

GENERAL ARTICLE

THE INDIAN OCEAN MEGATSUNAMI OF DECEMBER 2004: THE SCIENTIFIC BASIS OF THE CATASTROPHE

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Abstract: The Earth's surface is made up of 13 rigid lithospheric plates that move towards or away from each other, much like the pieces of a jigsaw puzzle. On the 26th of December 2004, three of these plates interacted in the eastern Indian Ocean to cause an earthquake of magnitude 9.3 and generated a tsunami or giant ocean wave that devastated the coastlines of nine countries including Sri Lanka, killing over 250,000 people. This is the greatest natural disaster to strike Sri Lanka in our recorded history. In this article, the geological and seismological basis of this awesome catastrophe is explained in terms of causes and effects and assesses the potential tsunamigenic risk to Sri Lanka. It is argued here on the basis of available data that a tsunami event of similar magnitude has a low probability of occurring in the "foreseeable future" within the Central Indian Ocean region.

Key Words: *convergent margins, earthquakes, high magnitude, Indian Ocean, megatsunami underthrusting plates.*

INTRODUCTION

Tsunamis are frequent events in the Pacific Ocean region, where 80% of the World's seismicity is concentrated (Figure 1). The Indian Ocean has been traditionally considered a "tsunami backwater", where destructive cyclones are more frequent. While a tsunami is to be expected somewhere in the Pacific about every ten years, it is more than a "century scale" event in the other Oceans. Yet, there have been seven tsunami occurrences in the Indian Ocean region during the period 1524 to 1943 (Table 1), but none of them had a transregional effect like the one in 2004. The December 2004 tsunami is now the greatest ever recorded anywhere in terms of loss of life and material destruction. In the last 300 years, there have been only three tsunami that caused comparable loss of life (from both the quake and tsunami). They were the famous Lisbon, Portugal tsunami (1755): 8.7M and 60,000 dead; Messina, Italy (1908) 7.2M and 160,000 dead; and Awa, Japan (1703); >100,000 dead. The largest earthquake ever recorded (9.5M) and accompanying tsunami (1964 in Chile), resulted in a total loss of life of less than 5000. It travelled

a distance of ~17,000 km in 22 hours before it struck Hawaii and Japan, when < 200 people perished. Basically there have been four catastrophic tsunami in 300 years and the first in the Indian Ocean. The 1881 and 1883 tsunami that were felt in Sri Lanka were non-entities. In 1970 and 1992 respectively, 330,000 and 210,000 people reportedly perished in the famous cyclones of the Bay of Bengal and over 300,000 in Calcutta in 1737. Destructive cyclones are more probable than a future tsunami affecting Sri Lanka.

It is a misconception to believe that all tsunami are caused by earthquakes. In fact, there is a class of tsunami that is totally unrelated to seismic activity and earthquakes. These are the massive submarine sediment slides (or undersea avalanches) generated within continental slopes due to slope and sediment instability; massive landslides or avalanches that end in the ocean (called mass-movement events); large meteorite impacts and violent volcanic eruptions. Even a slight tremor can trigger off a submarine slide. These have also occurred throughout geologic history. The huge sediment masses in motion will displace a massive volume of water to generate destructive tsunami. In 1958, an avalanche that landed in Lituya Bay, Alaska, created the largest recorded tsunami (524 metres high), bigger than the tallest building on Earth. The tsunami generated by the stupendous explosion of Krakatoa volcano in the straits between Java and Sumatra (in 1883) reached 40 metres in height and drowned 36,000 people on nearby coasts. Its effect was felt in Sri Lanka within hours of the eruption. The *Ceylon Observer* of 27th August 1883 reported the event. Only one death was reported. Fortunately, Sri Lanka does not appear to be in danger from these non-seismic tsunamis.

Alternatively, not every high magnitude submarine earthquake will generate tsunami. Just three months after the December 2004

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Table 1: Tsunami occurrences in the Indian ocean from 1524-1943

Date	Location
1524	Maharashtra, India
2 nd April 1762	Arakan, Myanmar
16 th June 1819	Rann of Katch, Gujarat
31 st October 1847	Great Nicobar Island, India
31 st December 1881	Car Nicobar Island, India (7.9M)
26 th August 1883	Krakatoa, Indonesia
26 th June 1941	Andaman Islands, India (7.7M)
28 th November 1943	Makran, Baluchistan

Tsunami, an 8.7M earthquake (March 2005) occurred again in Sumatra, but no big tsunami was caused. This earthquake destroyed the island of Nias with much loss of life. It is well to remember that the earthquake belt in Indonesia also coincides with a parallel volcanic belt along the trench (Figures 2 and 7). The purpose of this article is to give a general and semi-technical analysis of the science behind the 2004 tsunami catastrophe to a wide segment of readers and emphasize the importance of science in our country's affairs. Two newspaper articles by the author on the tsunami for the general public appeared in the *The Island* (4th January 2005), *The Daily News* (6th January 2005) and *The Sunday Times* (16th January 2005).

THE SEISMIC HISTORY OF THE EASTERN INDIAN OCEAN

The break-up of the Indo-Australian plate and the earthquake in Sumatra

The origins of the present seismicity in the eastern Indian Ocean goes back to well over 50 Ma (Eocene era) when the Indian subcontinent began its' great push northward towards Eurasia, resulting in the collision and uplift of the Tibetan Plateau and Himalayan Mountains. Starting about 8 Ma ago, the accumulated mass of these two continents and the accompanying stretching of the ocean floor became so great that the original Indo-Australian Plate buckled and fractured under stress, resulting in two separate plates – the Indian (which also carries Sri Lanka) and Australian, with the plate margin located at ~ 3°N latitude in

the eastern Indian Ocean.¹ Today, the two continents are moving independently of one another and in slightly different directions (Figure 2). A moving mass (India) forced into an immovable object (Eurasia) resulted in the buckling of the oceanic lithosphere at the equatorial latitudes. This splitting created the 13th lithospheric Plate. Geologists discovered a broad zone extending about 1000 km east to west in the equatorial Indian Ocean, where the ocean floor was compressed and deformed. Deep Ocean drilling recovered rock samples, which indicated that the buckling and fracturing started around 8 Ma ago – coeval with the maximum elevation attained by the Tibetan Plateau in the collision process.²

The 9.3M megathrust earthquake (Richter Scale) that generated the December 2004 tsunami originated offshore to the west of northern Sumatra close to the tiny island of Simeulue (the large star in Figure 2) and is probably the second highest ever recorded in the sea. The Sumatra area is known for its recurrent earthquake activity as it is on the boundary where four tectonic plates of the Earth interact.³ This boundary called a Subduction Zone is represented bathymetrically by the curved Sunda Trench, a long fault plane and a nearby volcanic arc. Here the north-east moving sea floor (at ~6 cm per year) of the Indian Plate is thrust (or subducted) under the adjacent and overriding Burma Micro-Plate at an angle of ~10°. Strain builds up in the subduction zone, until the "frictional lock" in the rocks is broken and a rupture occurs. The earthquake did not exactly happen at a point along the fault. It ruptured over a length of about 400 km. This initial rupture propagated northwards at around 2 km sec⁻¹ over a section of the long fault, producing rock deformation. The interplate thrust boundary region is in fact a decoupled thrust fault, where the overriding Burma Plate in addition has a right lateral slip component (transcurrent fault).

It is no coincidence that the epifocus of the earthquake at ~3.3°N latitude also lines up with the Indo-Australian plate boundary at its' eastern end and is the location of maximum compression where the three plates interacted (Figure 2). Trenches are the areas where sea floor is consumed by the Earth's mantle during the

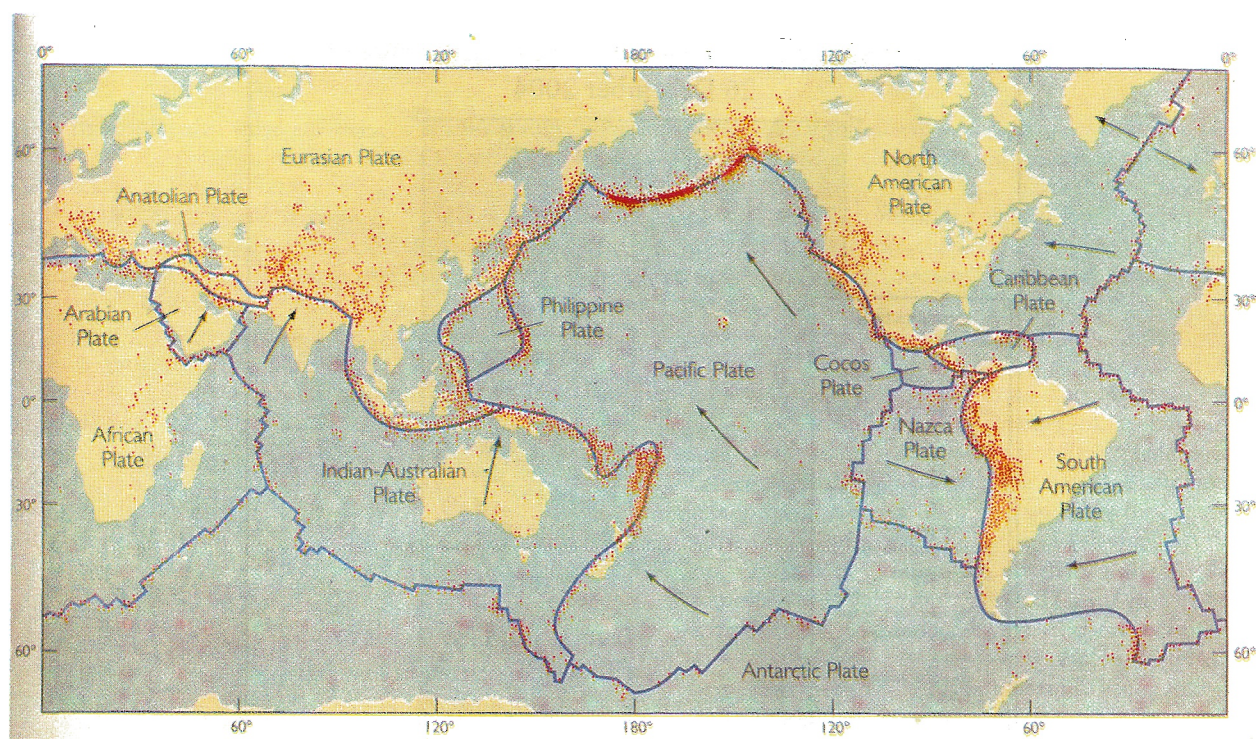


Figure 1: Distribution of the World's seismicity (red dots). Note that ~80% of the seismicity is in the Pacific Ocean region

Source: Press and Siever, 1994. W.H. Freeman & Co. New York.

(as the laws of physics demand). This happens at the mid-ocean ridges lying to the south and west of the deformed region in the Indian Ocean (Figure 3). It has been shown that the outward movement of newly created sea floor could be accommodated only if a distinct plate boundary existed between separate Australian and Indian plates across the equatorial Indian Ocean.⁴ In the eastern part of this new plate boundary the Australian Plate is moving counter-clockwise to the Indian Plate. On the western side (i.e. towards Sri Lanka), the two plates are moving away from each other. Accordingly, there should be compression, buckling and fracture in the east and the sea floor should be thrust upwards along the faults to release strain, with the amount of compression decreasing from east to west systematically across the said 1000 km long equatorial zone.

The tectonics of the region is very complex and involves the interaction of the Indian, Burma, Sunda, Australian and Eurasian plates (Figure 2). The N-E movement of the Indian and Australian plates at ~ 6cm/yr relative to the Burma plate results in oblique convergence at the Sunda

trench. An earthquake occurs when rocks being deformed suddenly break along the fault, releasing long accumulated stresses. The blocks of rock on either side of the fault slip suddenly, setting off ground vibrations. Slippage is most common along plate boundaries. The distribution of aftershocks from Sumatra to Andaman Islands suggests that the rupture had a maximum length of ~1200 km parallel to the Sunda Trench and a width of over 100 km perpendicular to the earthquake source. Much of the slip was apparently in the southernmost 400 km of the rupture. i.e. in the Sumatra sector. The amount of vertical displacement of the two fault blocks is the slip, which is ~20 m. The maximum displacement of the sea floor was about 8-10 metres to the WSW. The Sunda-Java Trench (the second largest after the Peru-Chile Trench) is about 4,500 km long and up to 7.5 km deep. The earthquake foci down an inclined subduction zone can extend to depths of up to 700 km in the mantle; however, it is shallow focus megaquakes like the recent ones in Sumatra (only 30 km below the sea floor) that are most destructive.

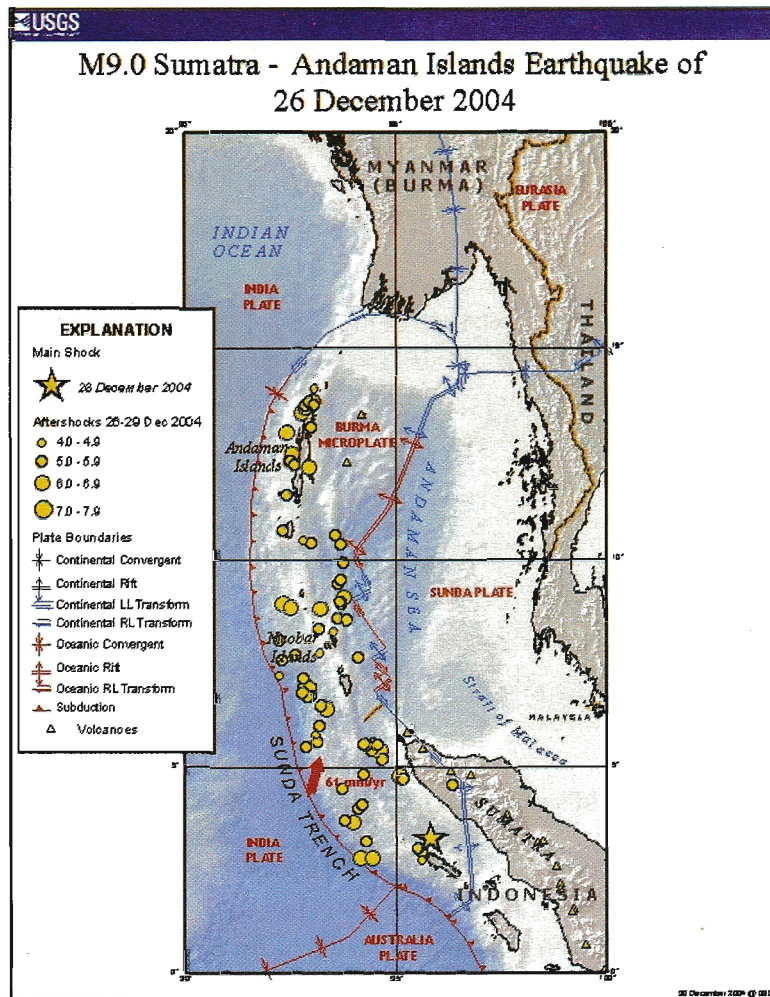


Figure 2: The seismotectonic setting for the earthquake and tsunami.

Source: USGS/NEIC, Denver, Colorado, USA.

subduction process (Figure 1). To compensate this loss, new sea floor has to be created elsewhere

THE TSUNAMI

How are these catastrophic waves generated? The mechanism is basically very simple.⁵ Most tsunami originate from a large and instantaneous displacement of the sea floor during submarine faulting, either when the sea floor drops down as a block, rises as a block or as a thrust during a major earthquake (see Figure 4). In the former case, a trough in the ocean surface results, temporarily withdrawing water from the coast. A wave is created as the water rushes in to fill the trough, overcompensates, and travels to land as catastrophic tsunami. When a part of the sea floor is thrust upward (as happened on 26th December 2004), water is displaced upward, pulling along a

vast volume of water from the shore, which soon returns to the coastlines as tsunami. Further, gravity and the incompressibility of water forces the sea surface to react instantly to changes thousands of metres below. A 1200 km long and ~100 km wide area about 30 km below the ocean bottom was pushed up by several metres, creating a giant piston effect, which vertically displaced a huge volume of water. The water at the surface then starts to move “downhill”, quickly gathering speed as ocean waves and generating tsunami. The waves move in a fashion similar to when a solid object is dropped into a body of still water, where the ripples spread outwards in all directions from a centre. The magnitude of a tsunami (which is a function of the maximum run-up) is dependent on the earthquake magnitude, the focal mechanism of the earthquake (a decoupled thrust fault) and the centroid or

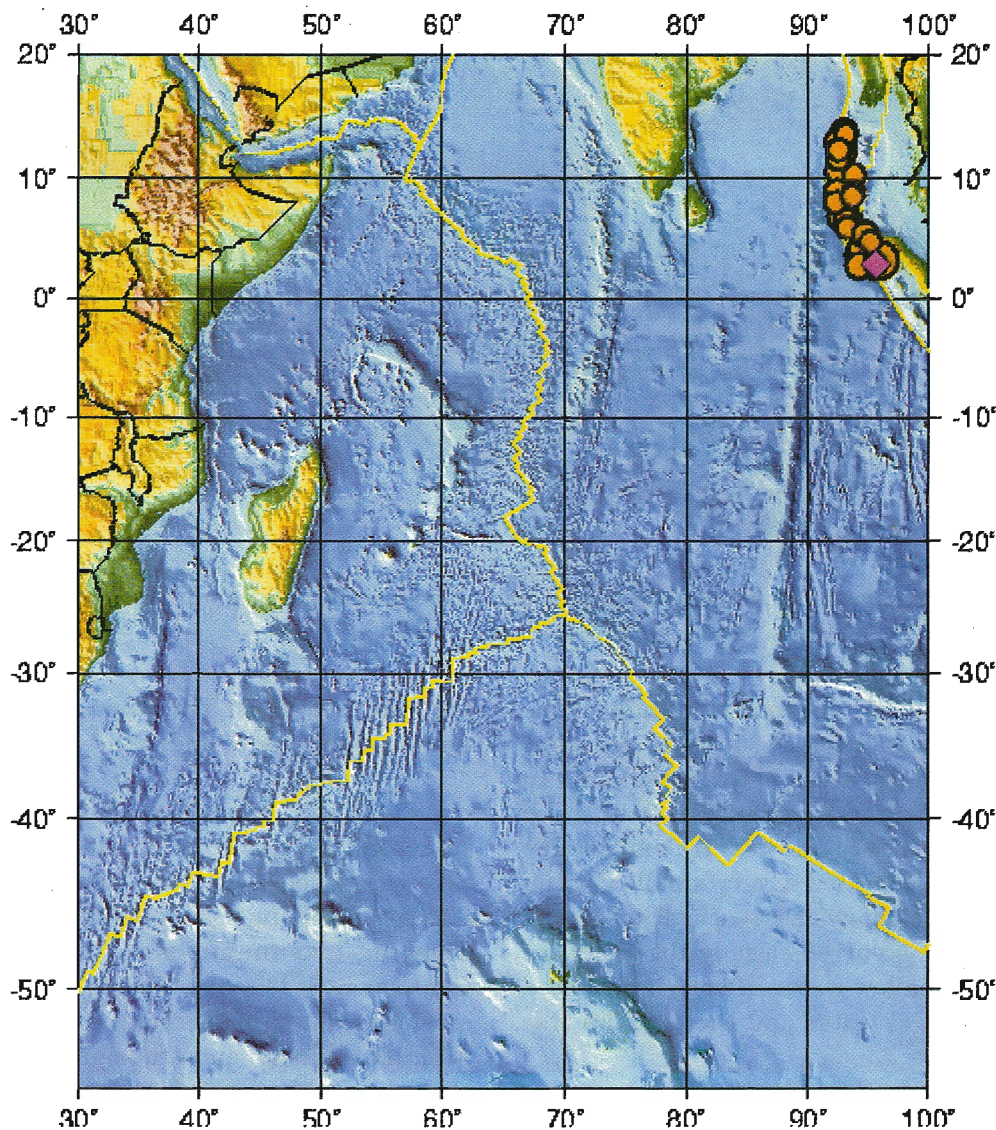


Figure 3: Indian Ocean sea floor topography. Note the Ninety-East Ridge which is parallel to the 90° longitude; the Chagos-Laccadiv Ridge is to the west of Sri Lanka-India. The three mid-ocean ridges (southwest, southeast and central) are also shown.
Source: USGS

location of the centre of energy release (Figure 5). The 2004 Sumatra centroid (Harvard University solution) is right on the trench in this earthquake. This indicates that most of the energy release was in deep water (proof was provided by the ~2 km long and several hundred metre thick submarine avalanches that were found on the sea floor between Sumatra and Andaman Islands, by the Survey Ship *H.M.S. Scott*; it also showed that Sumatra and the islands were shifted by 20-36 m to the SSW from its original position and that shipping lanes in the Straits of Malacca were affected). This usually results in a tsunami with larger potential energy than a similar tsunami

caused by a rupture located closer to the shore and in shallower water (due to the greater volume of water displaced). Since nearly all of the energy of the 2004 earthquake was released in a thrust motion, a large tsunami was generated. Large strike-slip or transcurrent earthquakes of similar magnitude are not efficient tsunami generators. Near the earthquake source, the local tsunami size increases with magnitude (9.3 in this case). Tsunami generated by a rupture of the sea floor as in the last 2004 seaquake is much greater than one generated without sea floor rupture. Tsunami run-ups (maximum height above normal waves) in Aceh, Sumatra were up to 32 m. The area had

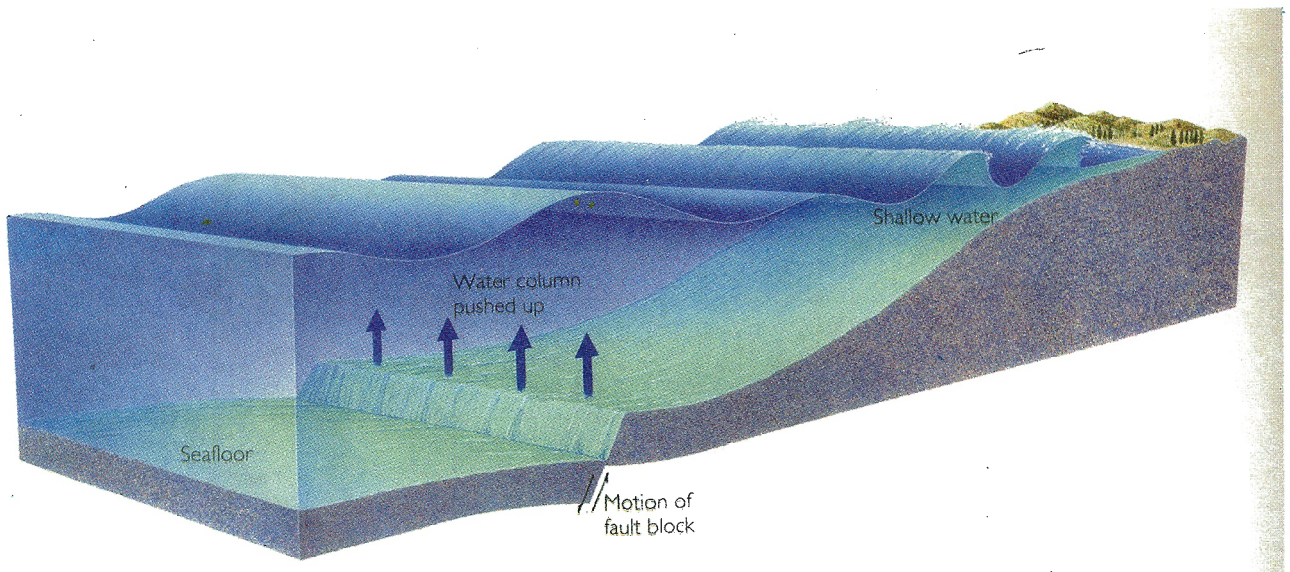


Figure 4: Block diagram illustrating the generation of tsunami due to an upthrust at a plate boundary

Source: Press and Siever, 1994. W.H. Freeman & Co. New York.

no chance at all, being right on the margins of the two plates. It was all too close to the epicenter and centroid and the accompanying tsunami. In Hambantota, run-ups were about 10 m, with much less destruction. The 8.7M Sumatra earthquake of March 2005 generated a very small tsunami (about 20 cm in height when it reached Sri Lanka). This earthquake occurred close to the shoreline of Sumatra in shallow water. Hence, it displaced a lesser amount of water and the tsunami was very small.

Tsunami usually occur as several large ocean waves (a wave train) that may arrive at irregular intervals at the opposite coasts from their point of origin at the earthquake epifocus (~250 km west of Sumatra in the present case, as shown in Figure 2). They are generally undetected before they strike coastlines thousands of kilometers away. At sea, the tsunami is hardly observable or perceptible. It was good fortune that two satellites (TOPEX/Poseidon and Jason-1) happened to pass overhead just as the tsunami's leading edge was approaching Sri Lanka. They took radar measurements of sea levels in the Bay of Bengal along a 3000 km stretch. What the satellites recorded was unique: two waves of about 50 cm amplitude travelling 500-800 km apart, with smaller waves in between about 100-200 km apart. These details were the first ever observations of a propagating tsunami and gives vital data as to the amount of energy released and

the way it travels. They slow down or change direction because of underwater topography.

50 cm may seem miniscule, but they represent the crest of a speeding body of water several km deep, as they reached speeds of over 800 km/h. Fishing boats would ride the wave, not knowing a tsunami is moving under them. Consequently, tsunami become visible only in the shallower waters of coastlines, harbours and bays, where the friction and drag against the shoaling sea floor causes the fast moving waves to bunch up and gain height as devastating walls of water. A wave 200 km across and 25 cm amplitude delivers 50,000 tons of seawater per metre of coastline. Sri Lanka with its very narrow continental shelf and coastal plain was particularly prone to damage as the tsunami released its energy suddenly. In wide and shallow shelves, the waves would have gradually dissipated much of the energy before reaching the shoreline. Wave run-ups may have been as high as 20 m, according to eye-witness accounts at Nilaveli on the eastern seaboard, but this authors investigations show a much smaller maximum value of ~8-10 m on the western seaboard. Quickbird Satellite images over the Kalutara coast indicate that the roll-back waves exposed around 400 m of the nearshore sea bottom. Additionally, seismic waves cause the water in enclosed bays, harbours or lakes to move back and forth rapidly across a basin, rising and falling.

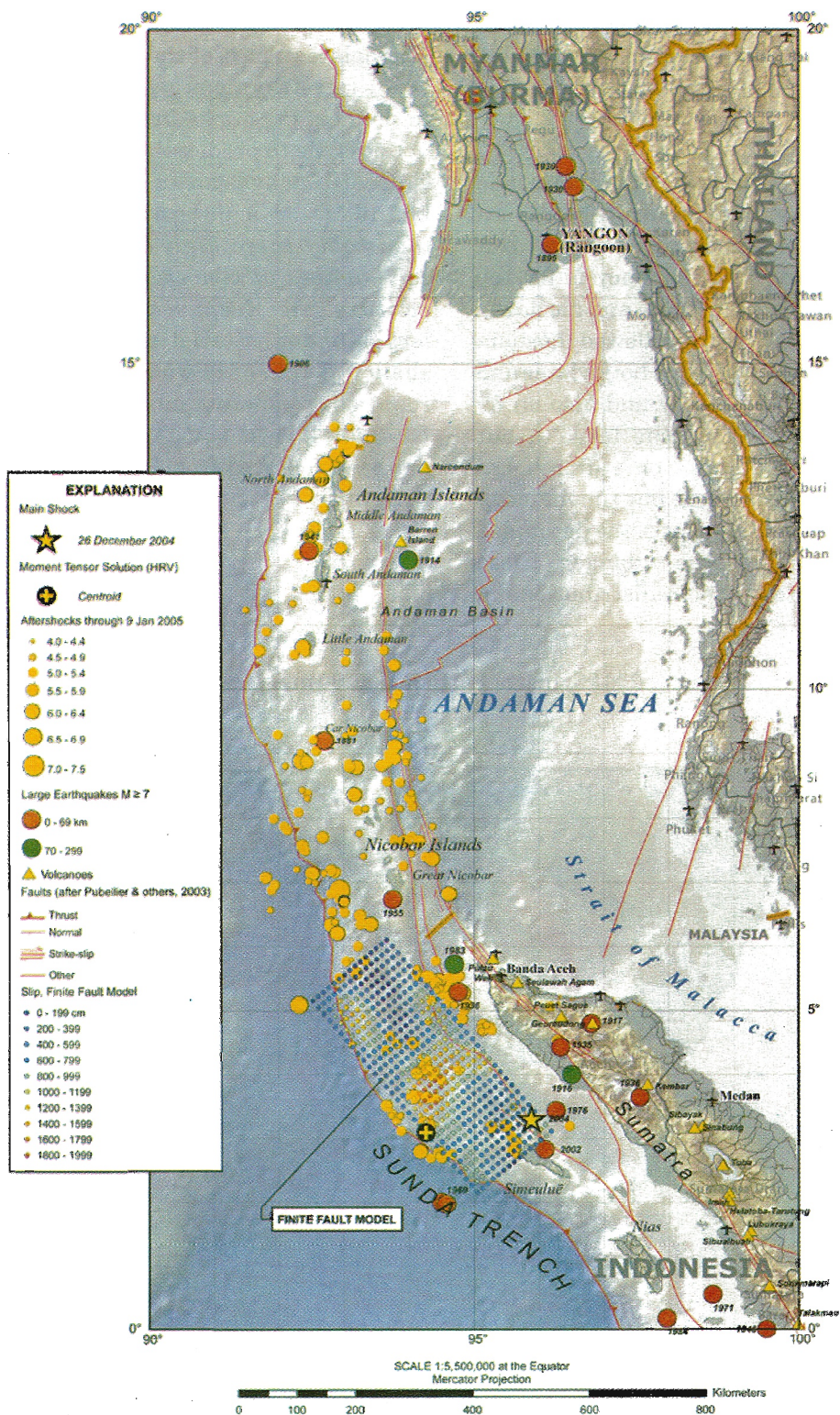


Figure 5: Map showing area of maximum energy release, centroid and epifocus of the Sumatra earthquake and detailed fault structures in the Sunda-Burma plates.

Source: USGS

This phenomenon is called a *seiche* and can develop at great distances from a quake epicenter. It is possible that *seiche* waves also compounded the destruction caused in some bay areas of the coast.

If after shocks of sufficient magnitude occur and cause further displacements on the sea floor, then a series of tsunami may follow. But this is extremely rare. The tendency is for the aftershock magnitudes to fluctuate and die down. So far over 100 aftershocks have followed the main quake. One measuring 7.1M a few hours later and 6.5M quakes on New Years day and also on 6th January 2005 were perhaps the largest, but caused no damage or tsunami. Some aftershocks were on the thrust plane itself, but the majority was on the transcurrent segment of the decoupled Burma Plate and did not pose a danger. These shocks are an indicator of the redistributions in

tectonic stresses still going on along the boundary between the converging India Plate and Burma Microplate (a part of the Eurasian Plate). These stress redistributions generally increase the time to the next big quake in the same area. But it is not possible to predict the time or its magnitude. This still leaves over 3000 km of the plate boundary as a potential danger zone. *It is invariably these high magnitude megathrust earthquakes at convergent plate margins that rupture the deep sea floor that generate megatsunami.* Statistically, it appears that a shallow depth, deep water earthquake of >8M is required to generate mega-tsunami. Further, as far as it is known, tsunamigenic earthquakes have not been reported from outside convergent plate margins.

2004 Sumatra Earthquake 100 min.

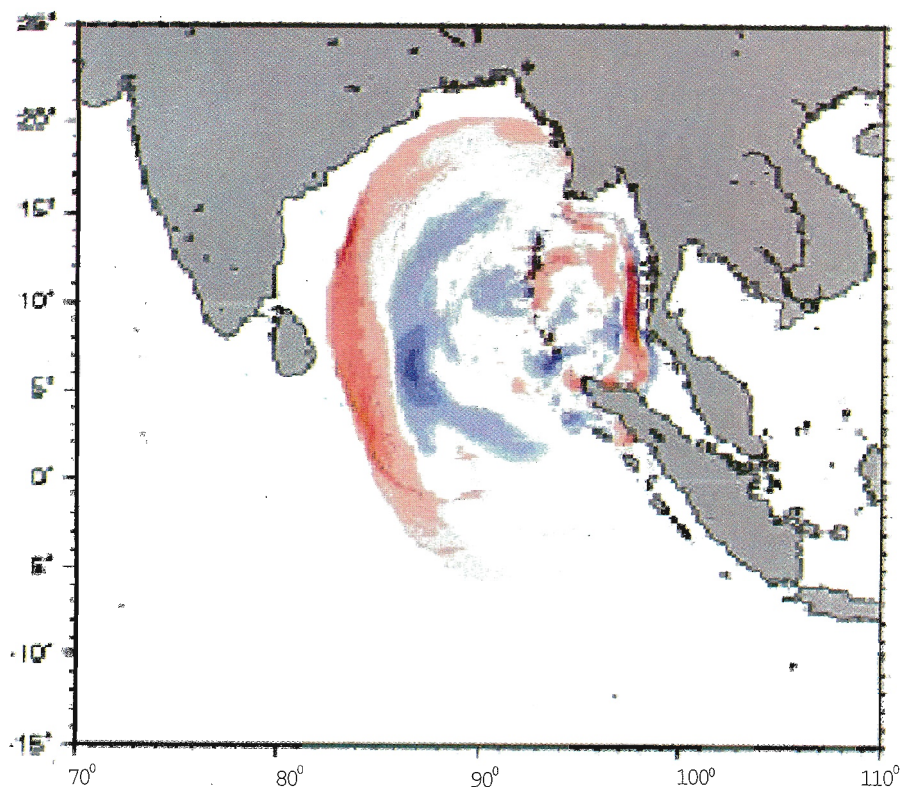


Figure 6: The Tsunami about 12 minutes before striking eastern Sri Lanka. The wrap-around effect is already evident in Myanmar and Thailand.

Source: National Institute of Advanced Industrial Science & Technology, Japan.

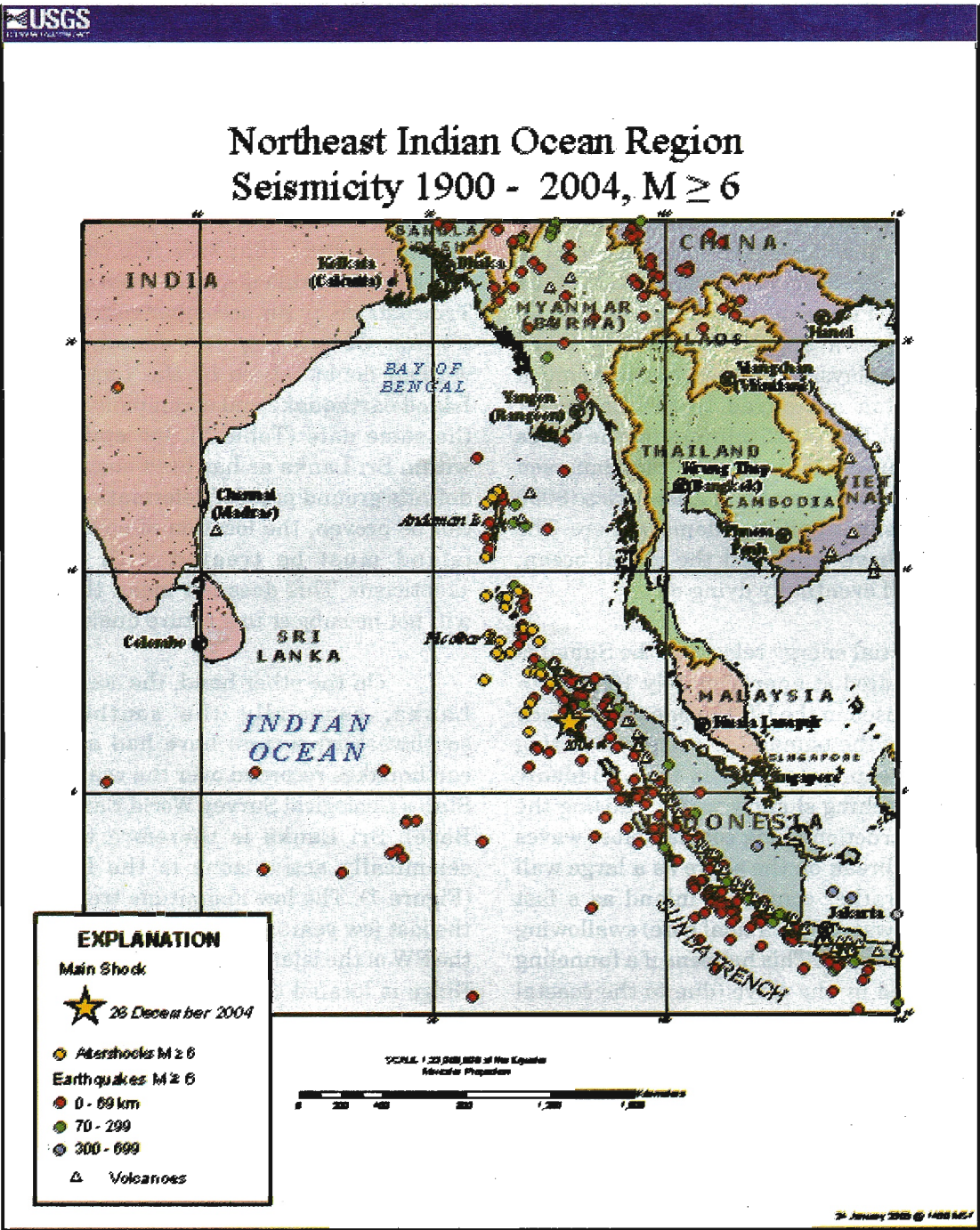


Figure 7: Hundred year-records of large earthquakes in the eastern Indian Ocean. Note the seismicity to the southeast of Sri Lanka.

Source: USGS

The 1500 km of open and Deep Ocean in the Bay of Bengal provided enough fetch for the ocean waves to build up momentum, forming a massive wall of high water on the coastlines. Further, the sea floor topography in the region may have focused the energy of the tsunami

towards Sri Lanka, particularly the Ninety-East Ridge (which parallels the 90° longitude), which may have acted as a reflector to the tsunami waves (Figure 3). The main reason why the east coast was hit so hard is because the 1200 km long failed fault segment along the Sunda Trench is oriented

N-S so that when the tsunami was generated all its energy was directed west, towards the eastern seaboard of Sri Lanka. In contrast, Bangladesh and Myanmar to the north suffered very little damage and loss of life. The extreme southeast of peninsular India escaped due to the "shadow effect" provided by the Sri Lankan landmass. The entire eastern seaboard of Sri Lanka and Tamil Nadu and the seaboard up to Negombo were affected due to the *wrapping-around* effect of the tsunami waves (Figure 6). The shallow Andaman Sea curtailed the wave speeds before they struck Thailand and Malaysia, which experienced much less destruction compared to Sri Lanka or Sumatra. It took just 20-25 minutes for the waves to reach the Sumatran coast! The tsunami even reached the coast of Somalia in East Africa (8000 km away), causing significant damage there. The waves would have traversed the global ocean, dissipating and eventually dying out.

The initial energy release of the Sumatra quake is estimated at approximately 10^{25} ergs (= all the energy used in the USA in one year). Much of the energy of the tsunami is conserved during its travel in deep water and is then suddenly released on reaching shallow water, causing the enormous destruction along coasts. Most waves do not exactly break on the shore as a large wall of water, but rather continues inland as a fast stream of high water (like a tidal bore) swallowing everything in its path. This happens if a funneling effect is created by the wave (due to the coastal geomorphology and bathymetry). Such a situation may have occurred in the Yala sanctuary and in the Mullaitivu area in N-E Sri Lanka, where the sea water column reportedly extended up to several hundred metres inland from the coast. In some areas of Sri Lanka, the walls of water were up to 10 m high when they lashed against the shoreline. Just two or three waves were enough to cause all the devastation. The city of Galle was so badly damaged because it was a deadly combination of bay and headland, with a compound funnel and wrap-around effect of the wave train. Modelling studies should now be able to identify the most potentially vulnerable and high risk areas of our coastline. This should be helpful in giving early warnings to the coastal areas and mitigate the risk factor.

The future potential for tsunami

There is a very long history of seismicity in Sri Lanka. The earliest account goes back to the Portuguese colonial period in 1615, when the island was affected by an earthquake and over 2000 people supposedly lost their lives.⁶ Its' epifocus is unknown. The earthquake of 31st December 1881 that was felt throughout Sri Lanka and caused some coastal damage in Trincomalee by an accompanying 1 m sea wave (*Ceylon Observer of 10th January 1882*), was without doubt caused by the 7.9M Car Nicobar Island earthquake and accompanying tsunami of the same date (Table 1). Its' epifocus was not within Sri Lanka as has been suggested. Unless definite ground proof of deformation and damage can be proven, the location of epifoci within the island must be treated with caution and skepticism. This does not mean that the island will not be subject to a future quake.

On the other hand, the ocean around Sri Lanka, especially the southeastern and southwestern sectors have had a multitude of earthquakes recorded over the years (the United States Geological Survey World Earthquake Data Base). Sri Lanka is therefore well within a seismically active zone in the Indian Ocean (Figure 7). The low magnitude tremors felt over the last few years probably originated offshore to the SW of the island where the Chagos-Laccadive Ridge is located (Figure 3). The equatorial zone of compression that has developed in the SE sector of the seafloor (at the Sumatran end) due to the splitting of the I-A plate into two separate plates, with a new plate boundary forming there, may be a potential new seismic zone in the making.⁴ But this is not an underthrusting situation at a convergent margin with a new trench. However, much of this compression is taken up by the rift and transform faults between the Burma and Sunda Plates, thus decreasing the stresses (Figure 2). Also, the southern part of Sumatra is within the Sunda Plate. In contrast, the western part of this zone (nearest to Sri Lanka) is a divergent margin and is expectedly of low magnitude seismicity. But here we are talking of geologic time scales. This plate margin is an enigma as it is convergent at one end and divergent at the other (a diffused margin) and is at a very early stage in

its evolution.^{7,8} The database does not record a single offshore earthquake in either of these sectors (Figure 7) that is of sufficient magnitude to generate a large tsunami (most experts indicate a >8M event and at a trench boundary). The Sunda Trench continues northwards up to 20°N latitude and will eventually connect with the Himalayan subduction zone (Figure 5). An earthquake in the Arakan coast of Myanmar in 1762 generated a tsunami, but probably did not affect Sri Lanka. As the Sunda Trench changes direction into an E→W orientation as it goes further south towards northern Australia, any tsunami threat to Sri Lanka from this sector of the trench should correspondingly decrease.

Indian Ocean seafloor will continue to be consumed by the Earth's mantle along the Sunda Trench. It will take a very long time to build up sufficient stress in the same region to cause another very high magnitude tsunami generating earthquake. Seismologists can now predict where some earthquakes are likely to occur, but not when exactly. Global stress distribution maps are already available for many plate margins. Subducting plate margins (called active margins) are present only on the eastern Indian Ocean side, where the potential earthquake danger lies. A seismic gap (or locked fault) is a region where large amounts of stress have accumulated over a very long period without causing an earthquake. The Sumatra-Andaman Island segment of the fault was a known seismic gap. Studies of such regions may give a clue as to where the next major earthquake and tsunami is likely to occur. Consequently, the existing seismic gap between the December 2004 and the 1861 earthquakes in Sumatra (i.e. between 2°N and 1°S latitude) could be a potential danger zone in the future for a major earthquake, which may or may not generate a megatsunami*.

The oceanic region between Sri Lanka and East Africa is devoid of such converging plate margins and hence is of low potential for high magnitude earthquakes (Figure 3). There is thus no threat of tsunami from the western Indian Ocean as it is made up mainly of Mid-Ocean Ridges and divergent or separating plate boundaries (called passive margins). The Oman-

Makran trench boundary (Figure 1) is not a threat to Sri Lanka, as any tsunami originating there would be directed towards the mountainous and steep Oman shoreline of the Gulf of Oman and Arabian Sea, which would smother the waves in no time. However, the Pakistan and Indian coasts may be affected by a tsunami as had happened in 1842.

(since this article was submitted in February, the March 2005, 8.7 M quake in fact occurred in this gap, but did not generate tsunami as was explained earlier. This was added in the proof stage).

CONCLUSION

The author is confident that the immediate danger has subsided and our present geological knowledge does not indicate the possibility of another megatsunami for many years to come. This is also the opinion of most seismologists. The prerequisite for a megatsunami is a shallow focus, megathrust seaquake at a convergent plate margin with deepwater energy release. Geologists are not prophets! They can only interpret the data based on current thinking of deep-seated geological processes within the Earth. At the same time, the deep Earth does not reveal its secrets or its intentions so easily. Caution and vigilance is necessary. Once an Early Warning System is in place, our fears and paranoia should be put to rest. However, a false alarm can negate the value of such systems. The historical and statistical record of earthquakes and tsunami in the central Indian Ocean and the current seismicity in the region should be a guide in our future endeavours. Neither earthquakes nor tsunami can be prevented, but mitigation measures can be taken to save lives. The threat from frequent destructive cyclones in the Bay of Bengal is very real and far more imminent.

If anything has come out of this disaster, it is the sad story of disinvestment in science and technology over the years in our country. A vast body of knowledge will become available as a result of this catastrophe. Extreme and costly solutions must be avoided in planning for reconstruction. The potential for good problem oriented scientific research related to the tsunami and its aftermath could be the bonus. Educating

the masses on the repercussions of natural disasters, public awareness programmes and dissemination of knowledge should be a priority (the concept of technology, communications and response). Yet, the management and coordination of this scientific activity may be the real challenge for the educators and scientists.

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