 1833, 2005 and 2007 have been reported from the subduction zone near and southeast of Sumatra. Recently, on 11 April 2012, two great earthquakes of unprecedented magnitudes of 8.6 and 8.2 occurred about 100–200 km west of the subduction zone in the Sumatra region (Fig. 3.1). As these earthquakes did not occur in the subduction zone, they are considered as intraplate earthquakes and are probably the largest magnitude intraplate strike-slip earthquakes recorded globally.

## 3.3 The 2004 Sumatra–Andaman Earthquake

The 2004 Sumatra earthquake nucleated off the western coast of northern Sumatra and propagated north-northwest along the subduction zone right up to the North Andaman Island. Thus, the rupture length of the earthquake was about 1400 km (Fig. 3.1). This was the longest rupture ever reported for any earthquake (Fig. 3.2). Other than the extraordinary large rupture length, the earthquake had a few more distinctive features. Generally, the rupture speed during an earthquake is about 2.5 km/s, which is almost equal to the shear-wave velocity. The southern part of this earthquake rupture exhibited normal speed with a magnitude of slip reaching 20 m. However, the northern part of the rupture, under the Andaman Islands, exhibited a slower rupture speed (Fig. 3.3). Because of the slow rupture in the northern part, the seismological data do not constrain the slip on the rupture under the Andaman and Nicobar Islands reasonably well, as most of the slip in this part occurred at a time scale beyond the seismic band (Lay et al. 2005, Ammon et al. 2005) and therefore

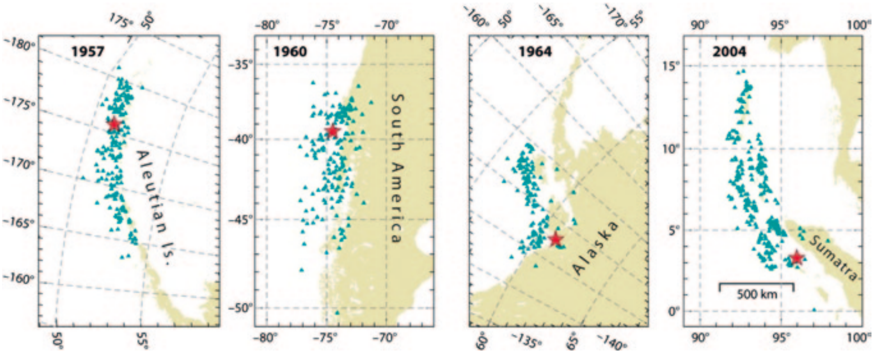


**Fig. 3.2** Rupture lengths of the 1957, 1960, 1964 and 2004 earthquakes (Mw $\geq$ 9), which are based on the epicentral distribution of the aftershocks that occurred within one month after the mainshock. Red stars show the mainshock epicenters. The scale is the same on all the maps. Note the longest rupture length is for the 2004 Sumatra–Andaman earthquake. Figure after Ishii et al. (2005)

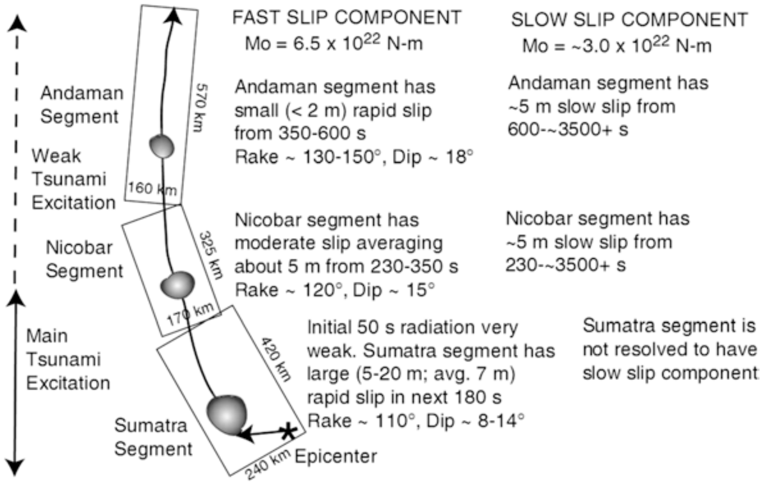


**Fig. 3.3** Three stages of rupture propagation of the 2004 Sumatra–Andaman earthquake (after Lay et al. 2005)

uncertainty in the estimate of the magnitude prevails. This earthquake was the best monitored earthquake until that time, as almost all the instrumentation were in place to record such an imposing event. The GPS data provided additional information about the rupture length and slip (Gahalaut et al. 2006). It was only after the occurrence of this earthquake that seismologists realized the problem in estimating earthquake magnitude and the energy released during exceptionally large earthquakes (Mw > 8.5). For this earthquake, the estimates based on energy released by surface waves of up to a 500 s period, led to an Mw estimation of 9.0. However, due to the high-quality seismic data available for this earthquake, seismologists could estimate the energy released by the waves of periods >500 s, which caused the revision of the magnitude by 0.1–0.3 units (Fig. 3.4).

## 3.4 Tsunami Generation

Because of its large magnitude and huge slip (>20 m) on the rupture, this earthquake caused a tsunami of unprecedented magnitude, which devastated the coastal regions around the Indian Ocean. The reach of the tsunami waves was so enormous that it caused damage at distances as far as 6000 km from the source (Fig. 3.5). The population in the coastal region around the Indian Ocean has not experienced tsunamis as frequently as in the Pacific region and hence the tsunami took people by surprise. This resulted in a huge loss of human lives and damage to coastal establishments. There is some debate on the source of the tsunami. The tsunami generation process depends on rupture speed. Typical rupture speed is the shear-wave speed in rocks. In case the rupture speed is slow, then the process of

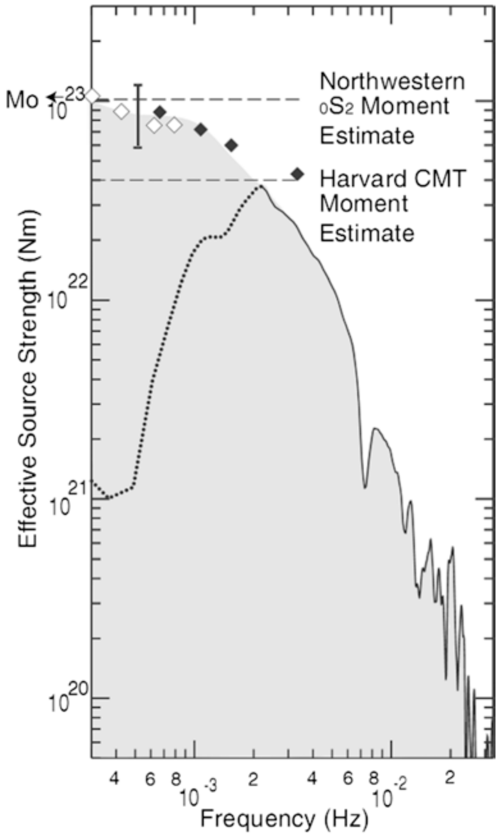


**Fig. 3.4** Estimation of the seismic moment of the 2004 Sumatra–Andaman earthquake. The conventional Harvard CMT moment estimate is $4 \times 10^{22}$ Nm, whereas the estimate obtained from lower frequency (longer period) surface waves is about $10^{23}$ Nm, which corresponds to a magnitude of 9.3 (after Stein and Okal 2005)

coseismic elevation changes of the sea-bed would be slow and hence the water will not be displaced vertically. In the case of the 2004 Sumatra–Andaman earthquake, it appears that the northern part of the rupture did not contribute to the tsunami generation. Lay et al. (2005) analyzed the seismological data and rupture process of the earthquake. They suggested that about one-third of the total seismic moment was released due to a slow slip. The Sumatra rupture segment (about 420 km) did not exhibit a slow slip but in the Nicobar region (rupture segment of about 325 km), about one half of the total slip occurred through a slow slip. In the Andaman segment (about a 570 km long rupture segment) the slip was predominantly slow. Shearer and Burgmann (2010) provided a nice comprehension of possible tsunami models of the 2004 Sumatra–Andaman earthquake. All these models point towards an at least 1400 km long rupture that extended from the point where the earthquake initiated to the North Andaman Island. However, there is some disagreement in the estimation of the tsunami source, primarily because of lack of constraints on the extent of the slow slip in the northern part. This could easily be settled if there were near-source tide gauge instruments in the northern part of the rupture. Although there was a tide gauge at Port Blair, unfortunately, there was a timing problem

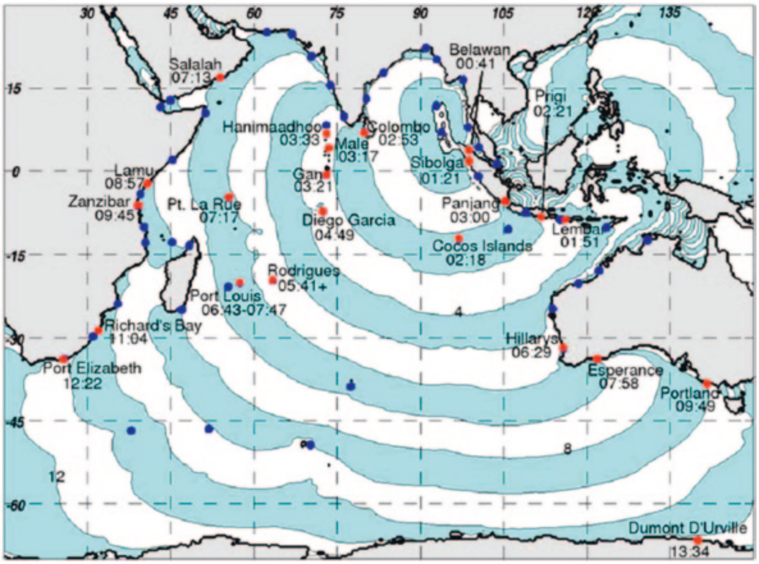


**Fig. 3.5** Tsunami traveltimes to the Indian Ocean tide gauge stations, in hours:minutes. The contours show predicted traveltimes (hours). The red and blue dots show the locations of the tide gauge stations (Merrifield et al. 2005)

at the tide gauge at Port Blair due to which the slow slip component in the region could not be resolved properly. Singh et al. (2006) attempted to rectify the timing errors in the tide gauge record at Port Blair and their preferred model consists in a mixed mode of slip in which about one half of the total slip occurred seismically in less than 5 min and the rest in the next 30 min. The existing tsunami modeling studies are not in complete agreement regarding the length of the best-fitting source region and the rupture velocity (Shearer and Burgmann 2010).

## 3.5 Description of the Tsunami

The 2004 tsunami affected a large region around the Indian subcontinent. The reach of the tsunami (beyond 5000 km) and its wave height at such large distances were unprecedented. Even more so because this region was not considered to be prone to a tsunamigenic earthquake, though a few cases of a tsunami, e.g., due to the 1945 Makran earthquake, 1833 Krakatoa volcanic eruption, etc., had been reported. Almost all the damage and loss of life occurred due to the tsunami caused by the earthquake, rather than shaking, despite the large magnitude of the earthquake. Even in the source zone in the Sumatra–Andaman Island region, the damage was mostly due to the tsunami. It was one of the deadliest natural disasters in recorded history. Indonesia was the hardest-hit country, followed by

Sri Lanka, India and Thailand. Because of the 1,400 km long rupture with an almost north–south orientation, the greatest strength of the tsunami waves was in an east–west direction. Because of the distances involved, the tsunami took anywhere from fifteen minutes to seven hours (for Somalia) to reach the various coastlines. The northern regions of the Indonesian island of Sumatra and the Andaman and Nicobar Islands of India were hit very quickly, while Sri Lanka and the east coast of India were hit roughly 90 min to two hours later (Fig. 3.5). Thailand was also struck about two hours later despite being closer to the epicenter, because the tsunami traveled slowly in the shallow Andaman Sea off its western coast. The tsunami was noticed as far away as Struisbaai in South Africa, some 8,500 km away, where a 1.5 m high wave surged on shore about 16 h after the earthquake. It took a relatively long time to reach this spot at the southernmost point of Africa, probably because of the broad continental shelf off South Africa and because the tsunami would have followed the South African coast from east to west. The tsunami also reached Antarctica, where tidal gauges recorded oscillations of up to a meter, with disturbances lasting a couple of days. Some of the tsunami's energy escaped into the Pacific Ocean, where it produced small but measurable tsunamis along the western coasts of North and South America, typically around 20–40 cm.

It is estimated that about 230 thousand people in the coastal region died due to the tsunami (Table 3.1). This makes it the worst tsunami in history.

### 3.5.1 *Tsunami in the Open Ocean*

The US-French satellites, TOPEX/Poseidon and Jason-1, passed over the Bay of Bengal two hours after the earthquake and captured the height of the propagating tsunami. It was 60 cm high. By 3 h 15 min after the earthquake, the height

**Table 3.1** Countrywide death tolls due to the 2004 tsunami

| Country where deaths occurred | Confirmed | Estimated |
|---|---|---|
| Indonesia | 126,915 | 167,799 |
| Sri Lanka | 30,196 | 35,322 |
| India | 10,610 | 18,045 |
| Thailand | 4,812 | 8,212 |
| Somalia | 298 | 298 |
| Myanmar | 61 | 400–600 |
| Maldives | 82 | 108 |
| Malaysia | 68 | 75 |
| Tanzania | 10 | 13 |
| Seychelles | 3 | 3 |
| Bangladesh | 2 | 2 |
| South Africa | 2 | 2 |
| Yemen | 2 | 2 |
| Kenya | 1 | 1 |

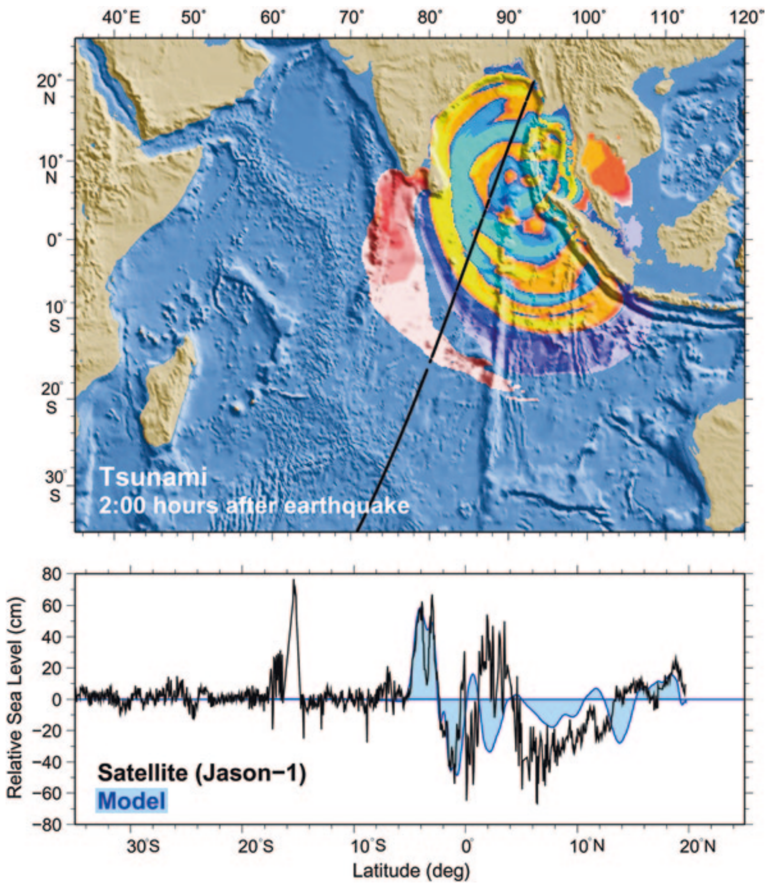


**Fig. 3.6** The tsunami wave height as measured by satellites two hours after the earthquake. Lower panel shows the tsunami wave height along the satellite track, shown by black line in the upper panel (after NOAA)

dropped to around 40 cm. By 8 h 50 min after the earthquake, the wave spread over most of the Indian Ocean and was quite small in most areas, with height as small as 5–10 cm (Fig. 3.6).

This tsunami was observed at several tide gauge stations located in the Indian Ocean (Figs. 3.7 and 3.8).

### 3.5.2 *Tsunami in the Indian Coastal Region and on the Islands*

According to official estimates in India, 10,136 people were killed and hundreds of thousands were rendered homeless. The most affected regions in India were the Andaman and Nicobar Islands and the eastern coast.

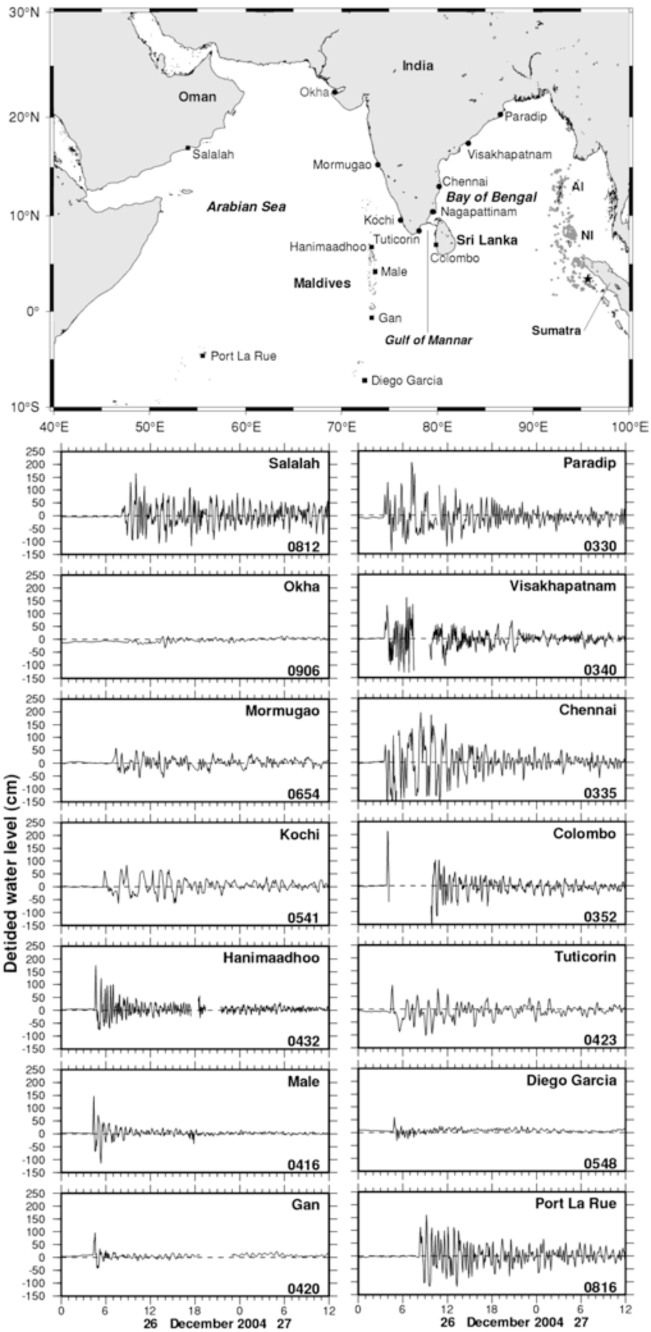


**Fig. 3.7** Detided records at various tide gauge stations showing the tsunami (Nagrajan et al. 2006). The epicenter of the 26 December earthquake (*asterisk*) and the locations of the aftershocks (*grey circles*) till 10 February 2005 are also shown on the top panel. *AI* Andaman Islands; *NI* Nicobar Islands. The time at the right bottom in each box is in UTC

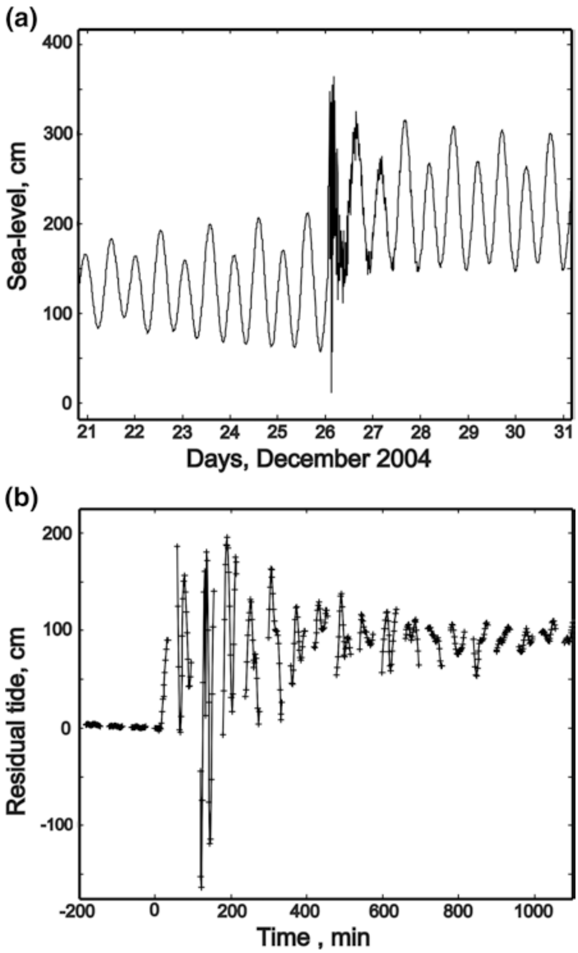


**Fig. 3.8** Corrected tide gauge record at Port Blair (Andaman Island) **a** before and **b** after removal of the tides (Singh et al. 2006)

Amongst the Andaman and Nicobar Islands, the Nicobar group of islands was most affected (Figs. 3.10, 3.11, 3.12, 3.13, 3.14, 3.15, 3.16). The height of the tsunami in this region was about 15 m (Fig. 3.9). The official death toll is 1,310 and about 5,600 are still missing. The unofficial death toll (including those missing and presumed dead) is estimated to be about 7,000. The Great Nicobar and Car Nicobar Islands were the worst hit among all the islands as this region is located just above the earthquake rupture where the coseismic slip was at its maximum. One-fifth of the population of the Nicobar Islands was said to be dead, injured or missing. Chowra Island lost two-thirds of its population of 1,500. Entire islands were washed away and the island of Trinket split into two islands (NRSC). Among the casualties in Car Nicobar, 111 Indian Air Force personnel and their family members were washed away when the wave hit the air base. Unfortunately,

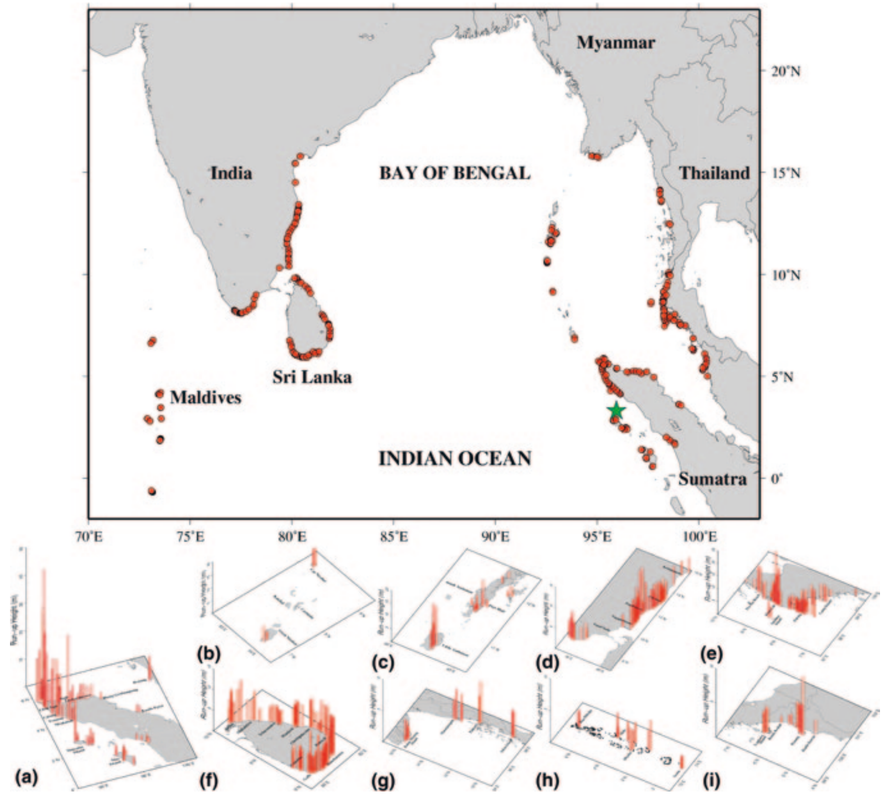


**Fig. 3.9** Locations and run-up wave heights of the measured points by the KSCOE survey team and the International Tsunami Survey Teams (a-i). Star indicates the 2004 Sumatra–Andaman earthquake. **a** Indonesia; **b** Nicobar Islands, India; **c** Andaman, India; **d** east coast of India; **e** Thailand; **f** Sri Lanka; **g** Myanmar; *h* Maldives; *i* Malaysia (after Choi et al. 2006)

the topography of all these islands is quite flat and hence it did not provide any resistance to the tsunami. In many cases, tsunami waves swept through entire islands.

The eastern coast of the Indian mainland (particularly in the Tamilnadu and Andhra Pradesh states) was severely affected (Fig. 3.17). It took about 2 h for tsunami waves to travel to the Indian east coast. In Tamil Nadu, the Nagapattinam-Cuddalore shelf was the worst affected by the tsunami where more than 7800 people died. Tsunami heights in this part were of the order of 2–5 m, with an inundation of 150–800 m into the interior coast, thus causing a huge loss of human life and property. The main reason for the great loss of lives and property is due to its relative proximity to the origin of the event, apart from the concave nature of the shelf with a gentle gradient. In Andhra Pradesh, more than 100 people died. The tsunami encroached up to 500 m to 2 km due to its flat region. The tide gauge at Vishakhapatnam showed a tsunami height of 1.4 m, though eyewitnesses reported a height of up to 5 m at some other locations.

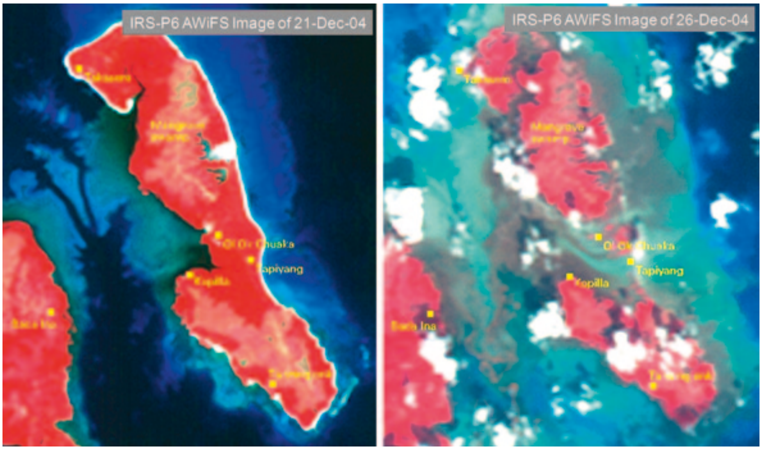


**Fig. 3.10** IRS P6 AWiFS images of Trinkat Island (Nicobar) before (21 December 2004) and after the tsunami (26 December 2004) (*Image courtesy* National Remote Sensing Centre)


**Fig. 3.11** The air base of the Indian Army at Car Nicobar Island was worst hit by the tsunami

### *3.5.3 Tsunami in Indonesia and Thailand*

The northern and western coast of Sumatra, Indonesia and smaller islands west of Sumatra, were seriously affected by the earthquake and the tsunami. There were more than 31,000 casualties and most of the damage took place within


**Fig. 3.12** The Ashton creek bridge in North Andaman was offset by more than a foot by extensive ground shaking


**Fig. 3.13** A log that was transported by the tsunami waves got trapped in the trees at Great Nicobar

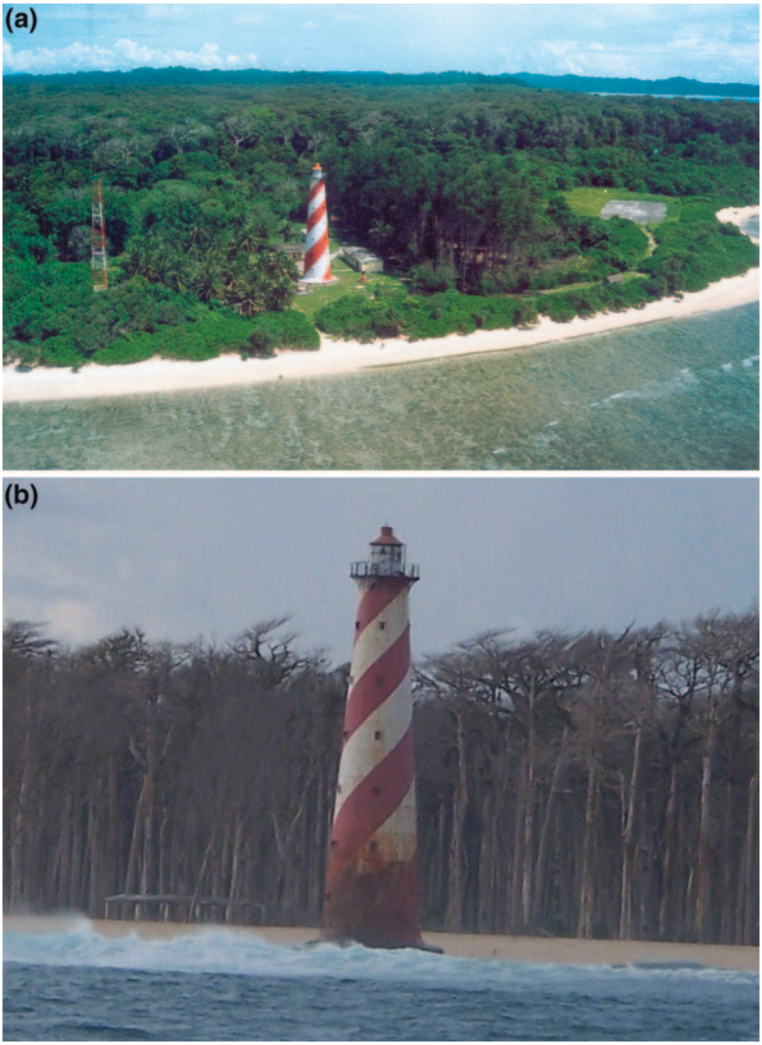


**Fig. 3.14** A photo combo of the light house at Indira point at Great Nicobar Island before and after the earthquake. Coseismic subsidence of more than 1 m and extreme inundation due to the tsunami can be seen here

the province of Aceh (Figs. 3.18, 3.19, 3.20). According to the country's National Disaster Relief Coordination Agency, 126,915 people died and 37,063 are missing. This region was the closest to the earthquake epicenter and rupture and thus people had very little lead time. Casualties in the Nias and Simuelue Islands were not very high despite strong ground shaking and a high tsunami of more than 10 m. This is mainly because the natives were aware of the hazards of a tsunami.


**Fig. 3.15** Mud-volcanoes erupted in the Middle Andaman Islands and one of them caught fire


**Fig. 3.16** There were large cracks in the mud-volcano region and in one case, the trunk of a tree got split

**Fig. 3.17** Devastation after the tsunami at Chennai, on the east coast of India

The Thai government reported 4,812 confirmed deaths and 4,499 missing after the country was hit by the tsunami. The popular tourist resort of Phuket was badly hit with 3,950 confirmed deaths. Quite a lot of these casualties are due to the fact that it is a very popular tourist destination and the tsunami struck this region at about 10–11 am on a Sunday morning when most of the people were on the beaches.

### *3.5.4 Tsunami in Sri Lanka*

The entire eastern coast of Sri Lanka was severely affected by the tsunami. Sri Lankan authorities reported 30,196 confirmed deaths. About 1,200 people died at Batticaloa in the east. At Trmcomalee in the northeast, where the tsunami encroached more than 2 km inland, 800 people were reported dead. In the neighboring Amparai district alone, more than 5,000 people died. Tragically, a holiday train, the “Queen of the Sea”, was struck by the tsunami near the village of Telwatta as it traveled between Colombo and Galle carrying at least 1,700 passengers, killing most of them (Fig. 3.21). The tsunami height at several places was about 10 m.

### *3.5.5 Tsunami in Somalia*

The reach of the 2004 tsunami was really extensive. Somalia, which is 5000 km beyond the earthquake epicenter, was badly hit by the tsunami. The confirmed


**Fig. 3.18** Satellite image of Banda Aceh, before and after the earthquake

death toll is 298. Most of the damage was in the coastal region of Puntland, particularly the area between Hafun in the Bari region and Garacad in the Mudug region. The narrow and low-lying peninsula of Hafun, 1,150 km northeast of Mogadishu, was particularly devastated.

## 3.6 Lessons Learnt

1. One of the most important aspects of the 2004 Sumatra–Andaman earthquake is the realization of the seismogenic and tsunamigenic potential of low-strain accumulating regions. Simple relations between rate, slab age, or structure of a subduction zone and the maximum size of events can be misleading.


**Fig. 3.19** A barge lying 3 km inside Sumatra after the tsunami

**Fig. 3.20** Total destruction at Banda Aceh


**Fig. 3.21** The holiday train "Queen of the sea" was struck by the tsunami killing almost all the passengers

Thus, all areas of active subduction should be considered at risk of being hit by great earthquakes (Burgmann and Shearer 2010).

2. The occurrence of this and other recent great earthquakes requires improved methods to quickly estimate the earthquake size and the tsunami potential worldwide to provide better advance warning of the hazards from future megathrust earthquakes.
3. The tsunami caused by the 2004 earthquake warns us of a possible longer reach, high run-up height and heavy destruction by tsunamis.

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