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The Asian Tsunami, 26 December 2004

Introduction

This **Geofile** looks at four aspects of the Asian tsunami that occurred on 26 December 2004:

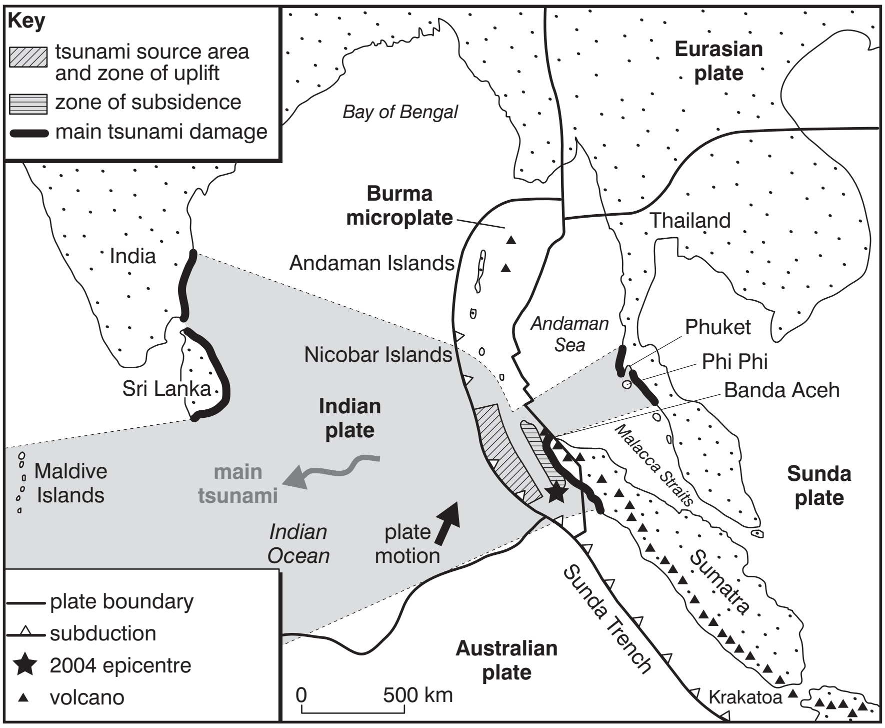
- the geological setting
- how tsunami are generated
- the impacts.

The geological setting

Plate movement

The earthquake (magnitude 9 on the Richter scale) that generated the Indian Ocean tsunami was the result of subduction of the Indian plate under the Sunda plate and the Burma microplate (microplate = a smaller, 'fragmentary' plate) (Figure 1). The Indian plate carries both continental crust (the Indian landmass) and oceanic crust of the Indian Ocean. The continental crust is still ploughing (albeit slowly) into the Eurasian plate and this collision is responsible for the Himalayas. East of India, the oceanic crust of the Indian plate moves more quickly in a north-easterly direction and on its eastern edge the Indian plate subducts under the Sunda plate (the continental crust underlying the Indonesian Islands) and the Burma microplate (largely oceanic crust).

Figure 1: Plate movement behind the Asian tsunami. The plate motion was oblique to the subduction zone, at about 45° to the trench. The main tsunami headed west, to Sri Lanka and the Maldives, while the other headed east to N. Sumatra and Thailand. There was hardly any effect north or south.



Source: T. Waltham, 'The Asian Tsunami Disaster', *Geology Today*

The Indian plate subducts under these plates at an oblique angle of about 45°, at a rate of 6 cm/year (Tony Waltham, *Geology Today*, Volume 21 pp. 22–25). Subduction is marked by the Sunda Trench. The andesitic volcanoes that line the western edge of Sumatra and Java are all products of the subduction which occurs under these islands. Krakatoa was one example of the type of volcano in this setting. Being a destructive margin, the Indian oceanic plate dips down, producing a large thrust fault at a relatively shallow angle of 11°.

Subduction is not a smooth process. Although water is present in the subducted sediments and in oceanic crust, it does relatively little to ease the friction between the subducting and overriding plates. This friction caused the overlying Burma plate to jam against the continued movement of the subducting slab. As a result, the overlying plate was, over time, distorted by stress due to the continuing build-up of pressure. Eventually, the stress overcame the friction and the distorted microplate sprang back into a more 'relaxed' profile (Figure 2). The **focus** of the earthquake was about 30 km depth and about 200 km west of the coast of Sumatra. The **epicentre** (marked as a star on Figure 1) is the point on the earth's crust directly above the focus.

Characteristics of fault movement

The maximum horizontal movement along the fault was 20 m. However, earthquakes such as this do not 'pop' at a single point; they tend to tear or rupture. In this case, the rupture probably travelled 400 km NW in just 200 seconds (Katharine Davies, *New Scientist*, 15 January 2005). This means that a huge slab of crust 400 km long and about 100 km wide was displaced along the shallow fault plane. Such large movements are called 'megathrusts' and are responsible for all of the largest earthquakes that have been recorded. In fact the size of the largest earthquakes (magnitude 9+) are often a product of the amount of rock they move as well as the amount of energy released. In effect, the southern part of the Burma plate moved between 10 m and 20 m to the west as the plate sprang back into its new profile.

Although movement along the fault was up to 20 m the fault itself is inclined at about 11°. This means that there was a certain amount of *vertical* displacement too. This vertical movement meant that the sea floor moved up by about 3 m, displacing the entire column of water above it – about 5 km in depth. In contrast, there was also a relaxation of the plate, forming a slightly elongated depression in between the fault and the coastline of Sumatra. Similar depressions have been measured in other large megathrust earthquakes, notably the 1964 Alaskan earthquake (magnitude 9.2). It may be that this relaxation could lead to a slight subsidence of the Western Sumatran coastline.

Figure 2: (a) Prior to the earthquake, showing subduction of Indian plate.

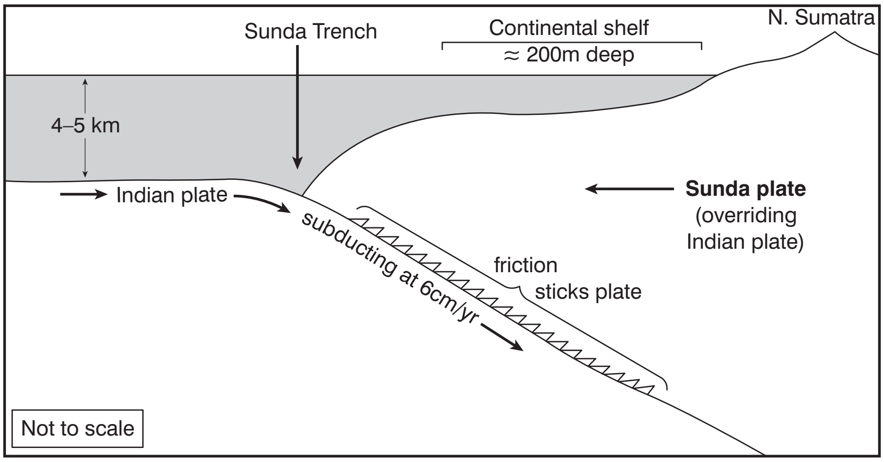


Figure 2: (b) Stress builds up, distorting the Sunda plate

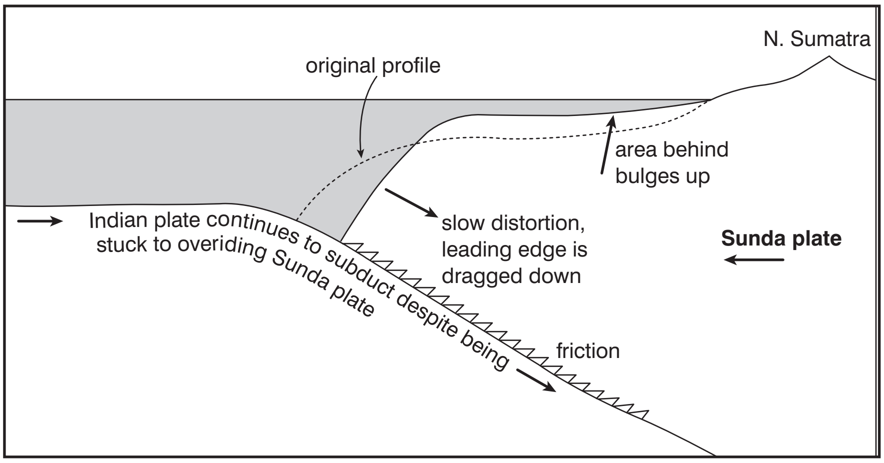
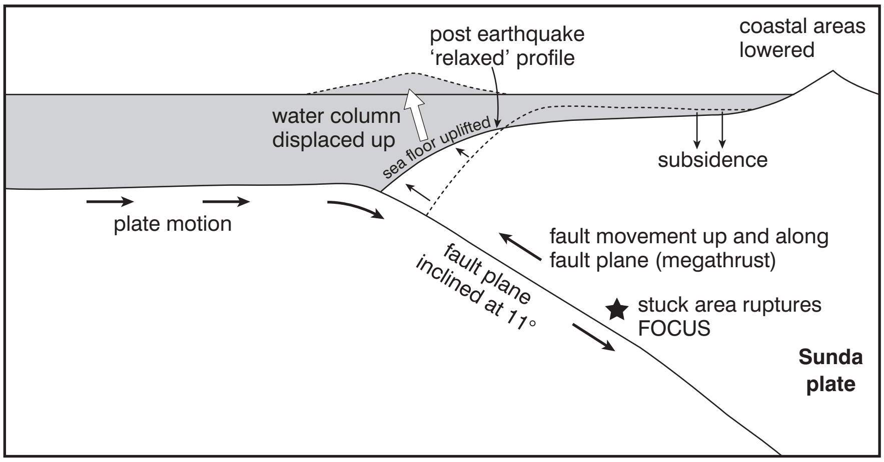


Figure 2: (c) The friction sticking the plates together is overcome by stress. The front of the plate springs out and up, raising the sea bed but lowering coastal areas



The tsunami

Tsunami are generated in a number of different ways. Anything which brings about a sudden, significant change to the volume of a localised area of the ocean basin can trigger a tsunami. In Lituya Bay, Alaska in July 1958 an earthquake triggered a rockslide of 1 km^3 which fell into the bay, setting off a tsunami which reached over 500 m high, stripping the trees off the hillsides of the bay (David Petley *Geography Review* May 2005). In 1883, the eruption of Krakatoa and the collapse of the caldera generated a tsunami which reached up to 35 m high, killing 36,000 people.

Size and direction of the tsunami

In the Boxing Day tsunami, the change that took place was the 3 m vertical displacement of the sea floor. This pushed up a water column into a single large wave which, when it sank back, produced a ripple effect, in which a wave or a series of waves travelled out. The great size of the tsunami resulted from the disturbance of so much of the sea floor – an area 400 km by 100 km was moved, and this sent the wave out in two directions. Unlike the ripples in a pond which radiate out evenly in all directions, the tsunami was directional, i.e. uneven. Since the orientation of the subduction zone is roughly north–south, the main force of the waves travelled outwards in opposite directions either east or west, in other words the tsunami 'split' (Figure 3). The waves were larger in the direction of the thrust movement, which in this case moved up and out in an east to west direction. Thus the tsunami which went west over the Indian Ocean towards Sri Lanka and Africa was larger than the wave which travelled east and wreaked havoc on the Sumatran and Thai coastlines. However, the Sumatran wave was far more destructive, not least because these coastlines were much closer. The direction of wave travel meant that Bangladesh, which is directly north of the subduction zone, escaped (*Geo-News Review* Volume 7 No. 3), although two children drowned when their boat capsized in the swell of the rather reduced tsunami (Tony Waltham, *Geology Today*, Volume 21 p. 22–25). Its low topography (most land is less than 4 m above sea level) and crowded population make Bangladesh very vulnerable to such hazards.

Tsunami movement

Wind waves have orbital movements in the water that decrease rapidly with depth so that, at a depth of less than one wavelength, there may be no real sensation of the wave passing. Wind waves are essentially surface disturbances. Tsunami differ from conventional wind-driven waves in that they are started by disturbances that affect the whole of the water depth. Their wavelengths may be up to 100 km and, because they move in ocean basins which may be only 4 or 5 km deep, they behave as *shallow* water waves, since their wavelength is so much greater than the depth of the water. There are a number of observations regarding this:

- Tsunami transmit energy very efficiently, with relatively little

Figure 3: (a) Sudden uplift of sea bed uplifts vast column of water.

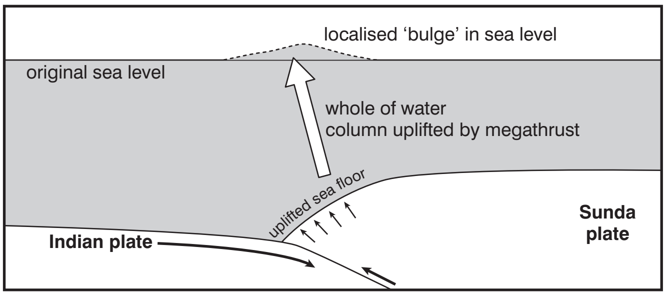


Figure 3: (b) Wave splits into westbound distant tsunami and eastbound local tsunami.

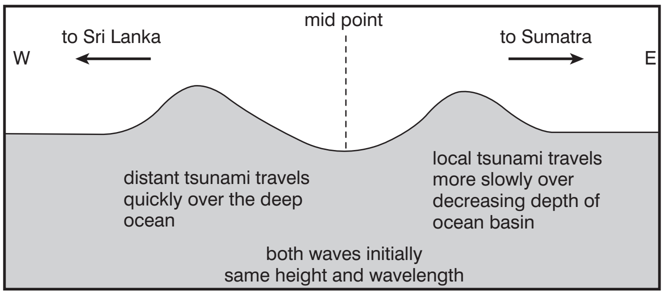


Figure 3: (c) The local tsunami passes over the shallower water of the continental shelf, getting taller and narrower; the distant tsunami travels faster and further, but when it meets land behaves in the same way as the local tsunami.

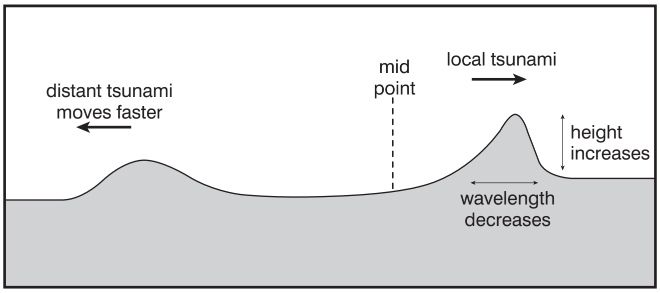
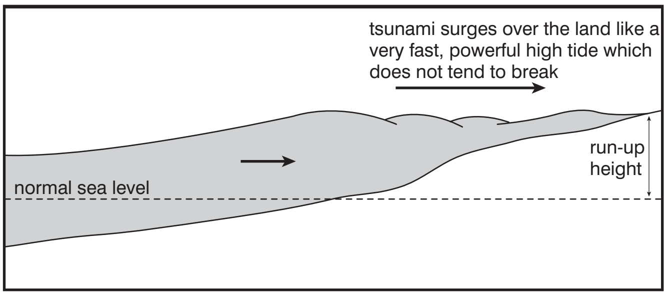


Figure 3: (d) The tsunami surges over the land.



loss over considerable distances, since the rate at which waves lose energy is inversely proportional to their wavelength (very long wavelength means very little loss of energy). This means that they are able to deliver a great deal of energy on to the coast when they arrive.

- The deeper the water, the quicker tsunami travel, so they tend to travel very quickly across the ocean basins, at speeds of 700-800 km/hr.
- In the open ocean tsunami heights are in the order of 30–50 cm – barely noticeable (John Pickrell *NewScientist* Jan 2005).

The westbound part of the tsunami crossed the Bay of Bengal and arrived at the shores of Southern India and Sri Lanka within 2 hours. The eastbound part moved towards Thailand and took 2 hours to cover a third of the distance of the westbound wave. The reasons for the difference are to do with water depth. As the tsunami moved eastward over the continental shelf, depth decreased and friction with the sea bed caused the wave to slow. Speeds are typically about 150–300 km/hr over the continental shelf (E.A. Bryant *Natural Hazards*, p. 208). The tsunami's energy flux (rate at which energy moves with the wave) is dependent on the height and speed of the wave and remains almost a constant, so the wave must grow in height in order to counteract the drop in speed. As the wave approached the coastline it grew in height, having lost little energy thanks to its ability to transmit energy very efficiently.

Tsunami run-up height

As a tsunami moves onshore some of its energy is lost with friction in the now very shallow sea bed and some is lost as the wave energy is reflected offshore. However, as holiday video footage shows, the Asian tsunami still contained tremendous amounts of energy, and rushed over the land at well above normal sea level. The height a tsunami reaches above this level is known as the **run-up height**. The run-up heights recorded for the Boxing Day event are as much as 32 m, some of the highest ever recorded, and some waves penetrated 2 km inland.

The impacts

The impact of the Asian tsunami generally decreased with increasing distance from the epicentre. For example, waves were up to 10 m high in Sumatra, but declined in height to 4 m in Thailand, Sri Lanka and Somalia on the African coast. (John Pickell, NewScientist.com January 2005).

On all the unprotected coasts the damage of the tsunami was similar. The tsunami developed as a steady but relentless rise of sea water, creating bores in river channels and surges over the land that were faster than people could run. The floodwaters were so strong and fast that swimming to safety was impossible. Also, the thick layer of debris which accumulated on top of the water as it rushed through towns and villages meant that it became increasingly dangerous and difficult for people to be seen and rescued once caught in the floodwater.

The damage and loss of life was most severe in Sumatra near the epicentre. The coastal towns were hit by the biggest waves and for the most part were totally destroyed. The relatively flimsy wooden buildings, many on stilts, had no chance against either wave or bore. The floodwaters, often laden with debris, had great destructive power.

Apart from the human tragedy there were also considerable impacts on the coastline itself. The coastal sediments were easily eroded and the return of the tsunami to the sea scoured huge volumes of sand, so that the land was now below sea level. Photos of Banda Aceh show the effects where the front of the town, which must have taken the full force of the wave, has been removed, leaving sea in its place. The possible subsidence as a result of the relaxation of the Sunda Plate may also have left a portion of the Western Sumatran coast at a lower level, transforming low-lying land to shallow sea.

In the Maldives, a group of over 1,000 islands, the tsunami swept over these low-lying coral islands (average height a metre above sea level) and rendered whole islands uninhabitable. Kandolhudhoo was completely swamped by the wave and residents were evacuated. The Maldives depend on their growing tourist industry for foreign income – 74% of the GDP is derived from tourism (*Geo-News Review* Jan 2005) – yet the investment in just one of their resorts runs to 29 million euros.

The ecological impacts have been more mixed. Not surprisingly, deep sea communities have remained unaffected. Coastal areas with mangroves were in some part protected against the force of the wave. Mangroves have a dense network of roots which bind the sediment together and act as a buffer against such waves. In Tamil Nadu in Southern India, those areas with mangroves suffered less damage than those areas where the mangroves had been removed. The Marriott Hotel in Phuket, Thailand was built with strict environmental controls in mind. This meant that the hotel was placed back from the waterfront and mangrove swamps preserved along the coast. Damage here was far less than to other hotels directly along the coast.

The most severe environmental impact has probably been to corals. The corals of the Indian Ocean were already under stress as a result of:

- El Niño warming during 1997 and 1998
- human impacts which these have been various and damaging, including waste water, dynamite fishing and a general acidification of oceanic waters (*Geo-News Review* January 2005).

However, the tsunami dealt a double blow to these coral reefs; one coming in, the other going out. The force of the wave along with any sea bed debris slammed into the reef. The backwash carried all the debris scoured off the land – cars, trees, and household items all capable of acting like a battering ram on the coral. The sediment dragged off the land can suffocate coral, which needs very clear water to survive.

The impact on the coral highlights important characteristics of the tsunami which contribute to their destructiveness. Water in wind waves moves in a circular motion so that when they shoal their breaking motion does not tend to swash up the beach very far. Tsunami water movement tends to be flatter – not only does it move further up the beach but their wavelength is in the order of tens of kilometres so as the wave surges ashore it keeps on coming and coming for several minutes, unlike breaking wind waves which break, swash and backwash in a matter of seconds.

Conclusion

A combination of factors meant that this was the costliest tsunami in terms of human life. Although people can learn from their experience, we easily forget that living in such a geologically active area carries its own health warning.

Bibliography and recommended reading

Waltham, T (2005) 'The Asian Tsunami disaster, December 2004' *Geology Today* Volume 21 (January-February 2005) (Blackwell Publishing)

Bryant, E.A. (1991) *Natural Hazards* Cambridge University Press

Geo-News Review Volume 7 Number 3 (January 2005) 'Indian Ocean Tsunami: a multinational disaster' (Bromley Publications)

Ross, S. (2005) 'Tsunamis – rare but devastating' *Geo Factsheet* April 2005 Number 179 (Curriculum Press)

Petley, D. (2005) 'Tsunami' *Geography Review* May 2005-

Websites

www.ess.washington.edu/tsunami/index.html
This has good links one of which takes you to 'Tsunami visualizations'.

http/:en.wikipedia.org/wiki/2004_Indian_Ocean_earthquake#Quake_characteristics
This has good animation of the spread of the tsunami west and east.

geology.com/articles/ tsunami-geology.shtml
http://walrus.wr.usgs.gov/tsunami/basics.html
These show a clear set of diagrams showing the plate interactions and wave generation.

www.NewScientist.com

Focus Questions

1. On a large map (A4 size) of the area mark in the epicentre of the earthquake. Annotate the map with the factors outlined above putting them, where possible, in the correct location. Use photos from the web to illustrate your annotations.

2. Explain why megathrusts can generate tsunami but movement along transform faults (on constructive margins) are less likely to do so.

3. Draw a flow chart which details the events telling us how a tsunami begins, travels and changes when it meets the shallow water of the continental shelf.

4. To what extent did lack of development contribute to the Asian tsunami disaster? You should consider population growth, land pressure, tourism, political unrest, lack of technological application.

5. What strategies could governments and NGOs use to reduce the impact of another tsunami?