1. Earthquakes, Plate Tectonics and the Indian Ocean Tsunami

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Summary

- The Indian Ocean tsunami originated from a 9.15 - 9.3 magnitude earthquake in Sumatra that released pressure which had built up over hundreds of years along the fault between 2 tectonic plates;
- In the 10 minutes after the fault break started off northwest Sumatra, the rupture spread north along a 1,300 km length of the fault line to the Andaman and Nicobar Islands;
- The tsunami generated many waves because the earthquake caused a sudden vertical displacement of a vast section of the ocean floor, displacing a huge mass of seawater;
- Tsunamis passing through the deep ocean are difficult to detect, can exceed speeds of 600 km/hour, and arrive at coasts thousands of kilometres from the earthquake as high energy, long wavelength waves;
- The waves slow as they encounter the continental shelf, bays, islands or estuaries and increase in height; thereby causing massive damage when they reach the shoreline;
- The Indian Ocean tsunami was not the first of this type in the region and more will occur in the future; and
- Natural hazard risk analyses should be undertaken and an early warning system implemented to better prepare vulnerable coastal communities for environmental threats in the future.

Introduction

The 26 December 2004 earthquake off northwest Sumatra, Indonesia was the largest seismic event on Earth in more than 40 years. The earthquake originated 30 km below the sea floor off the coast of Sumatra and triggered the rupture of a 1,300 km segment of the fault line between the Indian and Eurasian tectonic plates that extended through the Andaman and Nicobar Islands. The energy released was equivalent to a 100-gigaton bomb, over 1,500 times that of the largest nuclear bomb ever detonated and 100 times the energy of the 1906 San Francisco earthquake. This earthquake on the sea floor displaced more than 30 cubic kilometres of seawater and formed the most devastating tsunami in recorded history; more than 230,000 people were killed, and more than 1 million have been displaced in the affected countries in Southeast and South Asia and Eastern Africa. The tsunami has caused major economic losses in many of the Indian Ocean countries, devastating primary and secondary industries and disrupting the tourism economy. The impacts of this event were truly global; the tsunami was observed in all oceans of the world and the whole earth continued to 'ring' from the shock of the earthquake for months afterward. This chapter provides a brief summary of the origin of the earthquake and subsequent tsunami.

The technical details of the initiation of the Great Sumatra-Andaman Earthquake. The magnitude includes all activity over the next 10 minutes when the earthquake progressed in a northwest direction for 1,300 km to the northern Andaman Islands (from www.earthquake.usgs.gov).

Magnitude	9.15 - 9.3
Date	26 December 2004
Time	00:58:53 (UTC) Coordinated Universal Time (7:58:53 am local time at epicentre)
Location	3.307° North , 95.947° East
Depth	30 km (18.75 miles)
Region	Off of the western coast of northern Sumatra, Indonesia
Distances to major population centres	255 km (155 miles) SW of Banda Aceh, Sumatra, Indonesia 310 km (195 miles) W of Medan, Sumatra, Indonesia 1,260 km (780 miles) SW of Bangkok, Thailand 1,605 km (990 miles) NW of Jakarta, Java, Indonesia

What Is a Tsunami?

Tsunami is a Japanese word – tsu, 津, meaning 'harbour' and nami, 波 or 浪, meaning 'wave' – that is now used worldwide to denote a large sea wave generated by a sudden vertical displacement of the sea surface. This displacement of water may be caused by undersea earthquakes, landslides, major volcanic eruptions, or large meteorite impacts. Once a large volume of the ocean is displaced vertically, the disturbance spreads outward in a tsunami as the ocean attempts to re-establish its gravitational equilibrium. When the horizontal scale of the disturbance is much greater than the water depth, the whole column of water from surface to seafloor moves coherently in a horizontal direction. Typically a large tsunami will pass over the deep ocean as a small wave, often less than one metre high, but travelling at speeds of 600 km/hour or more. Thus it may pass under ships without notice, which is why Japanese fishermen coined the name to describe a wave that had destroyed their homes on land, whilst they had not noticed anything at sea. As the tsunami approaches shallow water, it slows down and increases dramatically in amplitude, sometimes reaching tens of metres in height.

The physics of tsunamis is that of shallow-water waves, because they have long periods (the time between 2 successive waves) and wavelengths (the distance between 2 consecutive waves). However, they are very different from the wind-generated waves which are the normal ocean waves. Wind-generated waves only cause water movement near the sea surface with typical periods of 10 - 20 seconds and wavelengths of 100 - 200 m. In contrast, tsunamis involve water movement all the way to the seafloor (e.g. 3 - 4 kilometres depth in the deep ocean), with periods of 10 - 60 minutes and wavelengths of 100 km or more i.e. they involve the movement of much larger masses of water. The destructive force occurs when the energy contained in a wave thousands of metres deep is concentrated in the shallows of the continental shelf, and particularly in shallow estuaries.

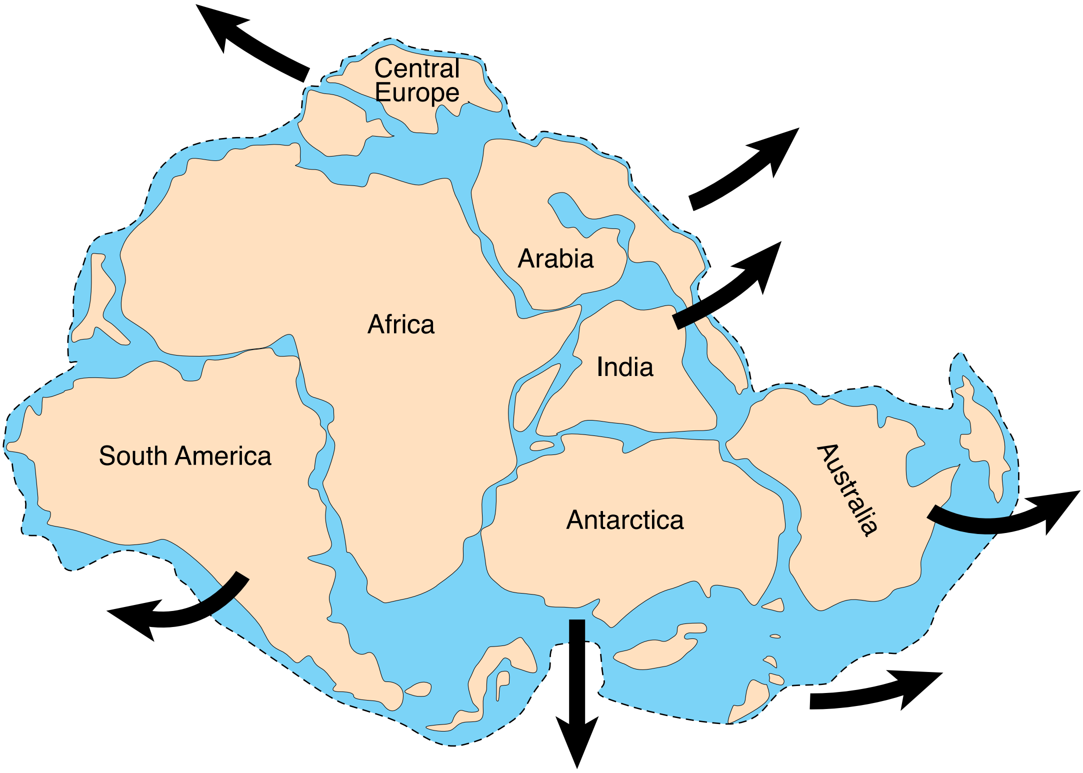
Although a tsunami large enough to affect an entire ocean basin is a rare event that may occur once in a generation, large tsunamis almost always cause major damage because they can efficiently transport energy over great distances at high speed. Tsunamis are among the world's most terrifying natural hazards as they may originate from a distant, unseen and unfelt source, and thus can arrive without apparent warning. Many past tsunamis have been responsible for major losses of life and property. Thus, they may be deeply embedded in folklore and are thought to have caused major disruption to some societies, such as the demise of the Minoan civilisation, which may be attributed to the eruption of the Santorini volcano and the ensuing tsunami around 1500 BC. Although the Pacific Ocean has the highest frequency of tsunamis of all the world's oceans, tsunamis have also caused considerable destruction in the Mediterranean Sea and the Indian and Atlantic Oceans.

Tsunamis and Subduction Zone Earthquakes

The earthquake and tsunami of 26 December took place along a major tectonic feature on the Earth's surface termed a 'subduction zone'. These zones are created because the Earth's surface is in constant motion as the outer rock 'carapace', termed the lithosphere, is created and destroyed. This outer carapace is composed of a number of rigid plates, which form along mid-ocean ridges and are destroyed at subduction zones, where the plates converge with one sliding beneath the other. This process of convergence and destruction is termed 'subduction', and plate boundaries along which the process is occurring are called 'subduction zones'.

The subduction zone where the 26 December 2004 earthquake occurred was formed due to the northward movement of the Indian and Australian plates that have been in motion since the break up of the Gondwana 'super-continent' between about 50 and 150 million years ago. As these plates moved northward at a rate of 6 to 7 centimetres per year (similar to fingernail growth), the oceanic lithosphere at their leading edges was driven into the Earth's interior beneath the Eurasian plate along the Sunda Arc. This arc extends from Timor in the east, through southern Indonesia to the Andaman Islands in the northwest. While precise measurements of ground surface movement have established that the Indian and Australian plates are separate entities, the boundary between the 2 is so diffuse that it is not clear which plate is subducting ('sliding') beneath the northern part of Sumatra. However, it is known that the Indian plate is subducting beneath the Nicobar and Andaman Islands. The tectonic structure of the overriding plate is also complicated. Not only is the Sunda block (sub-plate), on which most of Sumatra lies, separated from the Eurasian plate to the north, but also the southwest edge of the Sunda block, is separated from the Indian and Australia plates by a microplate, that is often referred to as the Burma Microplate or the Andaman Sliver. Despite this complexity, the earthquake effectively originated from the combined pressure of the 2 plates (sometimes erroneously referred to as the 'Indo-Australian plate') subducting beneath Sumatra.

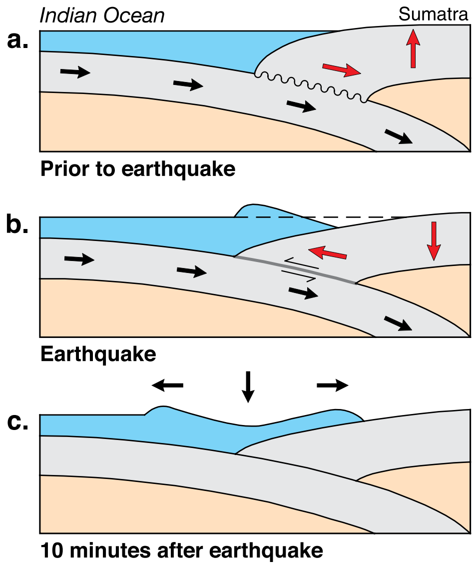
Subduction zones are typically characterized by intense geological activity. The subduction process pulls both the subducting plate and the overriding plate downward along the axis of the subduction zone, creating a deep trench. These marine trenches are the deepest parts of the



When the 'supercontinent' Gondwana broke apart about 150 million years ago, 2 large tectonic plates, India and Australia, broke away and started sliding in a northerly direction at a very slow, but a very steady and powerful pace. They collided with the supercontinent of Eurasia, thereby setting up the conditions for the 26 December 2004 earthquake.

ocean, ranging from 4 km deep at a shallow trench to 10 km deep at the Mariana Trench, east of the Philippines. The volatile elements dragged into the Earth's hot interior at subduction zones induce melting of the sub-crustal material above the subducting plate, often leading to the development of a chain of active volcanoes in the overriding plate parallel to the axis of the subduction zone. Krakatoa is one such volcano among more than 100 other active volcanoes along the Indonesian archipelago (see the map in Chapter 2, p 36).

These volcanoes are also important sources of tsunamis. Prior to 2004, the only historically documented Indian Ocean-wide tsunami was produced by the 1883 eruption of Krakatoa. This tsunami killed 36,000 people in Indonesia and caused considerable damage throughout the Indian Ocean, including the Seychelles: "At 4:00 pm on the 27th of August, a tidal wave suddenly came rushing at about 4 miles an hour, and reaching a height of about 2 ½ feet above the usual high springs. It receded in about a quarter of an hour, leaving boats high and dry. It then returned, and the same thing continued all the next day, …" (H. W. Estridge, Collector of Customs at Mahé, Seychelles, 1883). Other large tsunamis in the Arabian Sea, Bay of Bengal, and the Indian Ocean between Java and Australia (see Table p 25), as well as the 2004 tsunami, have been caused by earthquakes in subduction zones.



These 3 diagrams illustrate the sequence of a subduction earthquake. In (a) the tectonic plate to the left is attempting to subduct under the plate to the right. However, due to frictional forces, it has temporarily fused with the top plate, causing both plates to be deformed, especially the top plate which is being bent in the direction of the 2 red arrows; when the friction bonds (wavy line) break during an earthquake (b), the plate to the right 'springs' back into its original position (red arrows are reversed), thereby displacing large volumes of water. This displaced water then spreads outwards as a tsunami (c).

Subduction zones are the source of 90% of the world's earthquakes. Earthquakes occur when there is an almost instantaneous movement, either along the interface of the 2 converging plates or within the subducting plate as it bends and dives into the Earth's interior. At depths shallower than 30 km, the rocks are brittle and when stresses build up, either within the plates or at the interface between them, there may be an instantaneous fracture that results in an earthquake. Inter-plate earthquakes are the result of movement at these shallower depths, where the contact between the plates exhibits 'stick-slip' friction, meaning that the friction pulls the upper plate downward, causing massive stresses to accumulate around the point of contact. An earthquake occurs when the stress exceeds the frictional forces, the temporary point of fusion breaks, and the upper plate 'pops' upward. This shallow interaction along the plate contact zone is called a thrust fault, the geological term for the contact between 2 rock masses pushing against each other. These subduction zone thrust faults are much larger than typical thrust faults and are called 'megathrusts'. The large earthquakes which occur when the subduction zone plate boundary ruptures are called 'megathrust earthquakes'. Because a continuous megathrust can extend for thousands of kilometres along the axis of a subduction zone, these faults produce the largest earthquakes. Of the 12 largest earthquakes since 1900, 11 were megathrust earthquakes.

Most megathrust zones occur in deep marine trenches, therefore the vertical rebound of the overriding plate at the fault rupture point displaces massive volumes of water, thereby generating a tsunami. Megathrust and (in exceptional cases) other submarine earthquakes are responsible for 75% of the world's tsunamis.

Corals as Recorders of Subduction Zone Earthquakes

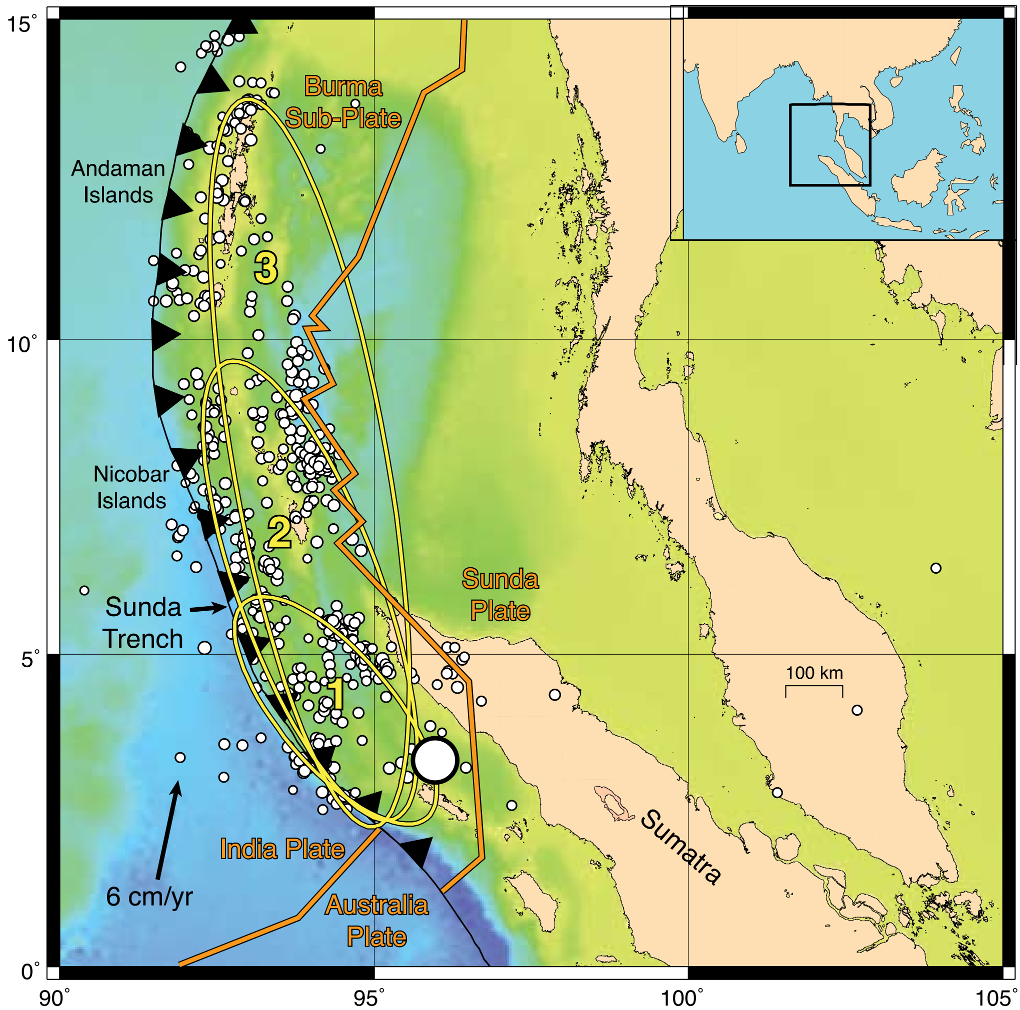
The damage to coral reefs by the 2004 tsunami and the protective function of reefs on coasts is discussed in the following chapters. Corals, however, are particularly valuable in recording the precise amounts of uplift and subsidence associated with subduction zone earthquakes. Charles Darwin recognized that corals record vertical movement by noting that barrier reefs form on subsiding coasts, while marine terraces form on uplifting coasts. Dating of marine terraces formed as a result of uplift during earthquakes, has often provided valuable information on the size and frequency of large subduction zone earthquakes. This information is especially important in the Indian Ocean, where the recurrence time of subduction zone earthquakes is long compared to the historical record.

Individual coral colonies can also be used to measure vertical movement. *Porites* 'microatolls', large colonies growing in shallow water, can be used to measure uplift and subsidence at the scale of centimetres. This technique has been refined over the past 20 years, so that it is possible to estimate with confidence the sudden uplift and subsidence associated with earthquakes, and also the slower vertical movements that occur due to strain accumulation in the crust prior to an earthquake. Researchers used this technique to estimate subsidence prior to the 2004 Sumatra earthquake and were so alarmed by the measured rate of strain accumulation (as well as the size of past earthquake events recorded in the coral growth structure), that they started distributing pamphlets to coastal communities in Sumatra to warn of the danger. These studies now suggest that a high rate of strain is accumulating to the southeast of the Simeulue 2004 and Nias 2005 earthquakes, close the site of a massive earthquake in 1833; another major earthquake is thought to be imminent. Since the 2004 and 2005 Sumatra earthquakes, coral studies have provided valuable data on the vertical movements which occurred before and after these earthquakes.

The Great Sumatra-Andaman Earthquake of 26 December 2004

This massive earthquake ruptured a 1,300 km segment of the Sunda Arc megathrust stretching from Sumatra (approximately 3°N) to the Andaman Islands (approximately 14°N). The earthquake began off northwest Sumatra near Simeulue Island at 7:59 am, when the initial rupture occurred deep within the earth's crust. The fault displacement reached its maximum of 15 - 20 metres near the northern tip of Sumatra as the rupture spread northward along the plate boundary at 2.4 kilometres per second (8,640 kilometres per hour). As the rupture propagated northward into the Andaman Islands, the velocity apparently slowed and the fault displacement lessened, such that 8 minutes after the initial rupture, the maximum fault displacement was 10 metres in the Andaman Islands. The entire rupture process lasted about 10 minutes. The initial earthquake was the largest earthquake since the 1964 Alaska earthquake. It caused severe shaking in Sumatra and the Nicobar Islands, and was felt thousands of kilometres away in Sri Lanka, northern Thailand and the Maldives. It generated seismic waves that circled the globe many times, and stimulated harmonic vibrations of the whole earth that were still detectable on seismometric instruments months after the earthquake. Large aftershocks continued for many months along much of the shallow plate boundary that was ruptured by the earthquake; this was the most energetic earthquake 'swarm' ever observed.

The earthquake caused widespread permanent movement of the earth's surface. There was over 6 metres of horizontal displacement in parts of the Andaman and Nicobar Islands as well as uplift and subsidence: the western margins were uplifted by about 1 m (maximum uplift was



This map of the affected area shows the 2 major tectonic plates (India and Australia) pushing up against the smaller Sunda Plate and the Burma Microplate. The 26 December earthquake started 30 km below the epicentre and the rupture of the plate boundary then spread in a northwesterly direction to the northern Andaman Islands. The initial earthquake was followed immediately by a swarm of earthquakes for 1,300 km in 3 stages (ellipses), slowing down in the north. The tsunami was generated by seafloor movement along the entire length of the rupture zone, especially the more southerly parts where the fault rupture extended to shallow depth.

1.5 m on Great Nicobar), while the eastern margins subsided by a similar amount, thereby permanently submerging many parts of these islands. There is spectacular visual evidence of these changes: some beaches were elevated, coral reefs were thrust out of the water (see cover photo), and mangrove forests and buildings were lifted and destroyed. Smaller earth movements of a few centimetres, were detected thousands of kilometres distant from the earthquake by GPS observations.

There were many examples of land displacements caused by the earthquake:

- The northwestern flank of Simeulue Island was raised 1.5 m (cover photo);
- The southeast end of the Nicobar Islands dropped about 2 m, permanently flooding the Campbell Lighthouse on Great Nicobar Island;
- Car Nicobar moved more than 6 m horizontally in a west-by-southwest direction;
- The island of Phuket in Thailand moved 28 cm to the southwest;
- Pulau Langkawi in Malaysia continued to slide southwest for another 80 days after the first rapid shift to add 6 cm to the original slide; and
- Singapore moved 2 cm westward.

There has been much debate about the actual magnitude of the earthquake (usually determined by the strength of the seismic waves that are generated). However, massive earthquakes like the

These 2 photographs from the Andaman and Nicobar Islands illustrate the tilting of the Burma Microplate. Parts of the northwest Andaman Islands were uplifted out of the water, here seen as a coral reef flat that is now permanently exposed (top photo); whereas in the southwest Nicobar Islands, some islands have permanently submerged, flooding buildings and fields(bottom photo). Photos contributed by Professors Sudhir K. Jain and Javed Malik, Indian Institute of Technology, Kanpur.

Sumatra-Andaman event generate such a complex pattern of waves that routine analyses may fail. The initial magnitude measurements during the first hour following the earthquake were 8.0 - 8.5, but these were gross under-estimates. More careful analysis later suggested that the magnitude was 9.0, which is the magnitude preferred by the U.S. Geological Survey. Even more sophisticated analyses performed in the months after the earthquake suggest that the magnitude was 9.15 - 9.30, which is probably a more accurate reflection of the earthquake size.

The fault movement associated with the Great Sumatra-Andaman Earthquake changed the stress field in the region surrounding the rupture area, altering the stresses on nearby faults. These changes in local stress conditions were predicted to generate another large megathrust earthquake along the Sumatra subduction zone. This prediction proved to be correct on 28 March 2005, when another massive earthquake (magnitude 8.7) occurred about 200 km to the southeast on that fault line. This earthquake destroyed 300 buildings and killed 1,000 people on the island of Nias. There was widespread panic that this earthquake would cause another tsunami; for example, 20 people were killed in Sri Lanka attempting to evacuate low-lying coastal areas. While a local tsunami of 3 m wave height was generated by this earthquake on nearby Simeulue Island, there was negligible impact on more distant coastlines. One of the reasons was that, unlike the December 2004 earthquake, much of the initial fault slip of the March 2005 earthquake was concentrated near 30 km depth beneath the earth's surface. This resulted in less vertical movement of the sea floor, and most of this vertical movement was on the islands of Nias and Simeulue. Thus, much less water was displaced than would be expected from a megathrust earthquake of this magnitude.

There is a long history of large earthquakes and tsunamis in the Indian Ocean that have resulted in major damage and loss of life.

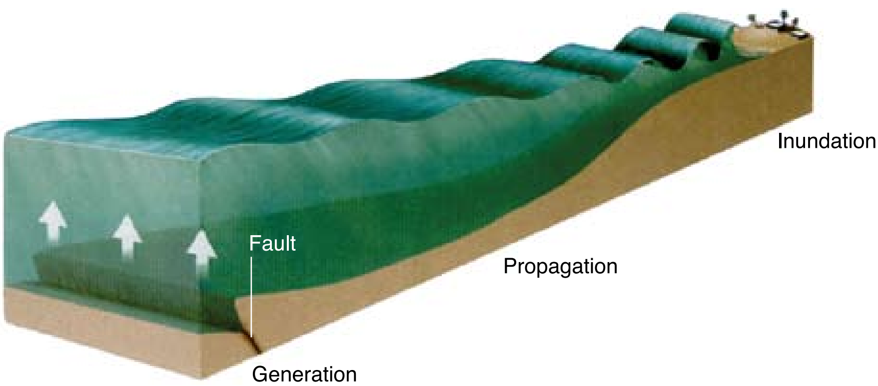
Year	Date	Source Location	Magnitude	Maximum Height (m)	Deaths
1762	2 Apr	Arakan coast (Myanmar)			
1797	10-11 Feb	West Sumatra	8.4		>300
1818	18 Mar	South Sumatra			
1819	16 Jun	Near Cutch	7.7		
1833	24 Nov	West Sumatra	8.7-9.2		
1843	5-6 Jan	North Sumatra	7.2		
1861	16 Feb	North Sumatra	8.3-8.5	7	>900
1881	31 Dec	Nicobar Is.	7.9	1	
1883	27 Aug	Sunda Strait (Krakatoa)		35	>36,000
1907	4 Jan	West Sumatra	7.6		>400
1921	11 Sep	Java	7.5		
1941	26 Jun	Andaman Is.	7.7		
1945	27 Nov	Makran	8.1	15	
1977	19 Aug	Java	8.3	30	
1994	2 Jun	Java	7.6	13	200
2004	26 Dec	West Sumatra-Andaman Is.	9.3	48	>230,000

THE INDIAN OCEAN TSUNAMI OF 26 DECEMBER 2004

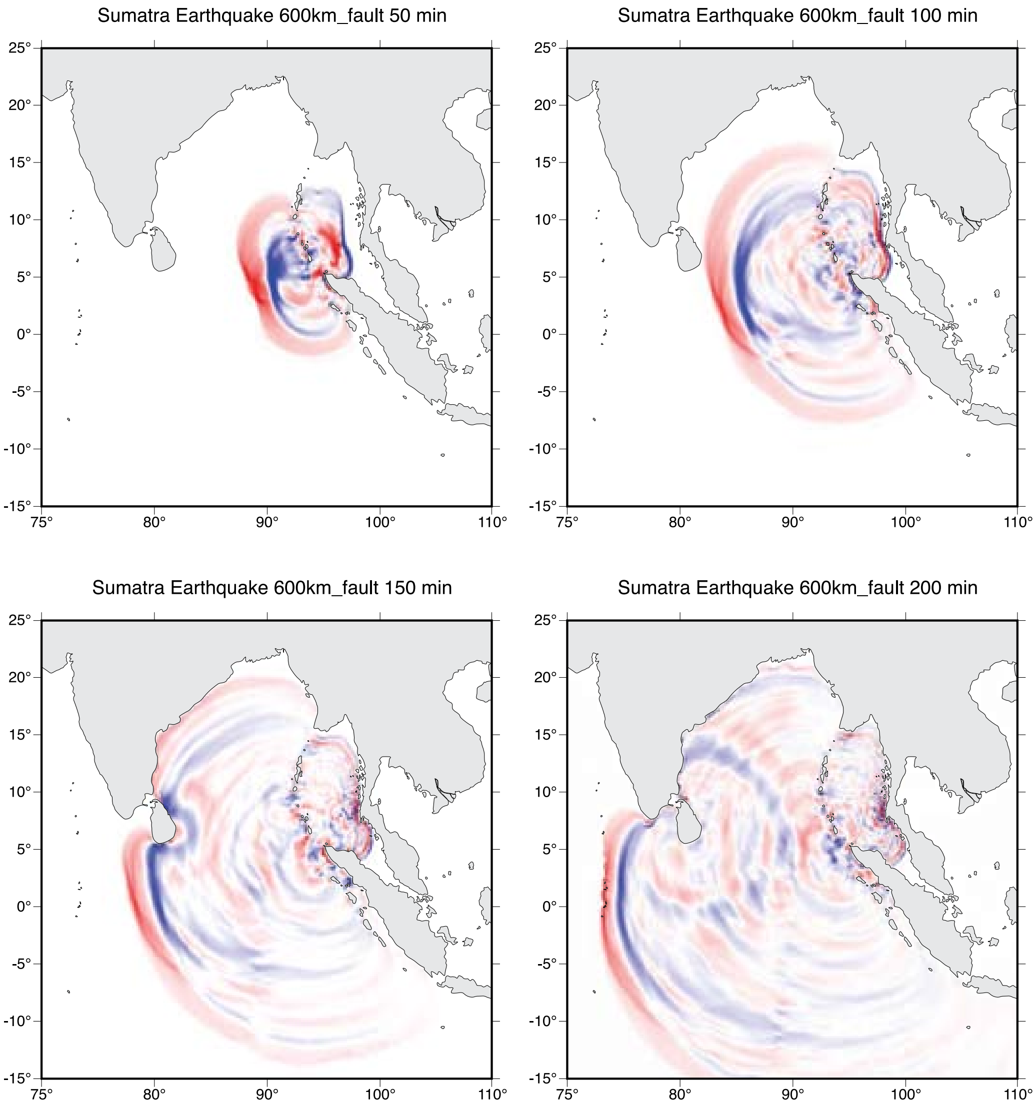
The Great Sumatra-Andaman Earthquake caused major uplift and subsidence of the sea floor, resulting in the displacement of approximately 30 cubic kilometres of sea water directly above the fault. This initiated the waves which spread outwards throughout the Indian Ocean in what is now known as the Indian Ocean (or 'Boxing Day') Tsunami.

Catastrophic effects of the tsunami were almost immediately felt along the coast in northwest Sumatra, closest to the earthquake epicentre. The tsunami arrived within 30 - 40 minutes, with measured run-up heights exceeding 30 m. Entire villages were flattened and there was little time to escape. The height of the tsunami was also influenced by local geography; waves entering bays often increased in height as the sides of the bay constricted the movement of the water thereby magnifying the wave height. Moreover, the waves increased in height as they travelled up narrowing valleys, with 48 m being the highest wave height recorded in a valley in Indonesia. Waves 5 - 10 m high hit Thailand and Sri Lanka approximately 1½ - 2 hours after the earthquake. Because of the geometry of the seabed movement, with uplift on the western edge of the overriding plate and subsidence further east, the leading edge of the tsunami travelling to the east resulted in an initial withdrawal of the sea, whereas the leading edge travelling to the west resulted in inundation. Thus, people who first saw the wave in Thailand were given an apparent warning by the sudden withdrawal of the sea; in some cases people were saved when this warning was recognized and they retreated. However, this natural warning was not well understood, and many people ventured out onto the reef flats. The subsequent waves claimed many lives. In Sri Lanka, the first effect of the wave was inundation, and people had little or no warning.

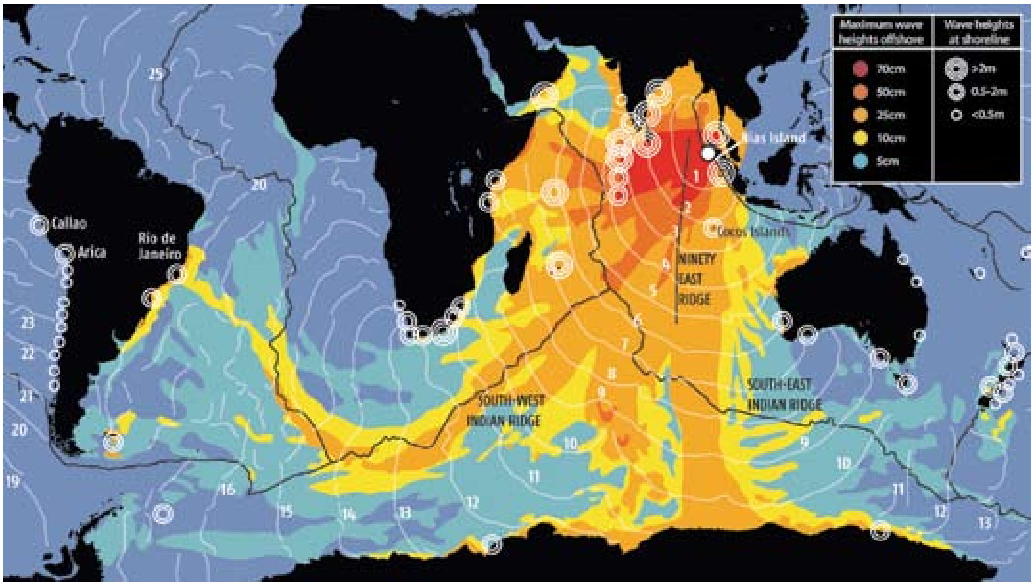
While the height of the tsunami which spread throughout the Indian Ocean was less than 1 m (as measured by radar satellites which happened to be measuring ocean height in the area when the tsunamis occurred), it still reached heights of 1 - 2 metres as it entered shallow water many thousands of kilometres away from the earthquake. For example, a 1.5 m wave was observed in South Africa, 8,500 km from the tsunami. The energy radiating at right angles to the fault line was much greater than that directed along the length of the fault; this is typical of



This diagram illustrates how a tsunami generated by an earthquake at a subduction fault builds up in height as it approaches the coast to arrive as a massive wave (from Viacheslav Gusiakov, Institute of Computational Mathematics and Mathematical Geophysics, Russian Academy of Sciences).



The Indian Ocean tsunami originated when the earthquake ruptured a section of the plate boundary fault stretching from Simeulue Island, off northwest Sumatra, to the Andaman Islands in the north. This sequence of figures, illustrating numerical simulations of the tsunami computed at 50, 100, 150 and 200 minutes after the earthquake, shows the complex interactions of the tsunami wavefront. As the tsunami approached the coast of Thailand it slowed considerably as it was impeded by the continental shelf, whereas the tsunami travelled more rapidly westward through the Indian Ocean to wrap around the island of Sri Lanka and cause major loss of life along the south west of the island (from Kenji Satake, Geological Survey of Japan and the National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan).



The tsunamis generated on 26 December were of such magnitude that they travelled around the world. This map shows that the waves followed the mid-ocean ridge down the Indian Ocean to break on the ice walls of the Antarctic and also around South Africa and along the Mid-Atlantic Ridge to break on Rio de Janeiro (reprinted with permission from New Scientist, ©2005).

earthquake-generated tsunamis. Thus, most of the tsunami energy was radiated in an east-west direction after the Great Sumatra-Andaman Earthquake, which occurred along a north-south fault line. This explains why Thailand and Sri Lanka were hit by large waves, while Myanmar and Bangladesh were not.

Looking Towards the Future

The 26 December Sumatra-Andaman earthquake was the first of its size to be recorded since the advent of modern seismic instrumentation. It generated data which will be used to study earthquakes and deep earth structure for many years to come. The tsunami was the first to be recorded and investigated with high-quality tide-gauges around the world and multiple satellite passes of wave height in the open ocean. Long after the tsunami had struck the Indian Ocean, scientists monitoring sea level gauges were able to observe the waves being propagated into the Atlantic and Pacific oceans. These instruments recorded the passage of the tsunami as far north as Kamchatka, Russia in the Pacific Ocean, Nova Scotia, Canada in the Atlantic Ocean and to the Antarctic. This is the first tsunami that has been continuously tracked throughout all oceans, and is now referred to as the world's first verified 'global tsunami'.

The catastrophic event of December 2004 was not an isolated event in the Indian Ocean or elsewhere. Tectonic plates will continue to move and compress other plates, and more earthquakes and tsunamis will occur in the future at scales equal to, or possibly greater than, the 2004 disaster. The level of destruction from the Great Sumatra-Andaman Earthquake and Indian Ocean tsunami was massive, due to the scale of the earthquake and because large numbers of people lived near the coast around the Indian Ocean. As human populations increase and continue developing coastal areas by felling coastal forests and reclaiming land from the sea, the threats from tsunamis will increase, potentially resulting in major losses of life and damage to property. Hopefully, this earthquake and associated tsunami will act as a warning to governments and international agencies to provide effective early warning systems and undertake natural hazard risk assessments to ensure that villages, towns and cities are not built in the most susceptible areas and preferably are built away from the water's edge. The damage caused by the tsunami also accentuates the call to protect natural coastal defences of mangrove forests and coral reefs. There is some evidence in the following chapters that mangrove forests attenuated the tsunami energy and provided direct shelter to human populations from debris carried by the waves, e.g. fishing boats, and prevented people being washed out to sea. Similarly, there is anecdotal evidence that offshore coral reefs may have broken some of the force of the tsunami and slightly mitigated wave damage.

The Great Sumatra-Andaman Earthquake, and the Nias Earthquake of 28 March, 2005, appear to have released much of the strain energy accumulated along a 1,500 km section of the Sunda-Andaman Arc. Therefore, the likelihood of another major earthquake occurring along this part of the subduction zone in the near future appears low. However, the occurrence of these earthquakes may have increased the likelihood that another large earthquake may occur either to the north or east of this segment. The subduction zone to the southeast (near central Sumatra), caused a major earthquake in 1833 and has accumulated substantial strain energy since then. While the tectonic setting and earthquake history of the northern extension of the Andaman Trench are not well understood, another great earthquake similar to the 1762 event along the Arakan coast of Myanmar is possible.

Greater international efforts are required to improve our understanding of the tsunami threat and to develop tsunami-warning capabilities in the Indian Ocean in order to better cope with the inevitability of future earthquakes. There was no effective early-warning system in the Indian Ocean prior to the December tsunami. An effective system would have saved thousands of lives by providing advanced warning of the coming tsunami and allowing time to evacuate to higher ground. For example, the tsunami took 2 hours to reach Thailand and Sri Lanka, and more than 4 hours to reach Australia. At the World Conference on Disaster Reduction in early 2005, the United Nations began extensive plans to create a global warning system to lessen the threat of deadly natural disasters as history shows that a similar event is inevitable.

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Useful Internet Sites

United States Geological Survey, www.earthquake.usgs.gov;
National Earthquake Information Center, http://neic.usgs.gov;
National Environment Research Council, www.nerc-bas.ac.uk/tsunami-risks;
http://geology.com;
Wikipedia, www.en.wikipedia.org/wiki/Tsunami.

The earthquake shattered this 7 km long bank of Heliopora *coral in Sumatra (Annelise Hagan)*