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THE 26 DECEMBER 2004 EARTHQUAKE IN INDONESIA - FUTURE EARTHQUAKES AND TSUNAMIS IN THE SUMATRA-ANDAMAN MEGATHRUST REGION

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Future major earthquakes in the Sumatra-Andaman megathrust region can be expected to generate destructive tsunamis that will result in great losses of life and property in countries bordering the Andaman Sea Basin, Sumatra and the Indian Ocean. Megathrust earthquakes with moment magnitutes of Mw=9 or more, similar to the Mw=9.2+ of 26 December 2004, at convergent tectonic plate boundaries closer to the oceanic trench west of Sumatra, can be expected to generate very destuctive tsunamis, along populated coastal areas of Indonesia, but also to other countries bordering the Indian Ocean. In spite of the better understanding of the risks and of the protective measures that have been implemented since 2004, the destructiveness of future events is expected to be significant in the Andaman Sea basin, coastal areas of Sumatra and countries bordering the Indian Ocean. In order to estimate the recurrence frequency of future tsunami-generating earthquakes in the Sumatra-Andaman megathrust region similar to the 2004 event, the present study examines briefly existing geodynamic processes in the north and west of the Island of Sumatra, as well as past and recent tsunami generating earthquakes in the vicinity of the Andaman Sea Basin, including the Andaman and Nicobar groups of islands. Specifically examined is the Andaman fault system, recently prolonged through the Sumatra zone (the Sumatra fault), which has been reactivated due to the lateral escape of the Sumatra forearc sliver plate, and as a result of the oblique convergence and subduction with the Indo-Australian plate to the south. The present study reviews and analyzes the active mechanisms for different tectonic zones in this Sumatra-Andaman megathrust region, and provides an assessment of the potential for future destructive tsunamis, based mainly on the recent historic record, on active tectonic forces, and on evaluation of recurrence frequency.

Keywords: *tsunami; Sumatra-Andaman megathrust, tsunami vulnerability of India, Indonesia, Thailand, Bangladesh, Pakistan; historical tsunami records, Indian Ocean.*

1. INTRODUCTION

As in the past, tectonic subduction and thrust faulting along the Sumatra-Andaman megathrust region can be expected to generate large magnitude destructive earthquakes and tsunamis in the future, similar to the 26 December 2004 which had an estimated moment magnitude of Mw=9.1 later revised to Mw=9.3. With this revision this became the second largest earthquake in recent history after the Mw=9.2 Prince William Sound, Alaska earthquake of 28 March 1964, and the Mw=9.5 Valdivia, Chile of 22 May 1960. Although relatively infrequent, future Sumatra-Andaman megathrust earthquakes will result in great losses of life and property in countries bordering the Andaman Sea Basin, the Andaman and Nicobar groups of islands, eastern Sumatra and other countries in the Indian Ocean. The present paper reviews thoroughly the 26 December 2004 earthquake and tsunami, and estimates the reccurrence of a similar disaster in the future. Such a future event is expected because the Sumatra-Andaman megathrust region is a portion of the collision zone of subduction megathrust plate boundary. The Sunda-Java trench further southeast, also accommodates the convergence between the Indo-Australia and Sunda plates and is expected to generate large earthquakes and volcanic activity in the future. This convergence is responsible for the intense seismicity in both Sumatra and Java and further east on the great Sunda tectonic arc.

The present study presents a brief overview of historical earthquakes and tsunamis in the Andaman Sea, including the Andaman and Nicobar group of islands, all comprising the Sumatra-Andaman megathrust. Furthermore, the study analyzes the active mechanisms of the different tectonic zones in this region, and particularly provides a detailed account of the impact of the 26 December 2004 tsunami in regions bordering the Indian Ocean, as well an assessment of the potential for future destructive events, based mainly on the historic record, on active tectonic forces.

Specifically examined in this review is the Andaman fault system, recently prolonged through the Sumatra zone (the Sumatra fault), which has been reactivated due to the lateral escape of the Sumatra forearc sliver plate, and as a result of the oblique convergence and subduction with the Indo-Australian plate. Thus, the present study reviews and analyzes the active mechanisms for different tectonic zones in the Sumatra megathrust region, which includes earthquakes and tsunamis in the vicinity of the Andaman Sea Basin, and the islands of the Andaman and Nicobar group. Additionally provided is an assessment of the potential future destructive tsunamis in the Sumatra-Andaman megathrust region, based mainly on the recent historic record, on active tectonic forces, and on evaluation of recurrence frequencies as estimated, based on older and more recent studies (Berninghausen, 1966; Pararas-Carayannis, 1978, 2000, 2001a,b, c, 2003, 2005a,b, c, d, 2006a,b, 2007a,b; Bilham, EtAl. 2005; Ishii EtAl 2005, 2007; Krüger & Ohrnberger 2005; Rastogi & Jaiswal, 2006; Hutchings & Mooney 2021).

Finally included are brief descriptions of recent historical destructive tsunamis, and of expected future events. Subsequent studies will examine future potential tsunami generation in other Indian Ocean regions in the Inland Red Sea, the Arabian Sea, the Java Sea, the Persian Gulf, the Sea of Zanj, the Java Sea, the Bali Sea, the Flores Sea, the Timor Sea, the Celebes Sea, the Sea of Arafora, the Makassar Strait between Borneo and Sumatra, and the Malacca Straight between Malaysia and Sumatra.

2. MAIN SOURCES OF TSUNAMIGENIC EARTHQUAKES IN THE SUMATRA – ANDAMAN MEGATHRUST REGION

Complex on-going seismotectonic processes in the Indian Ocean are mainly the direct result of the Indian and Australian blocks moving northward at a rate ranging from 59 to 68 mm/year as shown in Fig. 1, and colliding with the Eurasian continent. There are several regions where large earthquakes have occurred in the past and destructive tsunamis were generated. The same regions can be expected to generate destructive tsunamis in the future that will adversely impact countries bordering the Indian Ocean. As stated in previous publications the main regions that are identified as more critical for future tsunami generation are: 1) The Andaman Sea Basin, 2) The Northern and Eastern Segments of the Great Sunda Tectonic Arc, 3) The Makran Subduction Zone in the Northern Arabian Sea, 4) The Karachi and deltaic Indus region and the Owens Fault Zone, 5) The Kutch Grabben region, and 6) The Chagos Archipelago.

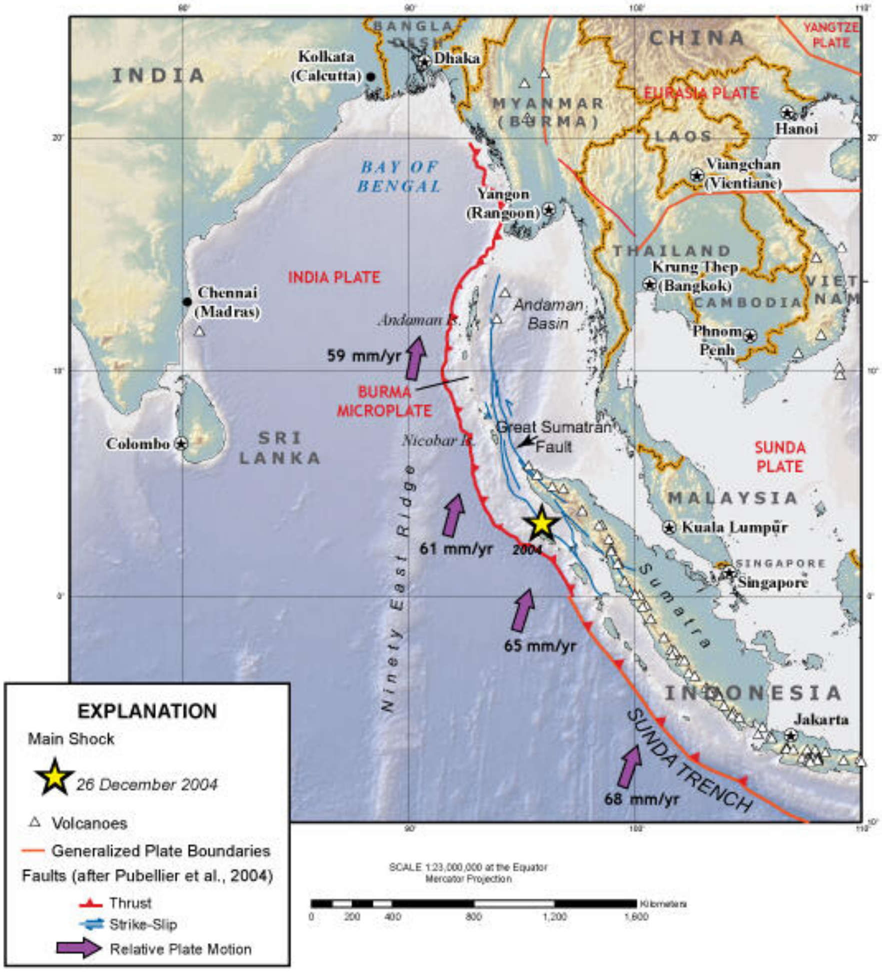

Fig. 1. Tectonic base map of the Sumatra subduction zone showing major faults and relative motion between the India and Sunda plates. Star marks the location of the main shock of the December 26, 2004 earthquake (USGS map).

Fig. 2 portrays an expanded view of the December 26, 2004 earthquake's tsunami generating area and its orientation paralleling the Sunda Trench along Northern Sumatra.

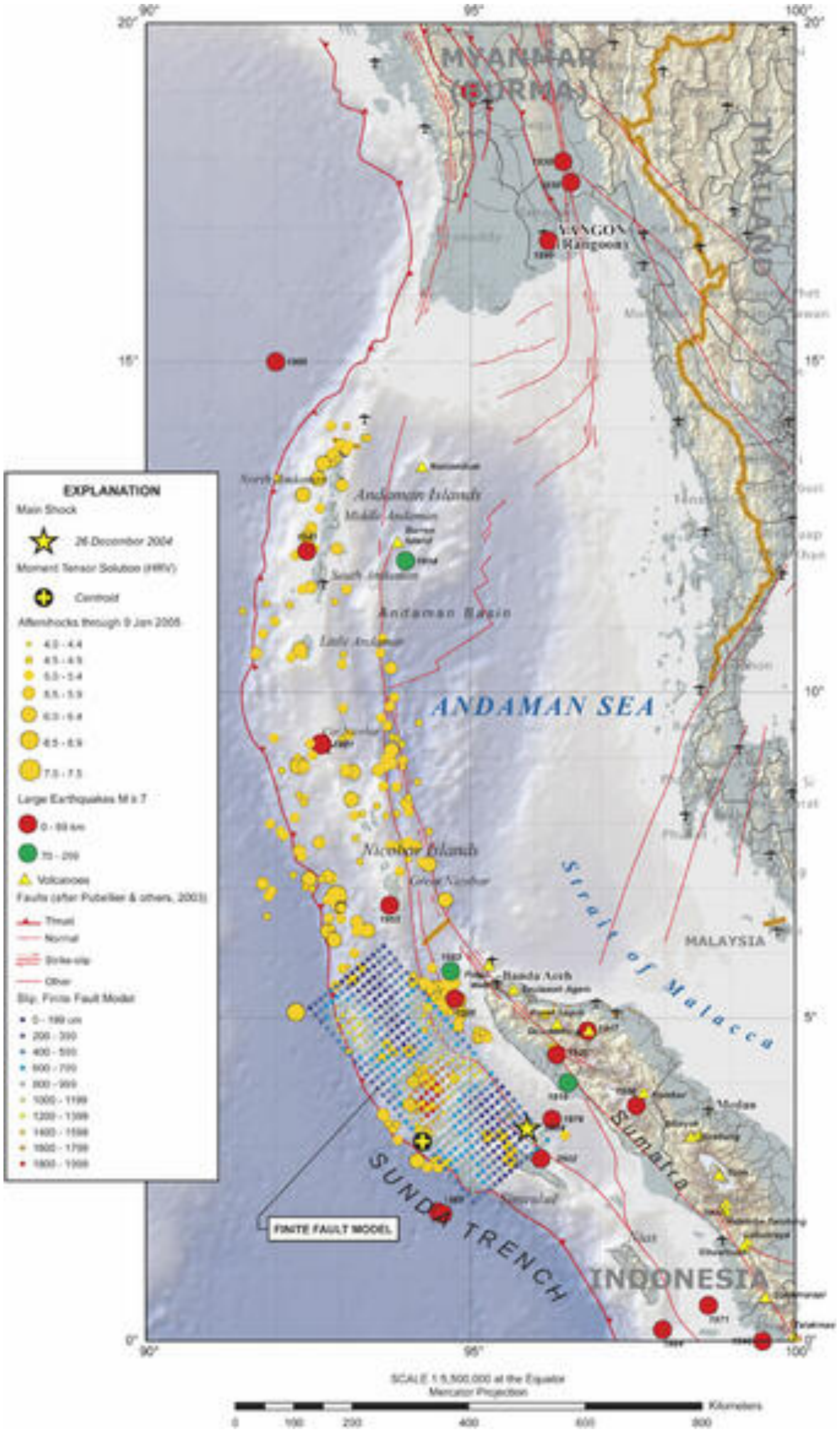

Fig. 2 Base map of the Sumatra subduction zone showing seismicity associated with the 2004 Sumatra-Andaman earthquake. (Figure based on info from the USGS Earthquake Hazards Program)

Fig. 3 is another illustration showing the local tsunami intensity and magnitudes of large earthquakes such as the 1994 and 2006 Java events, of the 2005 and 2007 Sumatra events, of the 1964 Alaska and 2004 Sumatra events, and of the 1960 Chile event. As shown the 2004 Sumatra earthquake had a moment magnitude of Mw=9.1, and a local tsunami intensity very close to that of the 1964 great Alaska earthquake (Pararas-Carayannis, 1967), both being even greater than that of the 1960 tsunami in Chile - the latter however being the strongest recorded earthquake which had a moment magnitude slightly greater than Mw=9.5.

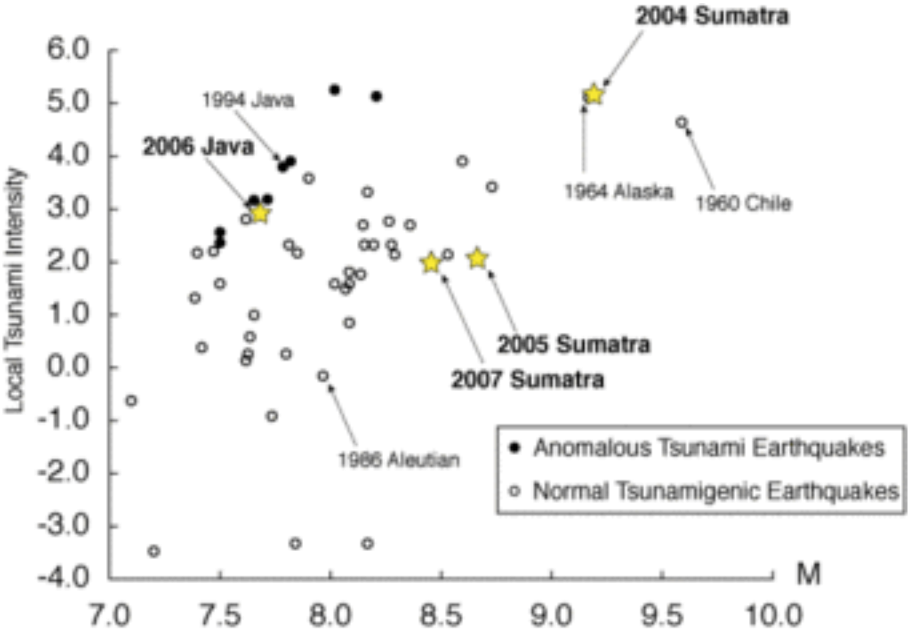

Fig. 3 Earthquake magnitude versus local tsunami intensity for subduction zone earthquakes from 1896-2005(Public Domain. Visit Media to see details)

The second largest earthquake of the 20th Century, and the largest ever recorded in the northern hemisphere, occurred in Alaska on 27 March 1964 (3/27/64, 05:36:14.0 p.m., local time; 3/28/64 03:36:14.0 GMT). This earthquake had a moment magnitude Mw=9.2 and caused extensive damage in Alaska. Local tsunami waves triggered by this earthquake were destructive in Prince William Sound, Valdez Bay, other areas of Alaska in the eastern Aleutian Islands, in Western Canada, Oregon, California and the Hawaiian islands January 2005 (Pararas-Carayannis G, 1967).

The present study reviews only the seismicity of the Sumatra-Andaman megathrust region, and the potential for future tsunami generation in this region of the Great Sunda Arc. Subsequent studies will address individualy the potential of other regions of the Indian Ocean, such as the Makran Subduction Zone in the Northern Arabian Sea, the Karachi and deltaic Indus region and the Owens Fault Zone, the Kutch Grabben region, and the Chagos Archipelago. The next section outlines briefly the 26 December 2004 Sumatra-Andaman earthquake and the tsunami that was generated.

3. THE GREAT EARTHQUAKE OF 26 DECEMBER 2004 ON THE SUMATRA-ANDAMAN MEGATHRUST

On Sunday, 26 December 2004, the greatest earthquake in 40 years occurred about 150 kilometers off the west coast of northern Sumatra Island in Indonesia. The earthquake generated a disastrous tsunami that caused destruction in 11 countries bordering the Indian Ocean. This great tsunamigenic earthquake occurred on Sunday, 26 December 2004, at 00:58:50 UTC (6:58:50 a.m. local time). The epicenter was at 3.298 N, 95.779 E and its focal depth was very shallow (much less than 33 km - possibly about 10km).The quake was widely felt in Sumatra, the Nicobar and Andaman Islands, Malaysia, Myanmar, Singapore, Thailand, Bangladesh and India.

According to the U.S. Geological Survey (USGS NEIC (WDCS-D)), the moment magnitude of the earthquake was Mw=9.1. Such magnitude would make this earthquake to be the third largest in the world in the twentieth century. However, on the basis of subsequent analysis of additional seismograms from around the world, scientists at Northwestern University determined the earthquake's magnitude to be Mw=9.3 and not 9.0 or 9.1, as originally estimated. Therefore, the calculated energy release was 1.13 X 10 (raised to the 30 power) dynes-cm, or three times larger than originally thought. The revised estimate makes this earthquake to be the second largest ever instrumentally recorded. The largest earthquake ever recorded, which measured 9.5, was in Chile on May 22, 1960.

The region where the great earthquake occurred on 26 December 2004, marks the seismic boundary formed by the movement of the Indo-Australian plate as it collides with the Burma subplate, which is part of the Eurasian plate. However, the Indo-Australian tectonic plate may not be as coherent as previously believed. According to recent studies reported in the Earth and Planetary Science Letters (vol 133), it apears that the two plates have separated many million years ago and that the Australian plate is rotating in a counterclockwise direction, putting stress in the southern segment of the India plate.

For millions of years the India tectonic plate has drifted and moved in a north/northeast direction, colliding with the Eurasian tectonic plate and forming the Himalayan mountains. As a result of such migration and collision with both the Eurasian and the Australian tectonic plates, the Indian plate's eastern boundary is a diffuse zone of seismicity and deformation, characterized by extensive faulting and numerous large earthquakes. See USGS graphic Fig. 4 below showing the migration of the Indian tectonic plate, and Fig. 5 showing the seismicity of Southern Asia.

Previous major earthquakes have occurred further north, in the Andaman Sea and further South along the Sumatra, Java and Sunda sections of one of the earth's greatest fault zones, a subduction zone known as the Sunda Trench. This great trench extends for about 3,400 miles (5,500 kms) from Myanmar (Burma) south past Sumatra and Java and east toward Australia and the Lesser Sunda Islands, ending up near Timor. Slippage and plate subduction make this region highly seismic. The volcanoes of Krakatau, Tambora and Toba, well known for their violent eruptions, are byproducts of such tectonic interactions.

The epicenter of the 26 December 2004 earthquake was near the triple point junction of three tectonic plates where major earthquakes and tsunamis have occurred in the past.

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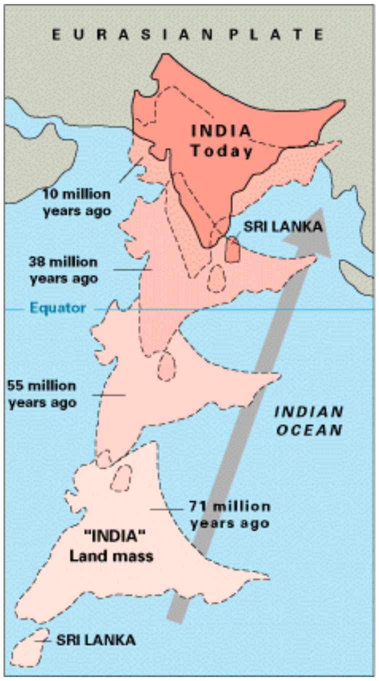

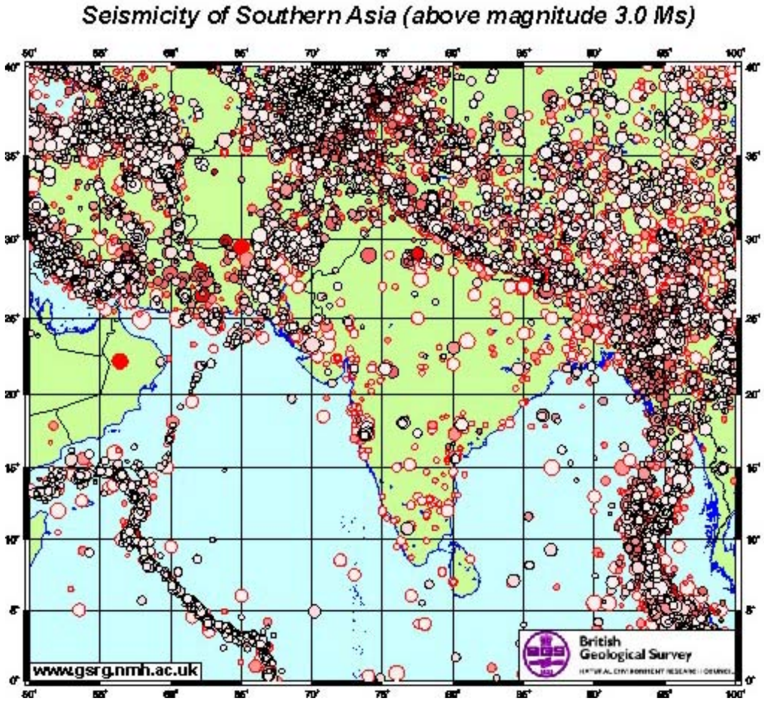

Fig. 4 Northward movement of India *Fig. 5 Seismicity of Southern Asia*

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In addition to the Sunda Trench, the Sumatra fault is responsible for seismic activity on the Island of Sumatra. This is a strike-slip type of fault which extends along the entire length of the island. The Burma plate encompasses the northwest portion of the island of Sumatra as well as the Andaman and the Nicobar Islands, which separate the Andaman Sea from the Indian Ocean. Further to the east, a divergent boundary separates the Burma plate from the Sunda plate. More specifically, in the region off the west coast of northern Sumatra, the India plate is moving in a northeastward direction at about 5 to 5.5 cm per year relative to the Burma plate.

The 26 December 2004 earthquake was followed by numerous strong aftershocks. As of 1 January, 2005, there were about 84 aftershocks with magnitudes ranging from 5.0 to 7.0 in the region of Northern Sumatra and the Nicobar and Andaman Islands. Twenty six (26) of these - including the largest- occurred on 26 December 2004, the same day as the main earthquake. Since 1 January 2005, many more aftershocks have followed continued for several weeks and months. Some of the major aftershocks occurred in the vicinity of the epicenter of a past earthquake which had occurred on 26 June 1941 and some in the area near the Nicobar Islands where the 1881 earthquake had occurred. The distribution of afteshocls suggests that the earthquake resulted by the sudden slip of these two plates and that there was a slip as well as an upward thrust of the Burma plate along this boundary.

3.1 Chronological Sequence of Major Aftershocks Along the West Coast of Northern Sumatra and in the Nicobar and Andaman Island Region Following the Major Earthquake of 26 December 2004

The distribution of the larger aftershocks indicated that the two tectonic plates (the India plate and the Burma subplate) slipped for about 1,200 km along their boundary. The aftershocks extended from northern Sumatra (approximately 3 degrees North Latitude) to the Andaman Islands (approximately 14 degrees North). Therefore, the length of the overall rupture is estimated to be about 1,200 km. However, the slippage does not appear to have been continuous. It appears that it occurred in two phases along two sections of the great fault that parallels the Sunda Trench. The rupture started near the epicenter off the western coast of North Sumatra and progressed - at a fast rate - northward to the Andaman islands along a preexisting major fault. For the first 500-600 km the orientation of the rupture (the quake's strike) was appoximately 320-330 degrees. Subsequently the rupture continued - at a much slower rate in an approximate North-South direction - for another 500-600 km along another segment of the northern Sunda fault system. This is probably the same segment that ruptured during the 1941 Andaman Islands earthquake - which also generated a destructive tsunami.

It has been estimated that this megathrust faulting along the India and Burma boundary has resulted in a shift that averaged about 15 meters with maximum slip being 20 meters. The vertical upward movement of the sea floor may have been several meters - possibly as much as 5 meters or more in some places. At some of the islands there may have been subsidence while at others there was upthrusting.

3.2 The Great Tsunami of 26 December 2004 in the Indian Ocean

The great earthquake of December 26, 2004 was extremely damaging and resulted in many deaths. However, most of the destruction and deaths were caused by the catastrophic tsunami waves it generated. Massive tsunami waves wiped out entire coastal areas across southeastern Asia, Sri Lanka, India, Thailand, Myanmar and islands in the Andaman Sea and the Maldives in the Indian Ocean.

The tsunami waves caused considerable destruction and killed people more than 2,000 kilometers away, in the Seychelles and in Somalia. As of February 10, 2005, the global death toll was raised to 226,566 and continued to rise. The demographics in this part of the world are not very good, so the final number of deaths cannot be established with certainty.. There are many remote islands in the Nicobar, Andaman, Maldives and off the African coasts, so there were many unreported deaths.

In total, the large tsunami struck 11 of the nations that border the Indian Ocean, and it was a complete surprise for the people living there, but not for the scientists who are aware of the tectonic interactions in the region. Many seismic networks recorded the massive earthquake, but there was no tide gauges or other wave sensors to provide confirmation as to whether a tsunami had been generated. There was no established communications network or organizational infastructure to pass a warning of any kind to the people coastlines. At the time, there was no Tsunami Warning System for the Indian Ocean as there was for the Pacific. The Pacific Tsunami Warning Center in Honolulu had no way of providing warning information to the region. Part of the problem was that most of the countries in the region had underestimated their potential tsunami threat from the Northern end of the Sunda Trench. Review of historical records would have revealed that a very destructive tsunami occurred in 1941, in the same general area. This particular tsunami killed more than 5,000 people on the eastern coast of India, but it was mistaken for a "storm surge". Thousands more must have gotten killed elsewhere in the islands of the Bay of Bengal in 1941, but there has been no sufficient documentation. Unfortunately, no Regional Tsunami Warning System, Preparedness Program, or effective Communications Plan existed at that time for this part of the world.

3.3 Tsunami Generating Area of the 2004 Earthquake on the Sumatra-Andaman megathrust

Based on the plate tectonics of the convergence zone that has formed the SundaTrench and on the earthquake’s aftershock distribution, the tsunami generating area is believed to be a somewhat irregular, broken up ellipsoid which changes from a Northwest-Southeast orientation of about 330 degrees in the lower section to an almost North - South 360 degrees orientation in the upper section.

The major axis of this ellipsoid is estimated to be approximately 1,200 km and its minor axis to be about 180 km. It is believed that this ellipsoid type of block movement occurred along an oblique but very shallow subduction angle, and that the Burma subplate was thrusted upward by several meters (by as much as 5 meters in some places) with an oblique lateral movement of as much as 15 meters and possibly as much as 20 meters along the southern tsunami generating region. Also, the earthquake's relatively slow slippage along the 1,200 kms long rupture added additional energy to tsunami generation.

A preliminary estimate of the Tsunami Generating Area in Fig. 6 is a modified USGS map showing the earthquake epicenter, the distribution of initial major afteshocks, and the interaction of major tectonic plates along the Sunda Trench. A personal communication received by the author in early 2005 from Indonesia indicated that at Simeulue, an island close to the epicenter off the coast of Northern Sumatra, there was only vertical displacement but no tsunami. Surprisingly, residents of beach communities claimed that no tsunami waves were observed, no deaths from the tsunami were reported, but that the island rose and was now several kilometers longer. No information was provided on how much the island rose, but preliminary data indicated that it may have been as much as 5 meters.

The reason that the tsunami did not cause deaths and destruction on Simeulu Island is because the amount of crustal uplift was greater than the height of the waves. Additional eyewitness accounts or observations helped clarify that this was indeed was the case. A preliminary estimate was that the tsunami generating area involved about 280-300,000 square kilometers of the ocean floor. This estimate was verified as more data on aftershock distribution became available and when tsunami travel times to operating tide gauge stations in the Bay of Bengal were obtained. Also, based on reports of subsequent field surveys and subsequently collected data, helped determine the net underea crustal displacements on the islands off Sumatra and in the Nicobar and Andaman Islands, and a more accurate determination of the catastrophic tsunami generation of the 26 December 2004 earthquake.

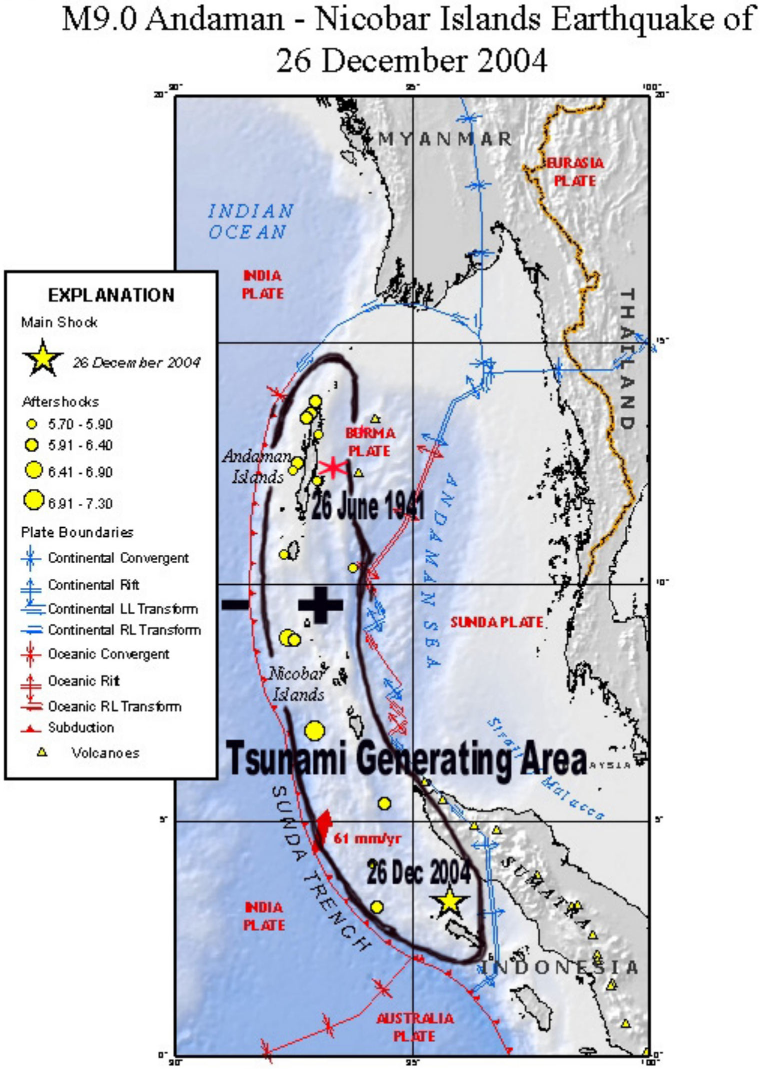

Fig. 6 Generating area of the 26 December 2004 Tsunami

These results have implications as to why Sri Lanka to the West of the tsunami generation area, suffered such a great impact, destruction and loss of lives.

3.4 THE TSUNAMI OF 26 DECEMBER 2004

3.4.1 Evaluation of Tsunami Reccurrence in the Region

Indonesia is surrounded by four major tectonic plates, the Pacific, the Eurasian, the Australian and the Philippine plates. All these major tectonic plates and their subplates are presently active. Major earthquakes and tsunamis can be expected in the semi-enclosed seas and along the Indian Ocean side of Indonesia. Major earthquakes in the semi-enclosed seas can generate destructive local tsunamis in the Sulu, Banda and Java Seas. Major earthquakes along the Sunda Trench can generate tsunamis that can be destructive not only in Indonesia but to other countries bordering the Indian Ocean.

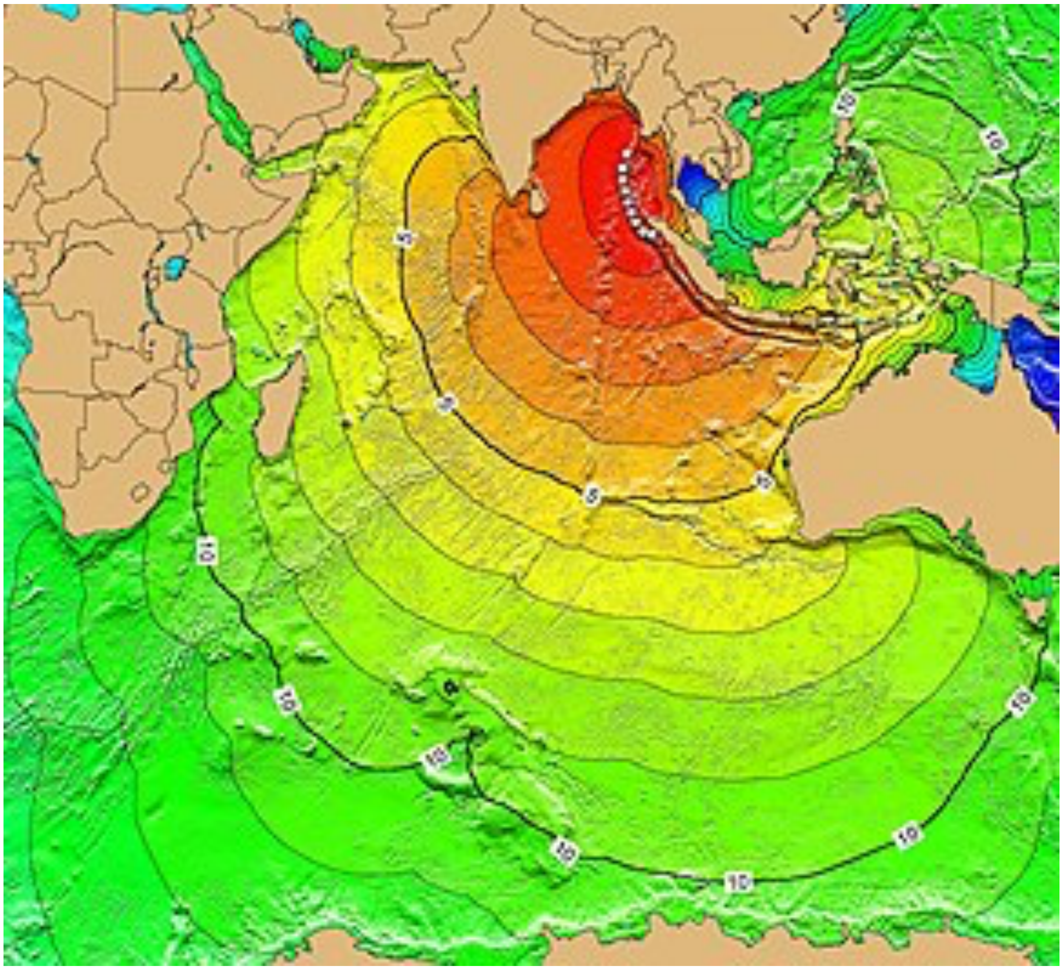

Fig. 7 Wave Refraction Map and Travel Times of the 2004 Tsunami in the Indian Ocean (Wikipedia)

In the immediate vicinity off Northern Sumatra, most of the stress and energy that had accumulated were released by the crustal movement that caused the 26 December 2004 earthquake. The subduction of the India tectonic plate underneath the Burma plate caused upward thrusting of an extensive block and generated the destructive tsunami. There was significant slip and rupture for about 600 km and possibly a less significant slip for another 400 km along the Nicobar and Andaman Islands (see Fig 8). Thus, it is unlikely that another major earthquake will occur in the immediate region off Northern Sumatra for a while, but stress has started building up again. Also, it is quite possible that not all of the energy was released in the Nicobar and Andaman section of the Sunda Trench by the 26 December 2004 earthquake - in which case the next major earthquake could occur there sooner than one closer to Northern Sumatra.

Fig. 8 Map of the Nicobar and Andaman Islands

Although the danger of another major tsunami has passed trmporarily in the region small local tsunamis could possibly be generated by smaller magnitude earthquakes. Aftershocks from such events can be expected to last for months in the region, but they would diminish in strength with the passage of time. Most of the aftershocks from subsequent to the 2004 earthquakes will result from the continuous gravitational adjustments of the crustal material that was moved during major earthquakes and the continuing stress to the North. Such aftershocks represent nature's way of restoring stability and temporary equlibrium. It is unlikely that a destructive tsunami will occur again soon in the same region, however caution is advised for the coastal residents in Northern Sumatra and in the Nicobar and Andaman islands. In fact, strong shaking of the ground in an earthquake is nature's warning that a tsunami may be imminent.

Furthermore - and though stress in the region off Northern Sumatra has been released by the 26 December 2004 earthquake, this does not necessarily mean that another earthquake further north or further south cannot occur. In the North, a repeat of the 1881 Nicobar Islands or of the 1941 Andaman Islands earthquakes and tsunamis can be expected in the future - although it is difficult to say how soon (see Fig. 9 below). Such events seem to occur on the average of every 50 years so a strong, destructive earthquake is long overdue.

Further to the South, the movement of the tectonic plates added stress along other tectonic boundaries. A repeat of earthquakes and tsunamis along the Sunda Trench off the central region of Western Sumatra, as in 1833 (magnitude 8.7) and 1861, is very possible in the future (see Fig. 9). Such earthquakes and tsunamis can be expected every hundred years or so. In fact, the 26 December 2004 earthquake occurred along the section that did not rupture during the 1861 earthquake. It took approximately 144 years to occur. However, this does not mean that it will take that long for the next destructive tsunami to occur again off central or northern Sumatra. Destructive tsunamis are possible in the next 20 years or less. A repeat of the 1833 earthquake could generate a devastating tsunami. This section of the Sunda megathrust is one of the more likely sources of a destructive tsunamis in the region.

Malaysia - Despite Malaysia's proximity to the tsunami generating area, the impact of tsunami was not as severe as in other countries in the region or countries thousands of kilometers away. Malaysia was partly sheltered by Sumatra and the tsunami waves attenuated somewhat in the Straits of Malacca. However, there were numerous deaths and destruction reported. The country's worst affected areas were the northern coastal areas and the outlying islands. Hardest hit were Penang, Kedah, Perak, Selangor and Langkawi. It was reported that the red flag warning system used by lifeguards on beaches in some resort areas in Penang helped reduce fatalities there. Houses in fishing villages along coastal areas were damaged in Batu Maung and Bayan Lepas in Penang. Coastal areas in Peninsular Malaysia and 13 villages in Kuala Muda, Kedah and Kuala Triang in Langkawi Island were also affected. About a quarter of the boats anchored in Rebak and Telaga harbour in Langkawi were damaged. The number of deaths was reported as 67 or 68 with 52 in Penang, 10 in Kedah, 3 in Perak and 1 in Selangor. Another 6 were missing and presumed to be dead.

Myanmar - The mainland of Myanmar was somewhat sheltered from the full impact of the tsunami by the numerous offshore islands. Also the approximate North-South orientation of the tsunami generating area resulted in waves of lesser amplitude traveling northward. Still the tsunami caused numerous deaths and destruction in Myanmar. Reportedly 90 people were killed, but eyewitnesses estimated that more than 600 people died. 788 buildings were reported as damaged or destroyed, and 30,000 people were displaced.

Andaman and Nicobar Islands – The 2004 tsunami hit hard the Andaman and Nicobar group, which comprises of a total of 572 islands of which 38 were significantly inhabited.

The waves literally washed away some of these islands, and there were reports that the island of Trinket had split in two. The Great Nicobar and Car Nicobar were the worst hit among all the southern Nicobar Islands because of their proximity to the earthquake's epicenter and relative low topography. The maximum tsunami wave reached a height of 15 meters. According to reports one fifth of the population of the Nicobar Islands were killed, injured or missing. Chowra Island lost two thirds of its population of 1,500. The official death toll was 812, but about 7,000 were reported as missing. However the unofficial death toll (including those missing and presumed dead) is estimated to have been about 7,000 or greater. Previous major tsunamigenic earthquakes in 1881 and 1941 impacted severely both the Andaman and the Nicobar group of islands (Fig. 9). On 30 December 2004, four days after the great 2004 earthquake, the Barren volcano on Barren Island - located 135 kilometers (80 miles) northeast of the capital Port Blair - erupted.

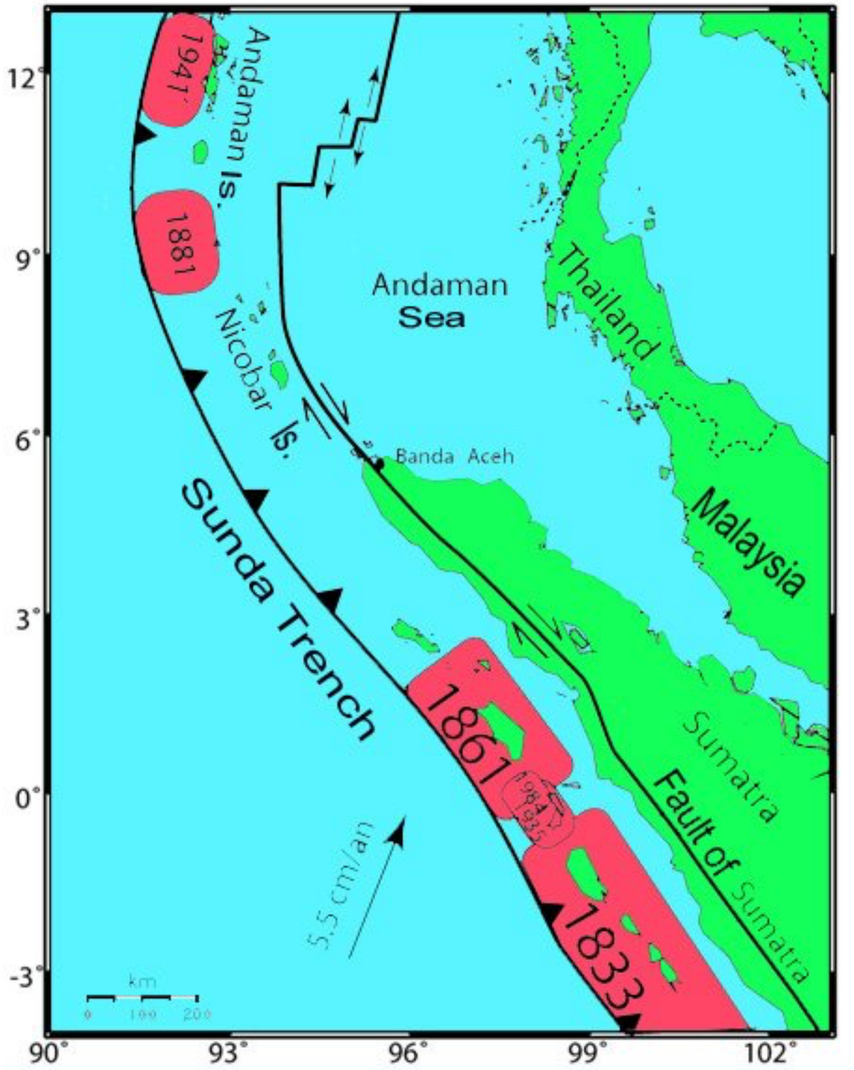

Fig. 9 Historical Earthquakes and Tsunami Generation areas of the 1941 and 1881 and of the 1861 and 1833 Earthquakes

Other seismic regions further South and East of Sumatra have the potential of generating destructive tsunamis even sooner. As in 1977, a major tsunami could be generated in the eastern section of the Sunda Trench that would affect not only Indonesia, but the northern and northwestern coasts of Australia.

Also impacted greatly by the 2004 tsunami was the Peninsula of Acep Meulaboh in Northern Sumatra - one of the hardest hit by the tsunami areas (Fig. 10).

Fig. 10 Peninsula of Acep Meulaboh in Northern Sumatra - one of the hardest hit by the tsunami areas.

3.4.2 Effects of the 26 December 2004 Tsunami in the Bay of Bengal and in the Indian Ocean

Waves of up to 10.5 meters in height struck Northern Sumatra, the Nicobar and Andaman Islands, Thailand, Sri Lanka, India. Destructive waves also struck the Maldives, Somalia, Kenya and the islands off the African coast. The tsunami was recorded by tide gauge stations not only in the Indian Ocean, but in the Pacific as well. In Manzanillo, Mexico, the tide gauge recorded a wave of 2.6 meters.

Eighteen (18) countries bordering the Indian Ocean were affected by the 2004 tsunami. These were: Indonesia, Thailand, India, Sri-Lanka, Malaysia, Myanmar, Bangladesh, Maldives, Reunion Island (French), Seychelles, Madagascar, Mauritius, Somalia, Tanzania, Kenya, Oman, South Africa and Australia.

Death Toll - The 2004 tsunami had its greatest impact and casualties in Indonesia, Thailand, India, Shri-Lanka, Malaysia, Myanmar, Maldives and Somalia. Eleven (11) countries reported deaths, some in tens of thousands.The reported death toll has been as 226,566. However, this is an underestimate as thousands more were reported as missing and many more may have been killed in remote islands. More than 1.5 million people were left homeless around the region.

The following is a brief summary compiled from numerous government, U.N., and media sources:

INDONESIA - Tsunami waves of the 2004 tsunami up to ten meters swamped the smaller outlying islands of Sumatra as well as its northern and western coastal areas - about 100 km (60 mi) from the earthquake epicenter. Hardesh hit was the northern Aceh province. Nearly all the casualties and damage took place within this province. Very heavy damage occurred as far South as Tapatkuan. The waves also propagated around the northern tip of Sumatra into the Straits of Malacca and struck coastal settlements along the northeast coast as far east as Lhokseumawe.

According to official reports (Ministry of Health) 166,320 people were killed, 127,774 were missing and 655,000 people were displaced in Northern Sumatra. A total of 110 bridges were destroyed, 5 seaports and 2 airports sustained considerable damage, and 82% of all roads were severely damaged. However the death toll was probably much higher. The following is a summary of the 2004 tsunami impact in Northern Sumatra:

Banda Aceh - The tsunami waves completely destroyed the city of Banda Aceh's infrastructure and killed thousands of its inhabitants. Banda Aceh is the capital of the Aceh province. in Northern Sumatra. Fig. 11 is a satellite image of Banda Aceh peninsula taken on 2 Jan 2005.

Fig. 11 Another Satellite image of Banda Aceh taken on 2 Jan 2005

Leupung - The tsunami completely obliterated Leupung, a town in the district (Kabupaten/Kota) of Aceh Besar, close to the city of Banda Aceh. Most of the town's 10,000 inhabitants perished. It is estimated that only two to seven hundred people survived.

Gleebruk - The waves completely destroyed Gleebruk, a village in the district (Kabupaten/Kota) of Aceh Besar just to the southwest of Banda Aceh.

Teunom - The tsunami hit hard Teunom, a town of 18,000 people in the Aceh Barat (West Aceh) district of the Province of Aceh. According to official estimates about 8,000 people lost their lives.

Calang - The waves completely devastated Calang, the capital of the district. Only about 30 per cent of the town's population survived. Prior to the tsunami the town's population was estimated to be between 9,000 and 12,000.

Meulaboh - A series of seven waves killed about 40,000 people and destroyed port facilities and most parts of Meulaboh, a town with a population of 120,000. About 50,000 people were left homeless.

Simeulue Island - Tsunami waves of about 5 meters in height struck the island. Although Simeulue was close to the earthquake's epicenter, suprisingly none of the island's 70,000 inhabitants were killed by the waves. Only five people died as a result of the earthquake which destroyed about 90% of all buildings along the coast. Apparently, the island rose which accounts for the lower wave heights that were observed. Also, villagers on the island had an awareness of the dangers of tsunamis, emphasized by traditions memoralizing a destructive tsunami in 1907 that had killed thousands of people.

Nias Island - The island was severely impacted by the tunami which killed many people and severely damaged all existing infrastructure. Original official accounts gave the number of dead at 122, but these appear to be underestimates. According to unconfirmed sources the waves killed 600 people and the final death toll may ecxeed 1,000.

THAILAND – The tsunami struck six provinces in West Thailand causing great damage and deaths. Figure 12 is a map of Thailand, showing in red the areas and coastal areas that which were impacted. The first of the tsunami waves reached the resort of Phi Phi island. The arrival of the tsunami was heralded by a recession of the water, which exposed the sea bottom for considerable distance, including previously submerged rocks. According to eyewitness reports, the first wave arrived at about 10:30 am local time and it was about 4 meters high. The second wave arrived about 2.5 minutes later and it was 7 meters. The third wave was about 11 meters. The waves destroyed all beachfront hotels, bungalows and other structures at Phi Phi, hurling boats and other floating objects. All electricity and phone lines were cut. The highest reported wave was 11.6 meters at Khao-Lak beach (Fig. 14). Thai Government sources initially reported 5,313 deaths, 8,457 injuries and 4,499 missing, including more than 1,000 foreign tourists. Many of the missing were presumed to have died. Most probably the death toll was higher than what it was initially reported. Fig. 13 is a photo of tsunami destruction at Thailand's Khao Lak Beach.

Fig. 12 Inundation of the 2004 tsunami in Thailand

Fig. 13 Tsunami destruction at Thailand's Khao Lak Beach

INDIA

The estimated number of casualties in India was reported at 16,000, with at least 6,000 more as missing. Then death toll was probably underestimated. Along India's southeastern coast, several villages were swept away, and thousands of fishermen at sea were missing. On the western coast of India' mainland, hardest hit was the state of Tamil Nadu. Many tourist hotels in India had to be evacuated. The following is a brief description of some of the 2004 tsunami impact on coastal regions of India.

Andhra Pradesh - There was significant loss of life and destruction. The affected districts were Krishna, Prakasam, Nellore, Guntur, West Godavari and East Godavari.

Kerala - The tsunami killed many people (official toll 168) and caused extensive destruction particularly at Kollam (131 dead), Alappuzha (32) and Ernakulam (5) were also affected.

Pondicherry - In the Union territory of Pondicherry, the affected districts were Pondicherry (107 dead), Karaikal (453 dead). The latest official toll was 560. An estimated 30,000 people were rendered homeless.

Tamil Nadu - The tsunami had a great impact on the state of Tamil Nadu on India's mainland with entire coastal villages destroyed. According to official reports the overall death toll in the state was 7,793. The Nagapattinam district had 5,525 casualties. The latest reported death toll at Velankanni was 1,500. Kanyakumari district has had 808 deaths, Cuddalore district 599, the state capital Chennai 206 and Kancheepuram district 124. The death tolls in other districts were Pudukkottai (15), Ramanathapuram (6), Tirunelveli (4), Thoothukudi (3), Tiruvallur (28), Thanjavur (22), Tiruvarur (10) and Viluppuram (47). The death toll may be significantly higher as many are still missing. The nuclear power plant at Kalpakkam was shut down after seawater rushed into a pump station. No radiation leak or damage to the reactor was reported.

SRI-LANKA

The first of the tsunami waves took a little over two hours to reach Sri-Lanka. A clock on the western side of Sri Lanka at Colombo stopped at 9:20 in the morning, so the tsunami travel time to Colombo (first wave) must have been about 2 hours and 20 minutes. Sri-Lanka's south and east coasts were hardest hit. More than 50,000 people lost their lives - mostly children and the elderly. Most of them (more than 1,200) were in the eastern district of Batticaloa.

At Trincomalee in the northeast, the tsunami reached more than 2 km (1.25 mi) inland killing about 800 people. In the neighboring Amparai district alone, more than 5,000 people died. The naval base at Trincomalee was reported to be submerged. About 3,000 more people died in Mullaitivu and Vadamaradchi East. A train, known as the "Sea Queen", while traveling between Colombo and Galle, with 1,600 passengers on board, was struck and derailed by the tsunami. Only about 300 of the passengers survived. More than one and a half million people were displaced in Shri-Lanka and the death toll is expected to rise.

MALDIVES

The waves flooded two-thirds of Male, the capital. Hardest hit were the outlying low-level atolls. Some other low-lying islands were completely submerged, including some where major resorts were located. Preliminary reports stated that the tsunami killed 82, that 26 were missing, and that there was extensive destruction. However, communications with remote islands were down and the death toll must have been higher than what was reported. Thirteen islands were abandoned because all buildings were destroyed and the fresh water supply was contaminated by seawater.

SOMALIA

The tsunami waves traveled a distance of 4,500 km (2,800 miles) and struck Somalia on Africa's east coast. The height of the tsunami waves was unknown. Hardest hit was the semi-autonomous Puntland area, particularly the region between Hafun in the Bari region and Garacad in the Mudug region. The narrow and low-lying peninsula of Hafun, 1,150km (715 miles) northeast of Mogadishu, was particularly devastated.

The waves caused devastation in the Puntland area, striking the town mosque of Brava and destroying the villages of Beyla, Garacad, Muduy and Nugaal. Other coastal areas including Lower Juba were also affected. At Kulub and Hurdiye, all the fishing boats were either lost or destroyed.

According to a UN report 1,180 homes and 2,400 boats were destroyed. The main bridge, which connects Hafun to the mainland, was washed away. Te flooding rendered freshwater wells and reservoirs unusable. A total of 298 people lost their lives and 50,000 more were displaced. The final death toll is expected to rise as there are many more missing.

AUSTRALIA

No casualties were reported. The tsunami caused minor flooding along the northwestern coast and surging activity was reported along Western Australia. At Geraldton, 425 km north of Perth, several boats were ripped from their moorings. At Busselton, 325 km south of Perth, a father and son in a boat were washed out to sea, but were subsequently rescued. Swimmers at Christmas Island were sucked 150m out to sea by the tsunami. Subsequently they were carried safely back to shore.

BANGLADESH

The tsunami's impact was relatively mild. The waves killed two children and capsized a tourist boat.

KENYA

There was minor damage. One person was report

3.4.3 Lessons Learned from the 26 December 2004 Tsunami in the Indian Ocean

There were many lessons already learned from this tragic event in Southeast Asia. Indeed a bitter lesson has been already learned - that great earthquakes and destructive tsunamis do occur in this region of the Indian Ocean and will occur again in the near future. The magnitude of the 2004 tsunami disaster could have been mitigated with a proper disaster preparedness plan and a functioning early warning system. A warning perhaps could not have been of much help in the immediate tsunami generating area of Sumatra and the Nicobar and Andaman Islands and Northern Sumatra, because the tsunami waves reached the shore very quickly. However the strong shaking by the earthquake should have been nature's warning for the local residents that a tsunami was imminent and they should have run to higher ground to save their lives. A simple program of public education and awareness of the potential hazards could have saved many lives in the immediate area.

For the more distant coastlines of India, Shri-Lanka, and other locations in the Bay of Bengal and the Indian Ocean, there was ample time to issue a warning - if only an early warning system existed for this region of the world and if there was a way of communicating the information to the coastal residents of threatened areas. No such warning system existed at that time. It was reported that in many areas where there was extensive losses of lives, when the water withdrew before the arrival of the tsunami, the local residents went to the shore to collect stranded fish, instead of running to higher ground. People were totally unaware of the imminent danger. A simple educational program on hazard awareness could have prevented the extensive losses of lives - particularly of children. One third of those that perished were children.

The Tsunami Warning System - which operates in the Pacific Region - did not have at that time the capability of extending a warning to countries bordering the Indian Ocean. Although the magnitude and location of the earthquake were quickly determined, there were no wave sensors in the area to confirm the generation of a tsunami. Although both Indonesia and Thailand were members of the Pacific Tsunami Warning System network, they did not at that time operate wave sensors on the western coasts of their islands and territories.

Also India and Shri Lanka were not members of the International Tsunami Warning System in the Pacific and up to that disaster they had not shown interest in joining any regional early warning system. An erroneous belief persisted that tsunamis do not occur frequently enough to warrantee participation into a regional tsunami warning system. Local government authorities in the region did not even have a plan for disseminating warning information to the threatened coastlines - even if a warning had been provided. There was not even a basic educational plan for disaster preparedness. However, since 2004 countries bordering the Indian Ocean have initiated programs that will reduce similar tragedies and losses in the future. It should be obvious that such programs are necessary to prevent similar tragedies in the future.

4. THE ANDAMAN SEA BASIN

The Andaman Sea Basin (see Fig. 1) is is a forearc sliver plate and a seismically active region at the southeastern end of the Alpine-Himalayan belt. Its seismicity is extensively covered in the scientific literature (Sinvhal et al.1978; Verma et al. 1978). The seimotectonic history of the region indicates that an extensional feature developed along a leaky transform segment of the megashear zone - the Andaman fault - between the Indo-Australian domain and the Sunda-Indochina block (Uyeda and Kanamori, 1979; Taylor and Karner, 1983). This old shear zone acted as a western strike slip guide for the extrusion of the Indochina block 50-20 My ago, (Tapponnier et al., 1986) - and in response to the indentation of the Indian tectonic plate into the Eurasian block. Collision of Indochina with the Sunda and Australian blocks stopped this crustal extrusion process. Subsequently, the Andaman fault system, recently prolonged through the Sumatra zone (the Sumatra fault), reactivated due to the lateral escape of the Sumatra forearc sliver plate, and as a result of the oblique convergence and subduction with the Indo-Australian plate.

4.1 Potential for Large Earthquakes and Tsunamis in the Andaman Sea in the Future.

Most of the earthquakes along the eastern Andaman fault system involve lateral movements, as this represents an elongated extension of the strike-slip type of the great Sumatra faulting which extends along the entire length of the island. Earthquakes along this eastern region of the basin do not generate significant tsunamis. However, the western side of the sliver plate is an extension of the northern Sunda Arc boundary, which can break – as the 26 December 2004 and the 1941 events demonstrated - and generate destructive tsunamis. Furthermore, the region where the 2004 earthquake occurred was a seismic gap region where great stress had accumulated over the years. When this earthquake occurred, the Indian plate subducted the Burma plate and moved in a northeast direction. This movement caused further dynamic transfer and loading of stress to both the Australian and Burma plates, immediately to the south, on the other side of the triple junction point near Padang (Pararas-Carayannis, 2005, 2006, 2007). The following is a cursory evaluation of potential future earthquakes and of tsunami generation in the Andaman Sea basin. Fig. 1 showed the Andaman Sea Basin and the northern section of the Indonesian Island of Sumatra, as well as the southwestern coast of Thailand.

The present study reviews previous studies and expands on an analysis of potential future destructive earthquakes and the projected tsunami generation from this region of the Andaman Sea. Fig. 4 showed the northward movement of the Indian and Australian blocks and the collision with Asia. Fig. 5 showed the seismicity of southern Asia and the partial distribution of earthquake epicenters with Ms magnitude above 3 in the northern Indian Ocean. Active subduction and sinistral crustal movements in the Andaman Sea Basin, have caused many minor and intermediate earthquakes, a few major events, and only one known earthquake with magnitude greater than 8. The historical record indicates that on 2 April 1762, an earthquake with a moment magnitude estimated to be between 8.5–8.8 M_w at the Arakan Coast off Myanmar generated the earliest known tsunami in the Bay of Bengal (Rastogi & Jaiswal, 2006).

According to a study at the Australian National University of the fault model for this 1762 Arakan earthquake (Cummins, 2007), its rupture had length of 700 km, NS, a width of 125 km along the eastern coast of the northern Bay of Bengal, and a slip of 10 m. In brief, the author chose parameters to reproduce roughly the observed subsidence and uplift associated with this earthquake with the fault's upper edge coincident with the deformation front, thus estimating the maximum offshore heights of the generated tsunami, recognizing though that the onshore run-up could be much greater, and finally concluding that giant tsunamigenic earthquakes have occurred in the past off the coast of Myanmar and will occur again in the future. Fig. 14 below pertains to the earthquake tsunami generating area of the 1762 Arakan event and of the maximum offshore tsunami height in meters.

Specifically, on October 1847, an earthquake near the Great Nicobar Island generated a tsunami, but no details are available. On 31 December 1881 a magnitude 7.9 earthquake near Car Nicobar, generated yet another tsunami in the Bay of Bengal. Its height recorded at Chennai was one meter.

During an eighty year period from 1900 to 1980, a total of 348 earthquakes were recorded in the area bounded by 7.0 N to 22.0 N and 88.0 E to 100 E. These earthquakes ranged in magnitude from 3.3 to 8.5 (Bapat, 1982), but only five of these had magnitudes equal to or greater than 7.1 and generated tsunamis (Murty and Bapat, 1999). For the shorter period from 1916 to 1975, only three of the earthquakes had magnitudes greater than 7.2 and generated significant tsunamis. (Verma et al., 1978).

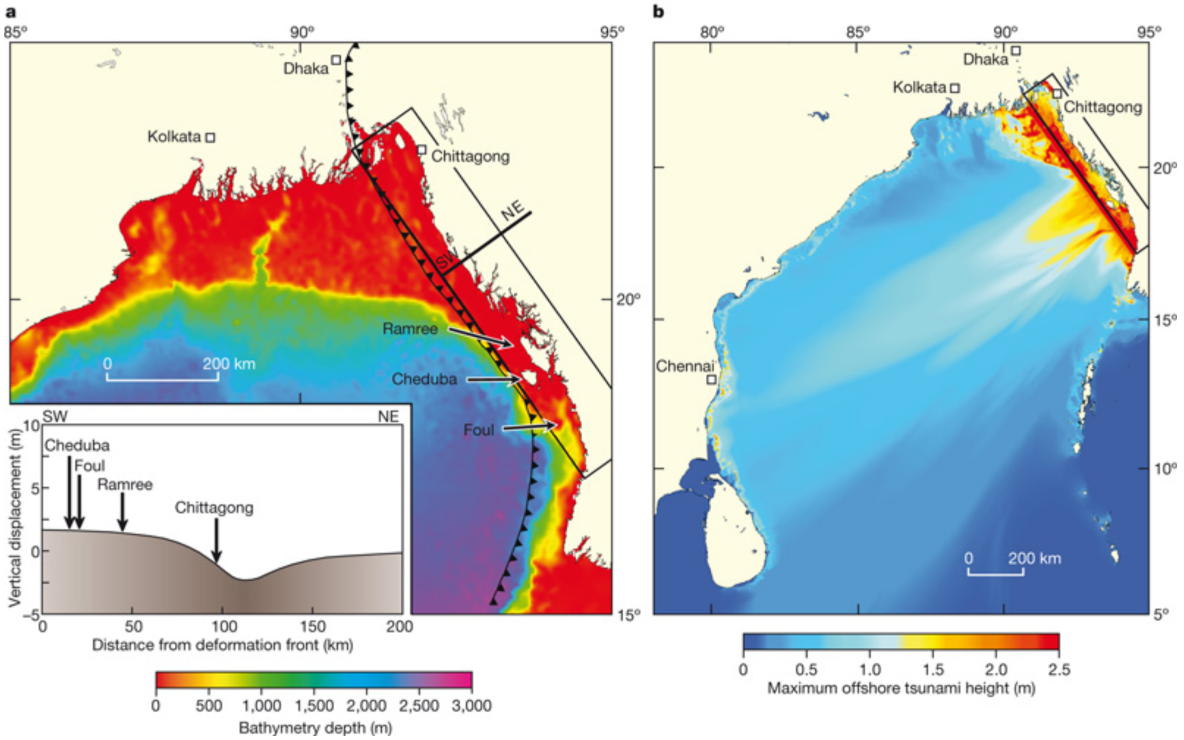

Fig. 14. Models for the 1762 Arakan earthquake and tsunami (after Cummins, 2007)

Until the great earthquake of 26 December 2004 (Pararas-Carayannis 2005; Ishii EtAl 2005, 2007; Krüger & Ohrnberger 2005; Rastogi & Jaiswal, 2006; Hutchings & Mooney 2021), only the earthquake of 26 June 1941 had been the strongest ever recorded in the vicinity of the Andaman and Nicobar Islands (Fig. 15) in generating a destructive tsunami. Two other earthquakes on 23 August 1936 and 17 May 1955, with magnitudes 7.3 and 7.25, respectively, did not generate tsunamis of any significance.

Fig. 15. World Atlas map of the Andaman and Nicobar Islands, North of Sumatra are the two main island groups separating the Bay of Bengal and the Andaman Sea (image of GraphicMaps.com)

Based on the statistical information, it can be concluded that most of the earthquakes in the Andaman Sea Basin, even those with magnitudes greater than 7.1, do not usually generate significant tsunamis. The possible reason for the low number of tsunamis is that most of the earthquakes in the Andaman Sea are mainly associated with strike-slip type of faulting that involves lateral crustal movements. The exception was the 26 December 2004 earthquake which, not only ruptured the Great Sunda Arc along the northern Sumatra region but also ruptured the same segment in the Andaman Sea as that in 1941. A possible explanation for the extreme tsunami generated in the Andaman segment on 26 December 2004 is that this event had a different mechanism and involved both thrust and bookshelf faulting within the compacted sediments of the Andaman Sea segment of the Great Sunda Arc (Pararas-Carayannis, 2005).

In view of the above historical record, it can be reasonably concluded that large earthquakes along the northern end of the Great Sunda subduction boundary in the Andaman Sea do not occur frequently. However, events with magnitudes greater than 7.1 have the potential of generating local destructive tsunamis. Finally, earthquakes with magnitude 8.0 or greater, associated with "dip-slip" types of vertical crustal displacements along thrust faults, have the potential of generating very destructive tsunamis. Reccurence of such larger magnitude events may be expected in the future, although rather infrequently.

5. FUTURE TSUNAMIGENIC EVENTS ALONG THE NORTHERN AND EASTERN SEGMENTS OF THE GREAT SUNDA TECTONIC ARC

The tectonic arc and the great trench formed by movement of the Indian and Australian tectonic plates and collisions on the eastern boundary have created a zone of subduction known as the great Sunda Arc. This zone extends for about 3,400 miles (5,500 kms) south from Myanmar, past Sumatra and Java and east toward Australia and the Lesser Sunda Islands, ending up near Timor. Fig. 16 is a map of the subduction zone of the great Sunda tectonic arc on the Indian Ocean. Also shown are major fault zones along the Island of Sumatra and on Celebes Island in the Banda Sea, and future potential tsunami generation in the marginal seas of the Indian Ocean, can be expected in the future.

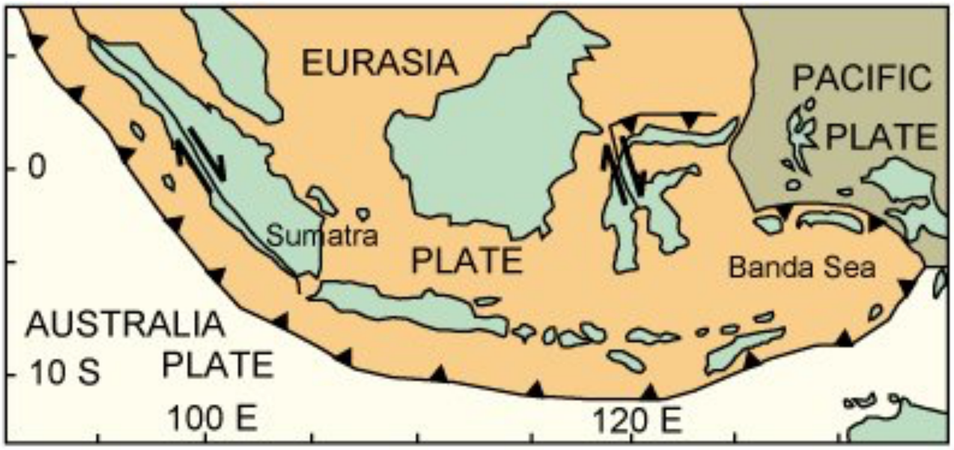

Fig. 16. Map of the subduction zone of the great Sunda tectonic arc in the Indian Ocean, and on major land fault zones along Sumatra and on Celebes Island in the Banda Sea.

In brief, the Sunda Arc is an island-arc structure of about 17,000 islands spread out along a belt of intense volcanic and seismic activity. Such tectonic features characterize the region with a deep oceanic trench on the Indian Ocean side, a geanticline belt and volcanic inner arc, and several marginal basins. This region of the Indian Ocean has about 400 volcanoes, of which about 100 are active. The best known of these volcanoes is Krakatau in the Sunda Strait, between Java and Sumatra. The 1883 explosion and collapse of this volcano generated an enormous tsunami that killed close to 37,00 people (Pararas-Carayannis, 2003). Also, other volcanoes such as Tambora have the potential of generating catastrophic tsunamis that could have an impact on the islands and countries bordering the Andaman Sea

The Sunda Arc comprises of two distinct zones of subduction North of Sumatra (Fig. 17). In the eastern part, further south which is relatively old (more than 100 million years), oceanic lithosphere subducts offshore from Java.

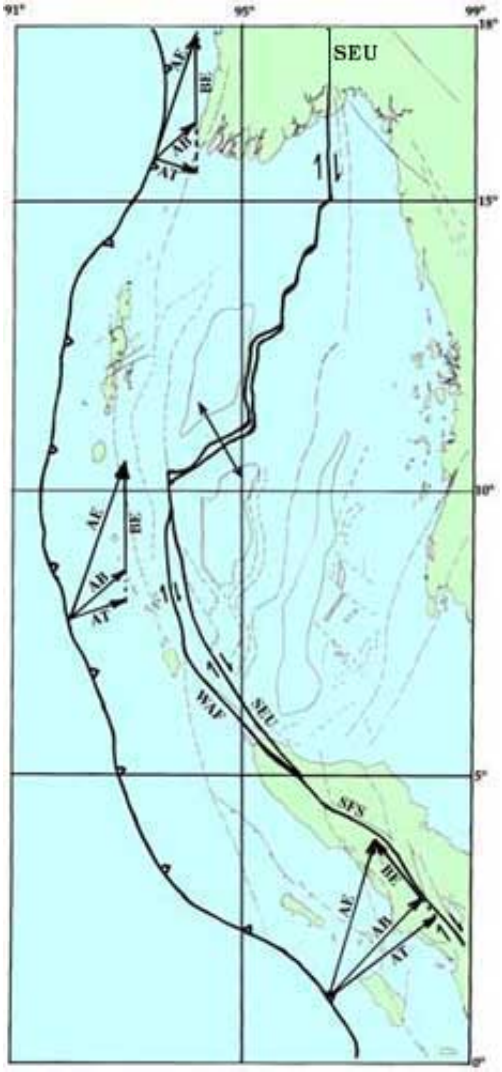

Fig. 17. Subduction zone and directionality of crustal movements of major faults along the northern segment of the Great Sunda tectonic arc near northern Sumatra and the Andaman and Nicobar Islands further North.

The younger (40 million years) northwest segments of the Arc mark the boundaries formed by the movement of the Indo-Australian plate as it collides with the Burma sub-plate, which is part of the Eurasian plate. A divergent boundary separates the Burma plate from the Sunda plate. The Burma sub-plate encompasses the northwest portion of the island of Sumatra as well as the group of the Andaman and the Nicobar Islands (Fig. 17).

In the region off the west coast of northern Sumatra, the India plate is moving in a northeastward direction at about 5 to 5.5 cm per year relative to the Burma plate. Because of this migration and collision with both the Eurasian and the Australian tectonic plates, the India plate's eastern boundary has become a diffuse zone of seismicity and deformation, characterized by extensive thrust faulting and numerous large earthquakes that can generate destructive tsunamis in the future that could affect the Andaman and Nicobar islands and countries bordering the Andaman Sea.

5.1 Potential for Future Tsunami Generation in the Andaman Sea and along the Northern and Eastern Segments of the Great Sunda Tectonic Arc.

Major and great earthquakes and tsunamis occur in the Andaman Sea and further south along the Sumatra, Java and Lesser Sunda segments of the great Sunda Arc. As shown in Fig. 18 of the northern segment of the great Sunda tectonic arc, the 12 September 2007 earthquake occurred offshore.

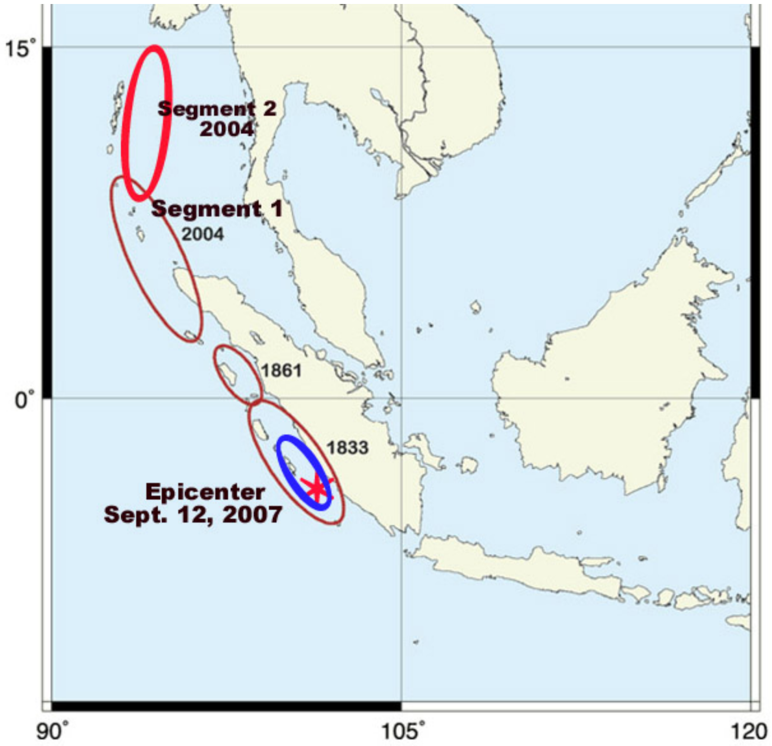

Fig. 18. Estimated dimensions of the tsunami generating source areas off the coast of the island of Sumatra and the Andaman Sea associated with the earthquakes of 1833, 1861, 2004, 2005 and 2007 (Pararas-Carayannis, 2005)
https://www.drgeorgepc.com/Tsunami1833Indonesia.html

Following is a review of studies of the different segments of the Great Sunda Tectonic Arc (Newcom & McCann, 1987). Also included is a summary of the seismic history and tectonics of the Sunda Arc with accounts and illustrations of past historical earthquakes (Fig. 18), which most likely will occur again in the future and may have an impact on islands and countries bordering the Andaman Sea.

Shown in Fig. 18 are major earthquakes which occurred in 2004 (on two segments 1&2) which generated tsunami events near the Andaman and the Nicobar Islands but also impacted the countries bordering the Andaman Sea Basin. Earthquakes in 1861, 1833 and 12 September 2007 generated destructive tsunami waves which, because of source orientation toward the south-west, had very little or no impact in the Andaman Sea Basin.

Apparently along the Northern and Easten segments of the Great Sunda megathrust (Fig. 19), destructive earthquakes and tsunamis can be expected to recur at least every hundred years, or even more frequenly in the near future, as each earthquake results in seismic stress tranference on adjacent tectonic blocks. Examples of such seismic stress transference is that caused by the 30 March 2005 and the 12 September 2007 tsunamigenic earthquakes shown above in Fig. 18.

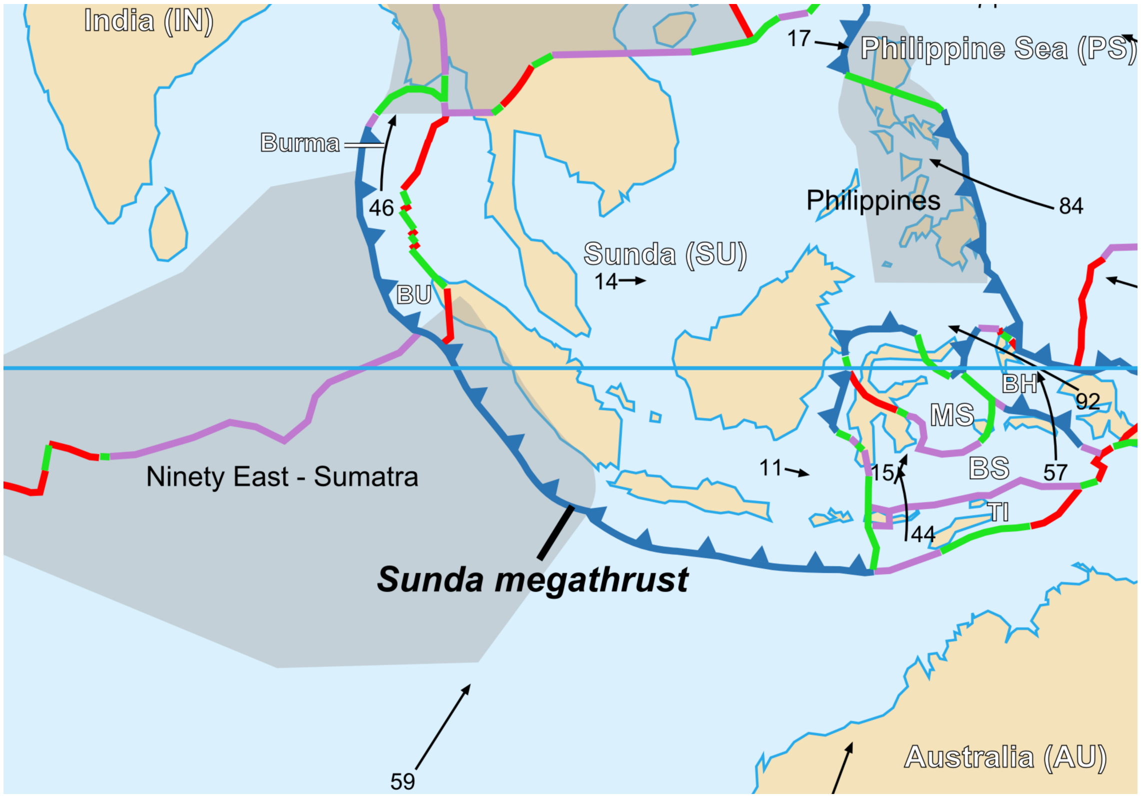

Fig.19. The Sunda megathrust and other subduction zones in adjacent seas of the Indian Ocean where future tsunamigenic earthquakes can be expected..

5.2 Sumatra Segment Tectonics – Past and Future Earthquakes and Tsunami

To summarize, the northern segment of the Great Sunda arc is one of the most seismically active regions in the world. The northern segment and its extension into the Andaman Sea is a region where large earthquakes and tsunamis can be expected frequently in the future. As the 26 December 2004 event demonstrated, tsunamis originating from this region can impact severely islands and countries bordering the entire Indian Ocean and the Andaman Sea (Pararas-Carayannis, 2005).

Because of seismic stress tranference, tsunamigenic earthquakes can be expected to occur in sequence, as the earthquake 28 March 2005, with revised moment-magnitude Mw=8.6 Mw, demonstated on the Sunda megathrust (see Fig. 18 above) near the Nias-Simeulue Island chain, paralleling the west coast of northern Sumatra. This earthquake generated a destructive tsunami of 3.0 meters (9.8 feet), and 915 to 1,314 people on the island of Nias lost their lives injuring also 1,146 people. This event occurred only three months after the great 25 December 2004 earthquake off the coast of northern Sumatra.

Also, the historic record shows that large earthquakes with magnitude greater than seven struck the offshore islands of Western Sumatra in 1881, 1935, 2000, and 2002. Earthquakes with magnitude greater than M=8 struck the same region in 1797, 1833, 1861, 2004, 2005, and as recently as on 12 September 2007, as shown in Fig. 18 (Pararas-Carayannis, 2007). Subduction of the India and Australian plates beneath the Burma plate was the cause, and this process will apparently continue in the near future. The following is a brief summary of some of the events cited above and of their expected recurrences in approximately the same areas, as in the past. Based on the history of past destructive earthquake and tsunami events, future large earthquakes are expected to occur in the region, which will generate destructive tunamis that will impact not only Sumatra and other areas of the Indian Ocean, but also the islands and countries bordering the Andaman Sea Following is a brief review of some of the historical earthquake and tsunami events in this region of Sumatra that could also affect the countries bordering the Andaman Sea, although to a lesser extent because of the southwest orientation of tsunami sources along the Sunda megathrust. Following is a brief discussion of major past events in the Andaman Sea, and adjacent Seas which had a far-reaching impact in coastal commuities in countries bordering the entire Indian Ocean.

The 25 November 1833 Earthquake and Tsunami - This was a significant Sumatra earthquake with a moment magnitude of 8.8 to 9.2 M_w which occurred on 25 November 1833 (see Fig. 9). Destructive tsunami waves struck mainly the southerwestern coast of the island. There are no reliable records of the loss of life, with the casualties being described only as "numerous". The magnitude of this event has been estimated using records of uplift taken from coral microattolls (Natawidjaja EtAl, 2006; Rastogi & Jaiswal, 2006; (Pararas-Carayannis, 2005c - http://drgeorgepc.com/Tsunami1833Indonesia.html).

The 1861 Sumatra Earthquake and Tsunami. This Sumatra earthquake of 16 February 1861 (see Fig. 9), was one of a series of events on the Sunda megathrust which generated a tsunami off the west coast of the island and caused several thousands of deaths. It was the last in a sequences of earthquakes that ruptured adjacent parts of the Sumatran segment of the Sunda megathrust. The earthquake was felt as far away as the Malay peninsula and the eastern part of Java (Newcomb & McCann, 1987). A future reccurence of a large magnitude earthquake on this segment of the Sunda megathrust is expected to also generate a tsunami which will affect the islands in the Andaman Sea, but not to the same extend because of the orientation of the fault zone and the tsunami maximum wave propagation towards the South-West of the Indian Ocean.

The 31 December 1881 Car Nicobar Earthquake and Tsunami. On 31 December 1881 (see Fig. 9) a submarine earthquake beneath the Andaman Islands generated a tsunami with a maximum crest height of 0.8 meters, which was recorded by tide gauges surrounding the Bay of Bengal. Very little is known about its rupture parameters or location. Modeling study of the tsunami indicates that it was generated by a $M_w = 7.9 \pm 0.1$ rupture on the India/Andaman plate boundary and that there was an uplift of 10–60 cm of the island of Car Nicobar (Ortiz & Bilham, 2003). Specifically, the referenced study concluded that the rupture consisted of two segments. The northern 40-km-long segment was separated from the southern 150-km-long segment by a 100-km region corresponding to the westward projection of the West Andaman spreading center. Also stated was that the main rupture of this earthquake occurred between 8.5°N and 10°N, had a total area of 150 km × 60 km, a dipping 20°E, and a mean slip of 2.7 m. The recurrence time for 1881-type of events was estimated to be about 114–200 years, based on the basis of inferred GPS convergence rates and inferred plate closure vectors, although slip partitioning in the region may extend this estimate by as much as 30%, a rather long period of time.

The 28 March 2005 Nias-Simeuele Earthquake and Tsunami. The Nias–Simeulue earthquake occurred on 28 March 2005 off the west coast of northern Sumatra in Indonesia (Fig. 19). The event caused panic in the Northern Sumatra region, which had already been devastated by the massive tsunami waves of 26 December 2004, but this earthquake generated a relatively smaller tsunami damage, although at least 915 people were killed, mostly on the island of Nias.

The earthquake had a focal depth of 30 kilometers (19 miles) and a moment magnitude of 8.6. It was the third most powerful earthquake since 1965 in Indonesia. What was surprising about this event was that it occured in less than three months after the great earthquake of 26 December 2004 and in close proximity. For two great earthquakes to occur so close to each other in time and space was very unusual. The affected area was 200 kilometres (120 mi) west of Sibolga, Sumatra, approximately halfway between the islands of Nias and Simeulue, or 1,400 kilometres (870 mi) northwest of Jakarta. Usually, when a great earthquake occurs, most of the stress is relieved and another great earthquake may not occur for many years in the same region. However, this is not always the case, as dynamic stress loading can accelerate the occurrence of another earthquake along an adjacent seismic zone. Sometimes the opposite occurs and the release of energy on one segment, may also release stress on an adjacent seismic fault. In this case it appears that the process was accelerated rather than delayed. Both of the recent earthquakes had their epicenters near the triple junction point where the Indian, Australian and Burma tectonic plates meet. Triple junction points of tectonic plates, particularly in areas of active subduction, are some of the most seismic areas of the world - capable of causing great earthquakes and tsunamis

(Pararas-Carayannis, G., 2005d). The 1960 Great Chilean Earthquake and Tsunami originated near such a triple point tectonic junction.

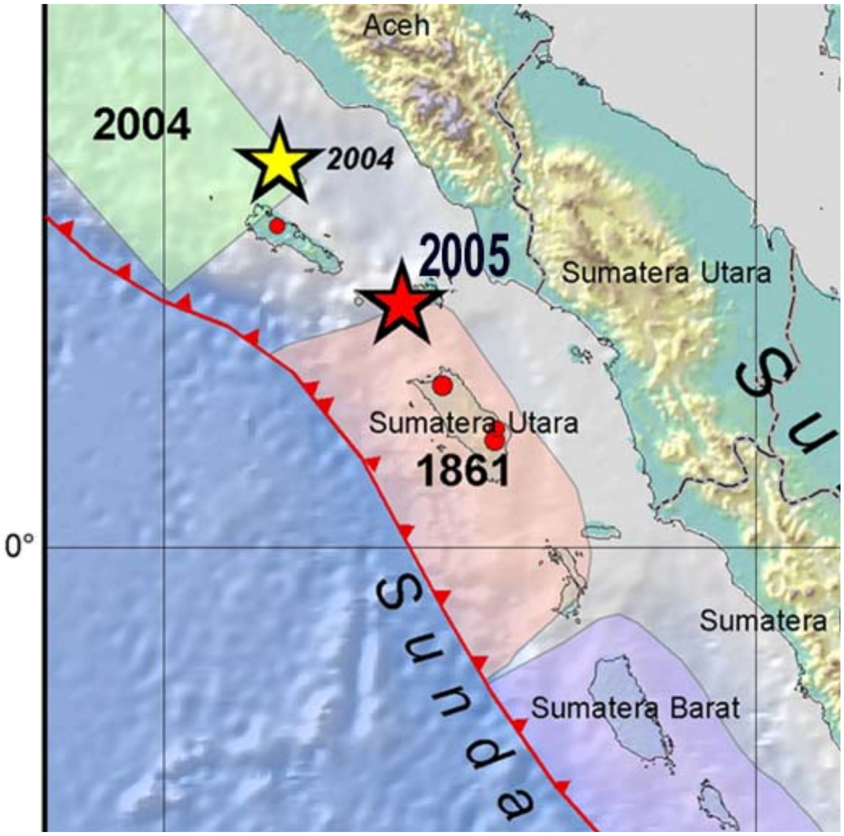

Fig. 19. Epicenter of the 28 March 2005 Earthquake in relation to the epicenter of the 26 December 2004 and the region affected by the 1861 earthquake (Modified USGS graphic)

The 17 July 2006 Earthquake and Tsunami - Fig. 20 below shows the epicenter of a more recent 12 July 2006 earthquake and the area of its tsunami generation.

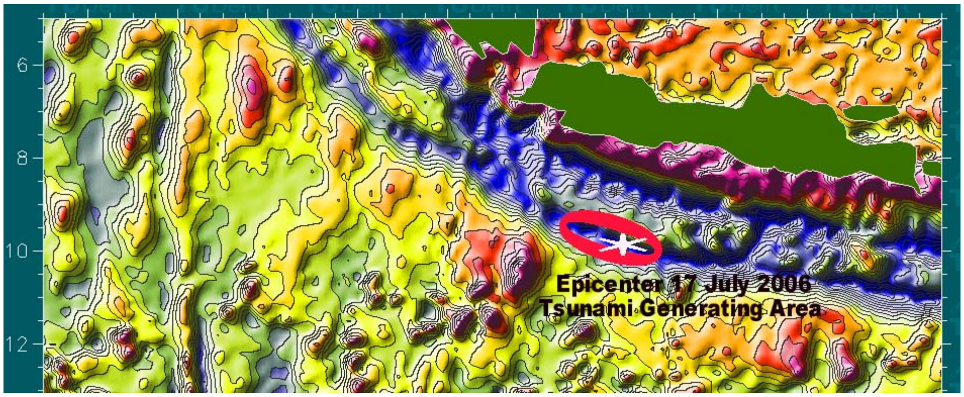

Fig. 20 Epicenter of the 12 July 2006 earthquake and the area of tsunami generation

5.3 Summary of Expected Future Tsunamigenic Earthquakes Along the Northern and Eastern Segments of the Great Sunda Tectonic Arc

To summarize, the tectonic regime of the great Sunda tctonic arc is complex and characterized by geomorphologically evident active faulting and syntaxis which accomodate the continuous morthward translation and collision of the Indian plate into the Eurasian plate. This is the northwestern segment of the Sunda subduction system, where the Indian Plate subducts beneath the Sunda plate in a nearly arc-parallel direction. The entire segment ruptured during the 26 December 2004 great Andaman-Sumatra earthquake. This thrust-dominated plate boundary and the extrusion of crust in its eastern side results in highly oblique strike-slip dominated boundaries which extend through Myanmar (Bates & Jackson 1987; Wang EtAl. 2014; Booth EtAl. 2009), and thus it is expected to have a impact on the seismicity, not only of the Andaman Sea, but also along the Great Sunda Arc. However this process is extremely slow, so it is thus difficult to predict or forecast the interactions and reccurence periods of both earthquake and tsunami events in the region.

When the 26 December 2004 earthquake occurred, the Indian plate subducted the Burma plate which moved in a northeast direction. This movement caused dynamic transfer and loading of stress not only to the North but also to both the Australian and Burma plates, immediately to the south, on the other side of the triple junction point. As a result of such load transfer, the Australian plate also moved in relation to the Burma plate and probably rotated somewhat in a counterclockwise direction, causing the subsequent great earthquake of 28 March 2005. However, the block that moved was relatively small. It is very difficult to forecast on whether this movement will continue and will stress load another segment of the great Sunda fault to the north and thus cause another earthquake and tsunami soon. However, another great earthquake similar to that of 1833 (magnitude 8.7) along the south coast of the western Sumatra, will eventually occur. That particular earthquake generated a great tsunami. The waves may have been as much as 10 to 15 meters on the western coast of Sumatra. Luckily, most of the energy from that tsunami was directed towards the unpopulated regions of the southwest Indian Ocean. When such an event will occur again, cannot be predicted with any certainty. The only thing known with certainty is that it will occur in this region. Thus, a Coulomb stress transfer analysis, based on rupture parameters and the geometric distribution of aftershocks for both the 26 December 2004 and the 28 March 2005 events, would help establish the space-time evolution of stresses and perhaps help determine both static and dynamic modifications that could possibly trigger future tsunami events along known faults in the region that may have an impact along northern Sumatra and in the Andaman Sea. Most of the energy from such tsunami will be directed towards the unpopulated regions of the southwest Indian Ocean. When such an event will occur again, is difficult to predict. The only thing known with certainty is that it will occur in this region near Sumatra. Thus, a Coulomb stress transfer analysis, based on rupture parameters and the geometric distribution of aftershocks for both the 26 December 2004 and the 28 March 2005 events, would help establish the space-time evolution of stresses and help determine both static and dynamic modifications in this region. In summary, major earthquakes can be expected to occur further southeast along the central coast of

Sumatra in the next few years. Any such major earthquake with magnitude greater than 7 could generate a tsunami in the region, but its impact in the Andaman Sea is not expected to be significant. Also, Talang volcano on Sumatra could experience a major eruption in the distant future.

In conclusion, because of load transfer, the Australian plate moved in relation to the Burma plate and probably rotated somewhat in a counterclockwise direction, causing the great earthquake of 28 March 2005. In fact, the 2005 earthquake had occurred in the same region as the 1861 earthquake (see Fig. 18). The block that moved was relatively small in comparison, thus the tsunami that was generated was not very destructive. However, following the great earthquakes of 2004 and 2005, it appears that there was additional significant transference of tectonic stress further south/southeast to the central region of Western Sumatra. The latest great earthquake (magnitude 8.2) of September 12, 2007 (see Fig. 18) and the other two events and aftershocks (and later a fourth event) occurred even further south/southeast and within the segment that ruptured when a great (estimated magnitude Mw=8.7) earthquake occurred in 1833 (Pararas-Carayannis, 2007). Apparently, the September 12, 2007 earthquake (Fig. 18) had a smaller magnitude and length of rupture than the 1833 event, which had generated a much greater tsunami. The shorter rupture (estimated roughly at about 200 km), and the smaller magnitude, was the probable reasons for the smaller 2007 tsunami. Fortunately, the energy release by two other earthquakes, which occurred subsequently in sequence, helped release gradually the tectonic stress along this segment. This may have contributed to the relatively smaller tsunami that was observed in Padang and elsewhere. This did not occur when the 1833 earthquake had struck the same region. All the energy of the 8.7 earthquake in 1833 was released at once and the rupture zone may have been as much as 300 km long, or even more. The effects of the 1833 tsunami in the region were probably great but poorly documented.

It remains to be seen if the earthquake of September 12, 2007 resulted not only from partial subduction but also from counterclockwise rotation of the Australian plate. Such rotation, with diminished vertical uplift, could account for the smaller 2007 tsunami. Further field studies of uplift and lateral motions on the offshore islands would confirm if the mechanism of the 2007 event was different from the one that generated the 1833 tsunami. Field studies on Sipora, North Pagai and South Pagai Islands of the outer-arc ridge of the great Sunda Arc, indicate that the great 1933 earthquake resulted in vertical uplift of up to 2.3 meters. Such extensive vertical uplift generated the greater tsunami. The uplift caused by the September 12, 2007 earthquake may have been much less than that of 1833.

In brief, destructive tsunamis can be generated from earthquakes originating anywhere along this northern segment of the tectonic boundary of the Sunda megathrust. Earthquakes and tsunamis similar to the 2007, 2005, 2004 and 1833 events can be expected every hundred years - or even more frequently - in this northern segment. This particular section of the megathrust along the western coast of the northern, central and southern Sumatra is one of the more likely sources of destructive tsunamis in the region in the future. Fig. 20 (see also Fig. 2) graphically illustrates the active ongoing processes of subduction West and North of the Island of Sumatra and extending to the Nicobar and Andaman Islands to southern Myanmar and Thailand.

A repeat of a single large earthquake with the same rupture and source dimensions as those of the 1833 or 2004 events, could generate devastating tsunamis that could affect Sumatra and other distant regions of the Indian Ocean such as Thailand, Sri Lanka, India, the Maldives, the Arabian Peninsula and northern Africa and somewhat the Andaman Sea region. Also, the northern segments of the great Sunda arc are source regions of tsunamis that can be particularly destructive in the Bay of Bengal, as well. The primary reason is the geographical orientation of this segment of the seismic zone and the directivity of maximum tsunami energy peopagation. Most of the energy of tsunamis generated further east along the coasts of Java or the Lesser Sunda Islands would tend to focus toward southern Africa and Australia and are not expected to be as significant in terms of destruction.

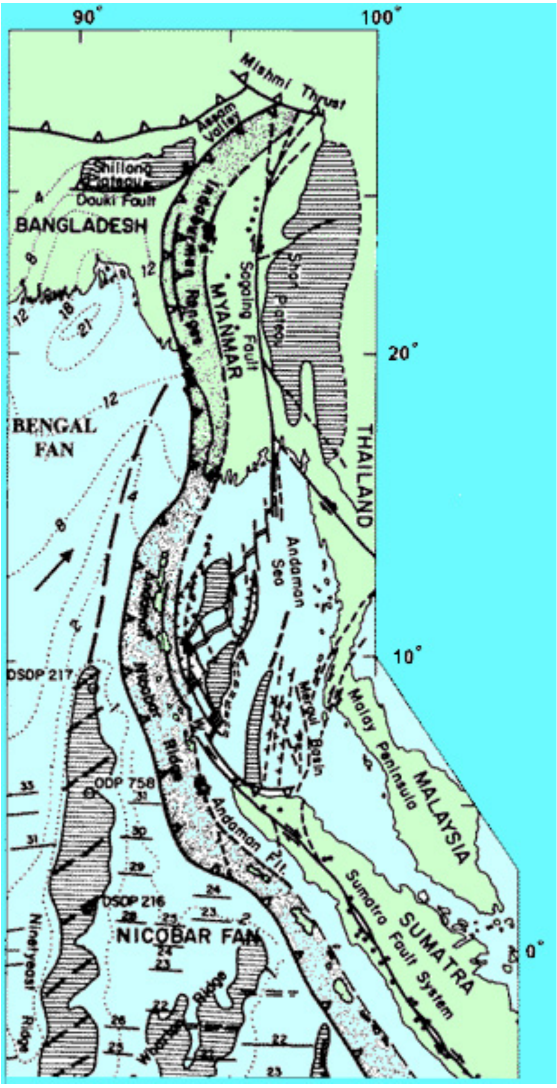

Fig. 20 Subduction zone West and North of the Island of Sumatra, of the land section of the Sumatra Fault System, and its NNW extension to Nicobar and Andaman Islands South of Myanmar.

5.4 The tectonic regime of the Andaman Sea and of Myanbar (Burma) - – Past and Expected Future Tsunami Generation

Fig. 20 illustrates the zone of subduction zone West of the Island of Sumatra, the land section of the Sumatra Fault System and its NNW extension to Nicobar and Andaman Islands South of Myanmar, as well as the secondary faults and offsets north of Sumatra near the Thailand border.

5.5 The Tectonic Regime of the Lesser Sunda Islands Segment – Past and Expected Future Tsunami Generation

The tectonic regime of the Great Sunda tectonic arc further southeast of the Andaman Sea region is also complex, active, and characterized by geomorphologically evident active faulting. In this region of the East Java Trench the rate of subduction is about 50 mm/yr. As previously stated, on August 19, 1977 a great earthquake with a moment magnitude Mw=8.3, westward of Sumba Island, generated a destructive tsunami which had observed run-up heights of up to 5.8 meters (19 ft) and a maximum run-up height of 15 meters at a certain location. This earthquake was the largest outer-rise earthquake ever recorded in Indonesia and its aftershocks along the trench extended for about 130 kilometres (81 mi) eastward and 110 kilometres (68 mi) westward from the epicenter (Gusman EtAl., 2009). The waves penetrated about 500 meters inland, killed more than 200 people, and left 3900 homeless (Pararas-Carayannis, 1977: Natawidjaja EtAl, 2006; Borrero EtAl., 2006). What was unusual about this earthquake was the fact that it had a very large magnitude for a shock with a normal faulting focal mechanism, in the southern segment of the Sunda Trench where other tsunamigenic earthquakes have occurrred in the past (Kopp, 2011) and that the tsunami waves had great height amplitude. Another destructive tsunamis occurred in 12 December 1992 at Flores Island and yet another one in 1994 in the same region (Pararas-Carayannis, 1992, 1994), but because of the tsunami’s source orientation towards the southwest, no significant wave was recorded or observed on the shores of the Andaman Sea.

6. CONCLUSIONS

The Sumatra fault has been reactivated due to the lateral escape of the Sumatra forearc sliver plate, and as a result of the continuous oblique convergence and subduction with the Indo-Australian plate to the south. The seismic stress on the Sumatra-Andaman megathrust is continuing. Megathrust earthquakes with moment magnitutes of Mw=9 or more, similar to the 26 December 2004, at convergent tectonic plate boundaries closer to the oceanic trench west of Sumatra and the offshore islands, can be expected to generate very destuctive tsunamis in the future, along populated coastal areas of Indonesia, but also in other countries bordering the Indian Ocean. Given the high rate of continuous northward movement of the Sunda plate at a yearly rate of up to 68 mm/year as it collides with Eurasia, it is estimated that major earthquakes on the Sumatra-Andaman megathrust region

– including the Sumatra Fault System and its NNW extension to Nicobar and Andaman Islands South of Myanmar - a major earthquake can be expected to occur at intervals of about 40 years more or less.

Future major earthquakes on this megathrust region can be expected to generate destructive tsunamis that may result in great losses of life and property in countries bordering the Andaman Sea Basin, Sumatra and the Indian Ocean, but hopefully to a much lesser extent than in 2004, now that better programs of warning, preparedness, and public education have been adopted for this immediate region, and tsunami warning systems have been instituted. In spite of such programs, the destructiveness of future events can be expected to be significant in the Andaman Sea basin, coastal areas of Sumatra and countries bordering the Indian Ocean, thus programs of preparedness and of public education must be continuous.

Continuous population growth rate and increased use of coastal areas, as well as rapid industrialization, excessive urbanization or lack of adequate planning, will contribute significantly to the vulnerability of coastal cities in Indonesia, Thailand, Bangladesh, India, and other countries bordering the Indian Ocean. Large metropolitan coastal cities like the Mumbai Metropolitan Region (MMR), will be particularly vulnerable to future tsunami disasters. The high population density and the uneven growth rate in similar metropolitan coastal areas will result in several environmental collateral problems. Effective strategies for mitigating future tsunami disasters will require more than warning systems or sophisticated instrumentation for detection and measurements of earthquake and tsunami parameters and the communication of warnings. Effective strategies for tsunami and other collateral disaster mitigation will require the adoptation of coastal management policies that integrate wisely economic developmental activities, land use, and engineering standards into a holistic framework of environmental goals that can provide maximum public safety and effective tools for sustainability following tsunami disasters in such urban coastal regions.

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