TSUNAMIGENIC SOURCES IN THE INDIAN OCEAN

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ABSTRACT

Based on an assessment of the repeat periods of great earthquakes from past seismicity, convergence rates and paleoseismological results, possible future source zones of tsunami generating earthquakes in the Indian Ocean (possible seismic gap areas) are identified along subduction zones and zones of compression. Central Sumatra, Java, Makran coast, Indus Delta, Kutch-Saurashtra, Bangladesh and southern Myanmar are identified as possible source zones of earthquakes in near future which might cause tsunamis in the Indian Ocean, and in particular, that could affect India. The Sunda Arc (covering Sumatra and Java) subduction zone, situated on the eastern side of the Indian Ocean, is one of the most active plate margins in the world that generates frequent great earthquakes, volcanic eruptions and tsunamis. The Andaman-Nicobar group of islands is also a seismically active zone that generates frequent earthquakes. However, northern Sumatra and Andaman-Nicobar regions are assessed to be probably free from great earthquakes ($M \geq 8.0$) for a few decades due to occurrence of 2004 Mw 9.3 and 2005 Mw 8.7 earthquakes. The Krakatau volcanic eruptions have caused large tsunamis in the past. This volcano and a few others situated on the ocean bed can cause large tsunamis in the future. List of past tsunamis generated due to earthquakes/volcanic eruptions that affected the Indian region and vicinity in the Indian Ocean are also presented.

1. INTRODUCTION

From GPS data, Subarya et al. (2006) inferred that the Sumatra-Andaman earthquake of 26 December 2004 was generated by rupture of the Sunda subduction megathrust over a length of 1500 km, width of <150 km and a slip exceeding 20m offshore of northern Sumatra, mostly at depths shallower than 30 km. Stein and Okal (2005), Lay et al. (2005) and Ammon et al. (2005) inferred a rupture length of 1300km, width of 160-240km and slip of 5-20m from seismological data. The rupture was wide in Sumatra and Nicobar segments (up to 260km width between the subduction front and Sumatra Fault) but narrows down to 160km in the Andaman segment (between the subduction front and West Andaman Fault) that is mapped east of Andaman Islands by Curray (2005). The tsunami due to this giant earthquake of magnitude Mw9.3 traveled throughout the Indian Ocean with large run up and was the most destructive in history causing some 300, 000 deaths. This tsunami has created great interest in predicting future occurrences of such tsunamis. Tectonics, seismicity and seismic gap areas of different earthquake belts in the Indian Ocean are assessed to infer future possibilities of tsunami generation.

List of past tsunamis generated due to earthquakes/volcanic eruptions that affected the Indian region and vicinity in the Indian Ocean are listed in Table 1 and also shown in Fig.1. Thrust type earthquakes along subduction zones that cause vertical movement of the ocean floor are usually tsunamigenic (Rastogi, 2005a, b). Such zones in the Indian Ocean are in Andaman-Nicobar region, Sumatra-Java region and Makran coast (Fig.2). Volcanic eruptions along the Sunda Arc can give rise to large tsunamis. Thrust-type earthquakes occurring along coastal zones of compressive stress along the Indus delta and Kutch-Saurashtra region in the west and Myanmar-Bangladesh border region in the east have given rise to occasional tsunamis and can again generate tsunamis in future. Minor tsunamis can be generated due to dip-slip faulting along oceanic ridges. The tectonics and seismicity in these zones are briefly discussed and long-term assessment of future great tsunamigenic earthquakes in these zones is presented.

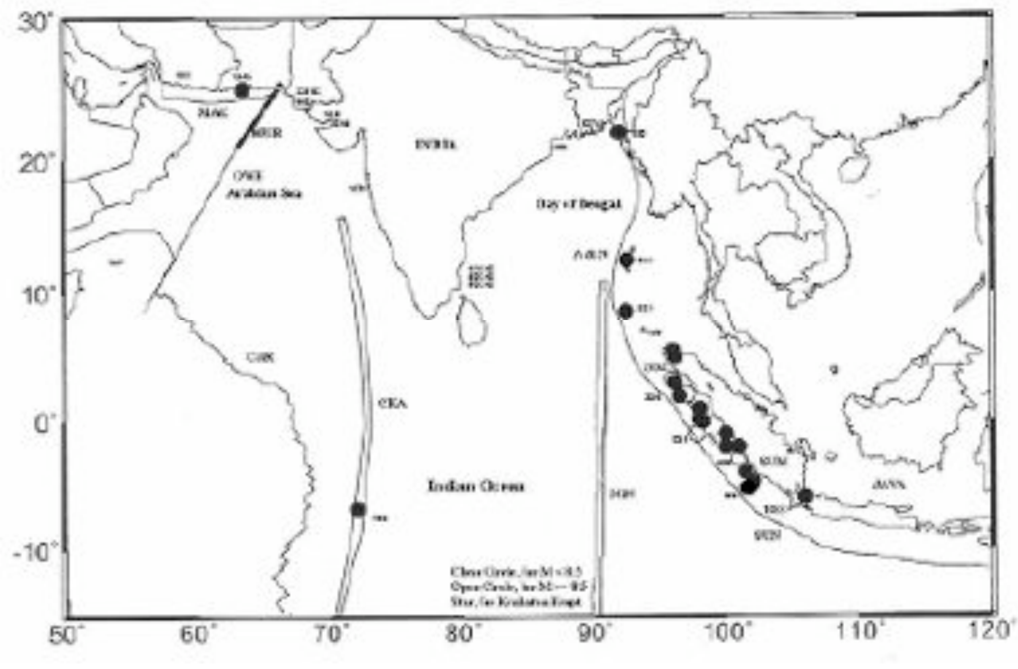

Fig.1. Locations of tsunamis generated due to earthquakes/volcanic eruptions that affected Indian region and vicinity in the Indian Ocean.

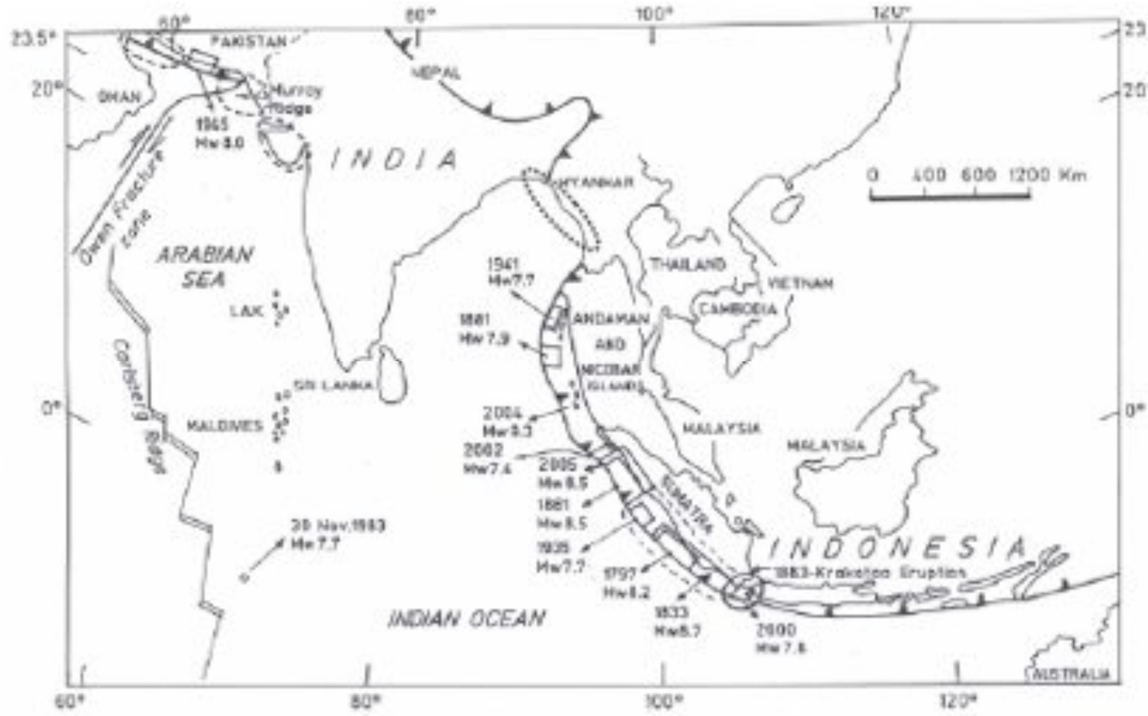

Fig.2. Rupture areas of great earthquakes of Mw□ 7.7 and inferred seismic gap areas that could be sites of future tsunamigenic great earthquakes in the Indian Ocean

2. TSUNAMIGENIC EARTHQUAKE SOURCE ZONES IN THE INDIAN OCEAN

The Sunda Arc

The Sunda Arc (Java, Sumatra and Lesser Sunda subduction zone) is one of the most active plate tectonic margins in the world, accommodating 67±7mm/yr, N11°E convergence (derived from GPS surveys) between the South Asian and India/Australian plates, which arcs 5,500 kilometers from Myanmar past Sumatra and Java toward Australia (Tregoning et al., 1994). Many characteristics of Sunda Arc change significantly along strike. Interplate motion normal to the arc near Java, becoming oblique at Sumatra, where motion parallel to the arc is accommodated by dextral strike-slip displacement along the Sumatra fault system lying parallel and north of the convergent margin (Newcomb and McCann, 1987). The plates meet 5 kilometers beneath the sea at the Sumatran Trench, on the floor of the Indian Ocean. The trench runs roughly parallel to the western coast of Sumatra and southern coast of Java, about 200 kilometers offshore. At the trench, the Indian/Australian plate is being subducted; that is, it is diving into the earth's interior and being overridden by Southeast Asia. The contact between the two plates is a “megathrust”. The two plates do not glide smoothly past each other along the megathrust but move in "stick-slip" fashion. This means that the megathrust remains locked for decades or centuries, and then slips suddenly a few (or a few tens of) meters, generating a large earthquake. Some coastal areas east of the megathrust sink by a meter or so, leading to permanent swamping of previously dry, habitable ground. Islands above the megathrust rise a few meters, so that shallow coral reefs emerge from the sea.

Newcomb and McCann (1987) identified from historic records two great interplate earthquakes (1833, Mw 8.7 and 1861, Mw 8.5) which ruptured 400-600km segments of the Sumatra fore arc. Great past Sumatran earthquakes in 1797 (Mw 8.2) and 1833 (Mw 8.7) produced large tsunamis on the islands and mainland coast (Newcomb and McCann, 1987). They also identified many other major and moderate earthquakes in Sunda Arc. Prior to their study, Sumatra was characterized as relatively aseismic due to lack of great earthquakes in the instrumental era. Java and Lesser Sunda islands had major earthquakes (Ms 6) in the historic record, but none as big as the great events near Sumatra.

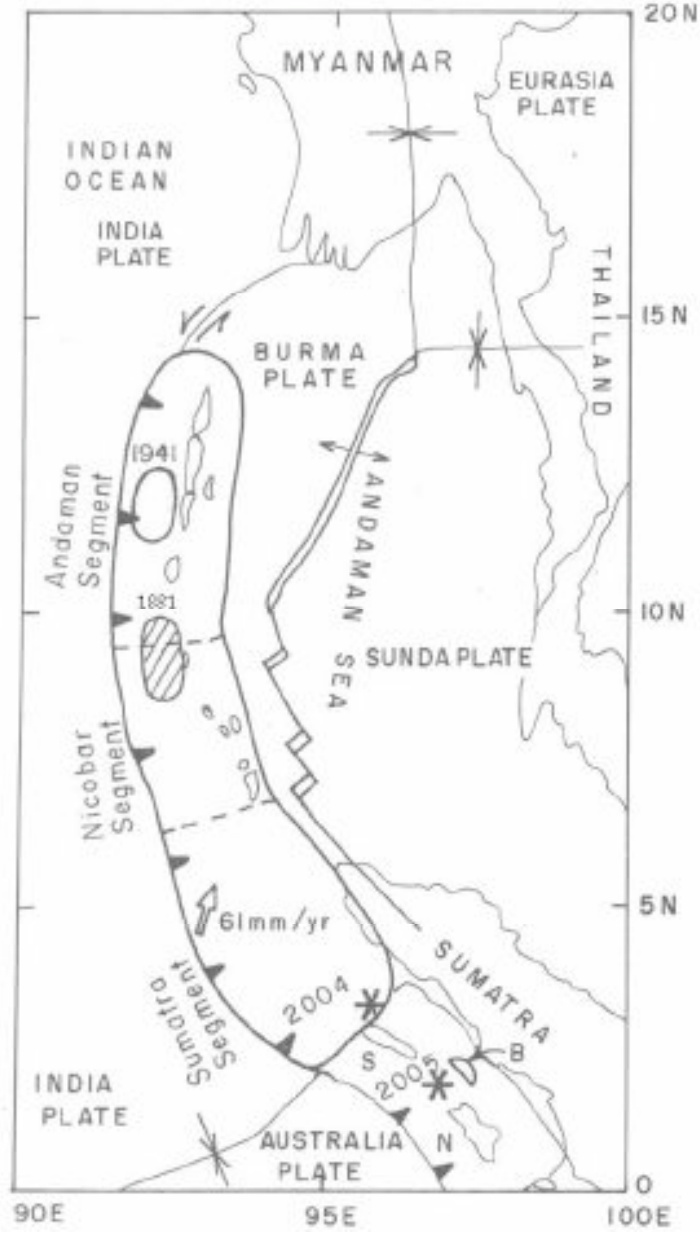

Fig. 3. Source zones of 2004 and 2005 earthquakes in Sumatra – Andaman Arc. Three of the Mentawai islands are Simeuleue (S), Banyak (B) and Nias (N). Rupture zone for 2004 earthquake is taken from Lay et al. (2005) and Stein and Okal (2005) and rupture zone for 2005 earthquake is taken from Ammon et al. (2005).

From coral uplift data Zachariasen et al. (1999) estimated the magnitude of the 1833 earthquake to be between 8.8 and 9.2. They also estimated a return period of such a giant earthquake to be 265 yr. They derived this interval by dividing the estimated slip of 13m by the rate of subduction. To estimate the rate of subduction, they subtracted the slip vector of the Great Sumatra Fault (11mm/yr, S35°E, Sieh et al. 1991) from relative plate velocity (67mm/yr, N11°E). The resultant vector for the subduction zone was 60mm/yr, N18°E. The component of this vector perpendicular to the subduction zone is 49mm/yr, N54°E. At a rate of 49mm/yr, 13m of slip would occur about every 265yr. However, it is noticed that ~M8 earthquakes and tsunamis have recurred more frequently. Great earthquakes occurred in 1797 (M8.2), 1833 (M8.7), 1861 (M8.5), 2000 (Mw 7.8), 2004 (Mw 9.3), 2005 (Mw 8.7) (Figs. 3 and 4).

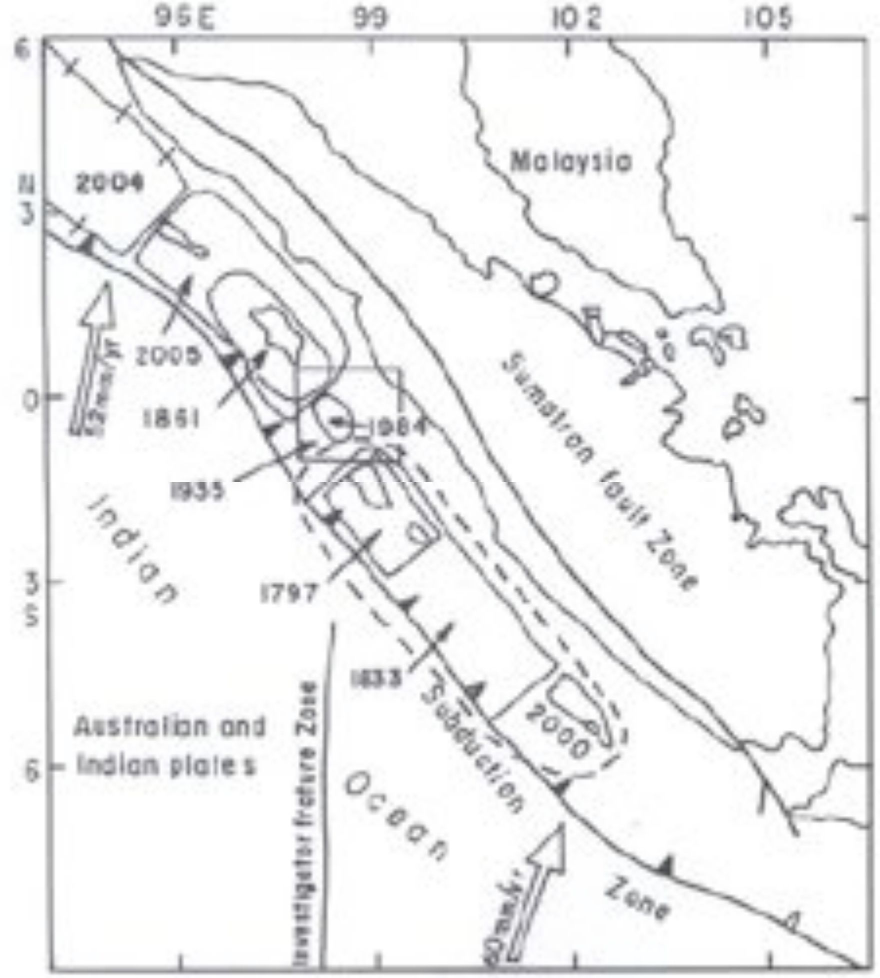

Fig. 4. Rupture areas of past great earthquakes along Sumatra. The Southern Sumatra zone marked by broken line was a possible site for future tsunamigenic great earthquake as earthquake of Mw 8.4 September 12, 2007 occurred 130 km off the SW of Bengkulu, Sumatra, Indonesia (4.52 °S, 101.374 ° E, NEIC) followed by two major earthquakes of Mw 7.9 (2.506°S, 100.906°E, NEIC) and Mw 7.1 (2.160°S, 99.588°E, NEIC) within 12 hrs and 15 hrs after the occurrence of Mw8.4 event within the rupture zone of past great earthquakes of 1833 and 1797 occurred in this broken line. This is presented by Rastogi & Jaiswal (2005) in IGU Jaiswal & Rastogi (2006) in ASC. Rupture zones of different earthquakes are taken from Natawidjaja et al. (2004) and Zachariasen et al. (1999).

The locations of some of these earthquakes are the same or overlapping. The giant earthquakes of M≥8.5 encompass the rupture zones of M~8 earthquakes of past decades as if these did not occur at all. For example the 1833 earthquake rupture encompassed rupture zone of the Mw 8.2 earthquake that occurred only 36 years earlier. Similarly the 2004 rupture encompassed rupture zones of 1881 Nicobar earthquake and 1941 Andaman earthquake. The 2005 M8.7 rupture has recurred in the same area as that of 1861 rupture for M8.5 earthquake after only 144 years. It indicates that great earthquakes can recur every few decades. Rastogi and Jaiswal (2005) & Jaiswal and Rastogi (2006) recognized that southern Sumatra (rupture zone of 1833 and 1797) has the potential for a great earthquake based on assessment of repeat periods of great earthquakes from past seismicity, convergence rates of subduction zone and paleoseismological results which are shown in Fig. 2 and Fig. 4 and marked by the broken line. However, the effect of tsunamis due to these earthquakes in India and Sri Lanka may be a limited one as the path of the tsunami will be oblique to the rupture zone. This became true as a great earthquake of Mw 8.4 struck 130 km off the SW of Bengkulu, Sumatra, Indonesia on September 12, 2007 (4.52° S, 101.374° E, focal depth 34km, NEIC) at 11:10:26 UTC (16:40:26 IST), killing 9 people and injured few tens, generated a relatively small tsunami near the epicentral zone followed by two major earthquakes of Mw 7.9 (2.506° S, 100.906° E, 30km, NEIC) and Mw 7.1 (2.160° S, 99.588° E, 22km, NEIC) within 12 hrs and 15 hrs after the occurrence of Mw 8.4 event within the rupture zone of past great earthquakes of 1833 and 1797. Since the Indian & Sri Lankan mainlands were not perpendicular to the rupture zone of the minor tsunami due to the earthquake of September 12, 2007 generating NW-SE oriented fault plane hence directivity of this tsunami is towards the SW and the tsunami with the maximum amplitude propagated in the SW direction.

The possible locales for near future earthquakes are seismic gap areas that have remained un-ruptured in the past few decades. The 2004 Sumatra earthquake occurred in one such gap (Fig.2). Kerry Sieh (CALTECH website) and Satyanarayana and Rastogi (2005) recognized that a segment of the subduction zone south of it as a possible site for a future great earthquake. The 28 March 2005 earthquake of M8.7 occurred in this gap (Fig.4). The boundary between rupture zones of 2004 and 2005 earthquakes is marked by a deep fracture named as Investigator fracture zone. The rupture zones of these two earthquakes have covered Northern Sumatra and Andaman-Nicobar regions, which are now assessed to be probably free from great earthquakes (M≥8.0) for a few decades (Rastogi, 2005b). Natawidjaja et al. (2006) recognized that the threat of another giant earthquake is high off central Sumatra. Pollitz et al. (2006) computed stress changes during co-seismic and post-seismic deformation after the occurrence of the 2004 and 2005 great Sumatran earthquake in order to focus on post-seismic deformation that is driven by viscoelastic relaxation of low viscosity asthenosphere. The December 26, 2004 Sumatra earthquake increased CFS (Coulomb Failure Stress) by 0.25 bar near the nucleation zone of the March 2005 earthquake at ~40km depth could be the region of occurrence of March 2005 earthquake. Co-seismic stress around 1797 and 1833 events of Sunda trench was negligible but post-seismic stress perturbation in CFS increased by 0.1 to 0.2 bars around these rupture zones between 2 to 8 year after the December 2004 event (Pollitz et al., 2006). They found that predicted the CFS increased by >0.1 bar over Sunda trench in coming years, raising seismic hazards along certain patches which already have a substantial amount of accumulated stress.

Co-seismic stress changes due to the 2004 event increased the stress may migrate farther south as a result of viscoelastic relaxation in the lower crust (McCloskey et al., 2005; Nalbant et al., 2005). Nalbant et al. (2005) also evaluated the stress at the hypocenter of 2005 earthquake induced by Sumatra-

Andaman rupture and found it to be between 0.07 and 0.17 bars. The size of this triggering stress reveals the extreme complexity and non-linearity of the earthquake nucleation process.

Two Sumatran events of 2004 and 2005 altered the state of stress near the surrounding region of earthquakes could be the probable cause of generating Simeulue, Indonesia earthquake of M7.4 on February 20, 2008 (2.778° N, 95.978° E, depth 35km, NEIC), epicenter located at 59km south of 2004 event and 139km NW of 2005 event. Stress changes indicate that greatest current seismic threat comes from the Mentawai segment between about 0.7 and 5.5° S (Nalbant et al., 2005).

Farther south in southern Sumatra and Java large earthquakes are possible in future (Ammon, 2006). Between latitudes of 1-6° S large/great earthquakes occurred during 1797 and 1833 and hence a great earthquake can be expected within a few decades now. Zachariasen et al. (2000) inferred from the study of coral microatolls that the Mentawai Islands in this region are submerging at rate of 4 – 10 mm/yr over five decades and the elastic strain is accumulating in the interseismic period. The northern Sumatra and Andaman-Nicobar regions may not experience great earthquakes for a few decades as 2004 Mw 9.3 and Mw 8.7 earthquakes have ruptured the entire 1600km length of the subduction zone from Andaman to northern Sumatra. However the possibility of an earthquake of magnitude 7.0-7.5 on the Sumatra fault north of 4° N has not receded (Nalbant et al., 2005).

Andaman-Nicobar Arc

The Sunda Arc extends further north to the region of Andaman-Nicobar group of islands, which is also seismically active zone and generates frequent large earthquakes. Large earthquakes in 1847 (Mw>7.5), 1868, 1881 (Mw7.9) and 1941 (M7.7) generated tsunamis. The convergence rates estimated by GPS measurements indicate repeat periods of 114-200 yr for great earthquakes (Ortiz and Bilham, 2003).

The Andaman and Nicobar islands form an island arc or ridge and are made up of ophiolites and sediments scraped off the down going Indian plate. The ridge lies on the Andaman plate as referred to by Dasgupta (1993) or Burma plate (as referred by Curray et al. 1982). The ridge is bound to the east by the Sunda plate boundary, that has strike-slip faults and spreading centers, and to the west by the subduction zone of the Indian plate (Fig. 5). At latitude 9° N the Indian plate converges at N 23° E obliquely toward the Asian plate at 54 mm/yr (DeMets et al., 1990, 1994). Further north the convergence is nearly perpendicular to the subduction zone. Between little Andaman and Car Nicobar at around 10° N, there are imbricate N-S trending thrust sheets dipping east. These thrusts are extending north and south for long distances and may be causing uplift of beaches in Car Nicobar. The Sumatra fault continues up to Nicobar. North of 10.2° N the fault is offset 100km eastward by the Andaman spreading center and becomes inactive. North of 10° N, the Benioff zone, west of the Andamans, is clearly expressed by microseismicity to 100km depth. Between 10° to 12° N, back arc spreading zone is also depicted by microseismicity (Ortiz and Bilham, 2003).

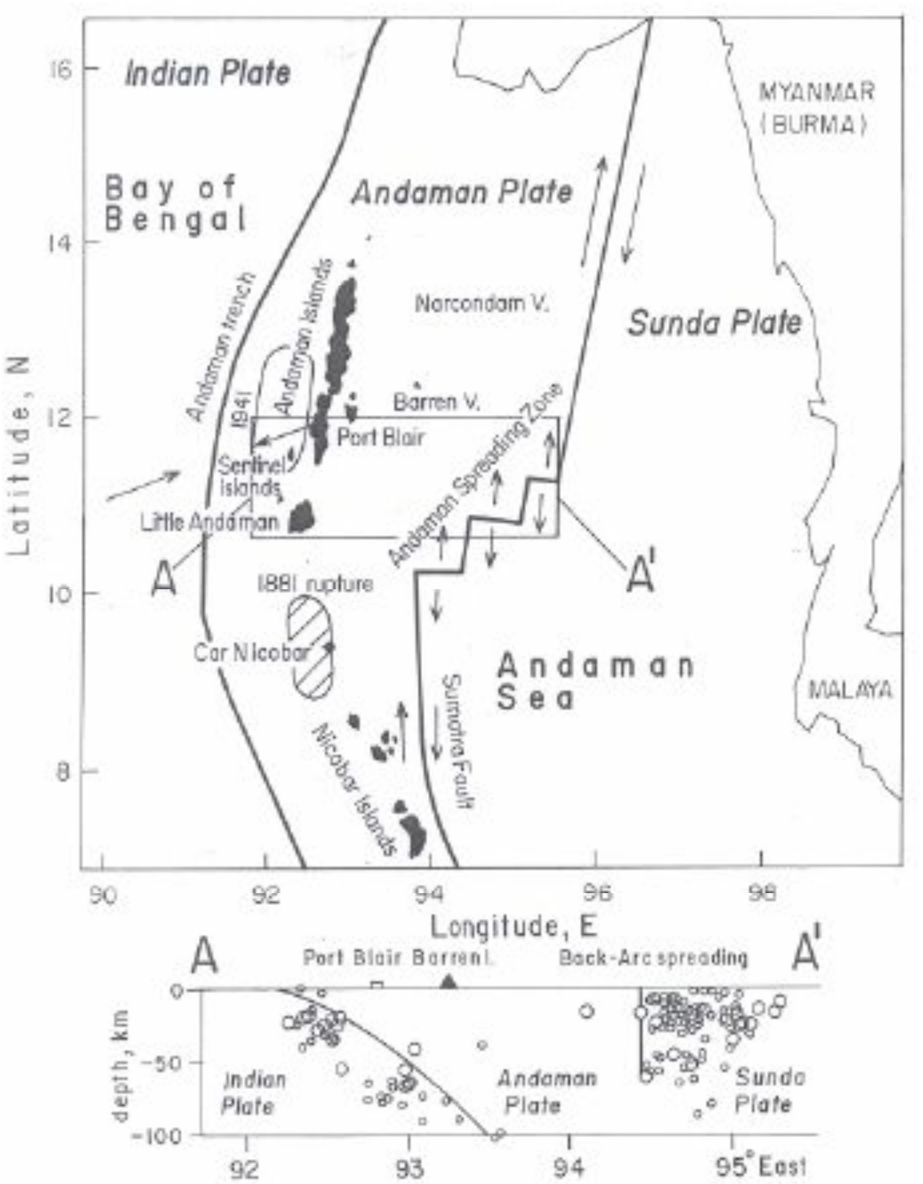

Fig. 5. The location of 1941 earthquake near Andaman Islands and 1881 earthquake near Car Nicobar are indicated. Seismicity between 10.8°N and 12°N are shown from Engdahl et al. (1998). The figure is from Ortiz and Bilham (2003).

The Makran Subduction Zone

The Makran subduction zone of Iran and Pakistan (boundary between Iran and Pakistan runs roughly N-S at about 62° E) is seismically less active but has produced great earthquakes and tsunamis. Great earthquakes of rupture lengths of about 200km each have occurred in 1483 (Long. 58 – 60°E), 1851 (Long. 61 - 63° E), 1945 (Long. 63 - 65° E) and 1765 (Long. 65 - 67° E) (Byrne et al. 1992). A tsunami is known to have occurred in Iran coast in 1008 (Murty et al. 1999). The 28 Nov. 1945 (Mw 8.0) earthquake generated the last major tsunami in the Arabian Sea. More than 4000 people were killed on the Makran coast by both the earthquake and the tsunami. The run up in Makran was 17m and at Kutch 11m. The tsunami caused damage in Bombay (now called Mumbai) with 2 m run up and affected Karwar (Karnataka) (Pendse, 1945; Mathur, 1998). This earthquake occurred in the eastern part of the Makran zone, two sides of which remain potential zones for great earthquakes. The Makran subduction zone is one of the largest sedimentary accretionary wedges on earth, covered with up to 7 km of thick sediments. Due to sudden slumping along Makran accretionary wedges with large amount of sediments may generate a large tsunami, somewhat similar to the 1992 Nicaragua earthquake of M_s 70-7.3 (Piatanesi et al. 1996) which generated a large tsunami due to fall of accretionary wedges.

The earthquake of 1945 in Eastern Makran is an interplate thrust event that ruptured approximately 1/5th of the length of the Makran subduction zone. Several earthquakes in this region show thrust mechanism The western Makran zone has no clear record of historic great earthquakes and modern instruments have also not detected shallow thrust events. Most earthquakes in western Makran occur within the down-going plate at intermediate depth.

Absence of plate boundary earthquakes in western Makran indicates either that entirely aseismic subduction occurs or that the plate boundary is currently locked and experiences great earthquakes with long repeat times. Evidence is presently inconclusive without GPS measurements and knowledge of velocity structure. However, presence of well-defined late Holocene terraces along portions of the coasts of eastern and western Makran could be interpreted as evidence that both sections of the arc are capable of generating large plate boundary earthquakes (Byrne et al. 1992).

Source Zones of Indus Delta, Kutch-Saurashtra and Bangladesh-Myanmar Regions

Our study indicates that the Indus delta and probably also the coasts of Kutch and Saurashtra are also potential zones for great thrust-type earthquakes and tsunamis. In May 1668 the Indus delta town of Samawani (or Samaji) with 30,000 houses was sunk due to an earthquake (Oldham, 1883) of magnitude 8. There might have been a tsunami to drown the coastal town. The 16 June 1819, Mw 7.8 and 19 June 1845 M7 earthquakes in Kutch probably caused tsunamis (Macmurdo, 1821; Nelson, 1846; Rastogi and Jaiswal, 2006). An earthquake in 1762 in Myanmar generated a tsunami and an earthquake in 1874 near Bangladesh had likely generated a tsunami. Some earthquakes in future also in these regions can possibly generate tsunamis.

Cummins (2007) observed similar pattern of generation of megathrust tsunamigenic earthquake along the coast of Myanmar as in the other parts of the subduction zones of the world. According to him the seismogenic zone of the Andaman-Nicobar subduction zone extends beneath the Bengal fan. Guzmn-Speziale and Ni (2000) interpreted that there is no active subduction between the Indian plate and Southeast Asia and suggested that all of the relative motion between the Indian and Eurasian plates is accommodated along the Sagaing fault in central Myanmar. But Global Positioning System (GPS) surveys suggested that only 60% of the relative plate motion is accommodated along the Sagaing fault and the remaining either by distributed deformation west of the Sagaing fault, or by locking of the Arakan subduction zone (Socquet et al. 2006; Vigny et al., 2003). According to GPS survey the Arakan subduction zone would be expected to produce a magnitude 8.5 earthquake every century or a magnitude 9 every 500 years (Socquet et al. 2006).

The northern Bay of Bengal is having a unique structure because it contains the world's largest submarine fan system i.e. called Bengal Fan, consisting of sediments that have been shed off Tibet and the Himalayas since the Early Miocene. The thickness of the Bengal Fan sediments reaches up to 20 km (Alam et al., 2003). Because even a 1-km-thick sediment cover can insulate the underlying plate enough to cause significant up-dip extension of the thermal regime required for seismogenesis (Wang et al., 1995).

One cannot be certain that the 1762 earthquake produced destructive tsunami; however the rapid rate of sedimentation in the Bay of Bengal could generate tsunamis caused by submarine landslides similar to other part of the world (Cummins, 2007). With the evidence of active convergence along a coastal region with an extremely high population density suggests that the risk of a major tsunami in the northern Bay of Bengal should be taken into consideration seriously.

Carlsberg Spreading ridge and Older Oceanic Ridges

Normal fault type earthquakes can also generate moderate tsunamis. Strike-slip earthquakes that cause horizontal movement of the ocean floor are not tsunamigenic but oblique-slip/dip-slip component in them can generate weak tsunamis. The Carlsberg spreading ridge and relics of past plate movements like Ninety-East ridge and Chagos ridge are sites of such earthquakes. The Chagos ridge east of Carlsberg ridge had given rise to a local tsunami due to a normal faulting earthquake of Mw 7.7 of 30 Nov. 1983 near Diego Garcia (Fig. 6). Hence, local tsunamis are possible in these regions.

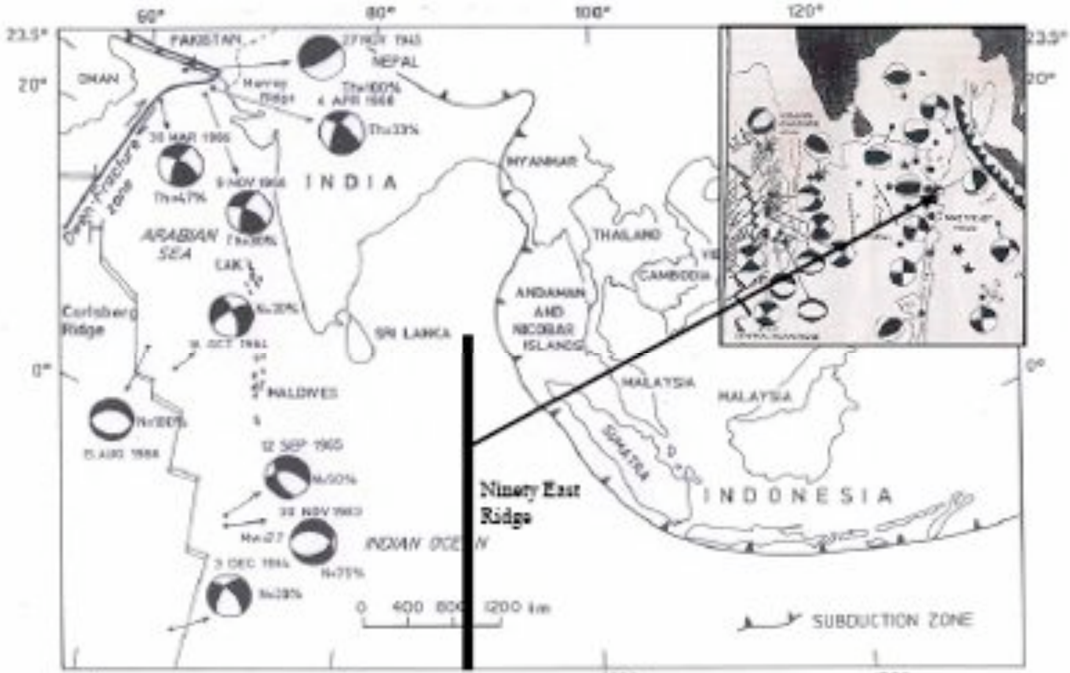

Fig. 6. Tectonic framework of the entire Indian Ocean and the focal mechanisms along the ridges in the Indian Ocean which indicate dip-slip component.

3. TSUNAMIS DUE TO VOLCANIC ERUPTIONS

The Sunda Arc (Indonesia) has the largest number of historically active volcanoes (76), has a total of 1,171 dated eruptions (Four fifths in the twentieth Century) and has suffered the highest number of damaging eruptions. However, most of the volcanoes are not on ocean bed and hence are not known to have caused tsunamis, except the Krakatau volcano. The renowned Krakatau volcano lies in the Sunda Strait between Java and Sumatra. The Krakatau eruptions in the third century AD (Chinese records), 416 AD (forming a 7km wide caldera), one between 416 AD and 1883, 1883 (7kmx5km caldera), 1927 and 1928 has caused tsunamis *(Smithsonian Institution Global Volcanism Program Website, 2000).*

According to ancient Japanese scriptures, the first known super colossal eruption of Krakatau occurred in the year 416 A. D. – Some have reported it to occur in 535 A.D. The energy of this eruption is estimated to have been about 400 megatons of TNT, or the equivalent of 20,000 Hiroshima bombs. This violent early eruption destroyed the volcano, which collapsed and created a 7 km wide submarine caldera. The remnants of this earlier violent volcanic explosion were the three islands of Krakatau, Verlaten and Lang. Undoubtedly the 416 A.D. eruption generated a series of catastrophic tsunamis, which must have been much greater than those generated in 1883. However, there are no records to document the size of these early tsunamis or the destruction they caused, except possibly a description from India.

Subsequent to the 416 A.D. eruption and prior to 1883, three volcanic cones of Krakatau and at least one older caldera had combined again to form the island of Rakata probably due to a large eruption. The volcanic cones on the island were aligned in a north-south direction. Overall approximate dimensions of the island were 5km x 7km (Pararas-Carayannis, 2003).

The historic record shows that the strongest tsunami was associated with the volcanic eruption of Krakatau in Indonesia on 27 Aug. 1883. The 35m-high tsunami took a toll of 36,000 lives in western Java and southern Sumatra. The island volcano of Krakatau exploded with devastating fury, blowing its underground magma chamber partly empty so that much overlying land and seabed collapsed into it forming a 7-km wide caldera. Tsunami waves were observed throughout the Indian Ocean, the Pacific Ocean, the American West Coast, South America, and even as far away as the English Channel. On the nearby coasts of Java and Sumatra the sea flood went many kilometers inland.

Subsequent local tsunamis in the Sunda Strait were generated by the 1927 and 1928 eruptions of the new volcano of Anak Krakatau (Child of Krakatau) that formed in the area.

4. CONCLUSION

Northern Sumatra and Andaman-Nicobar regions are assessed to be probably (M≥8.0) free from great earthquakes for a few decades due to occurrence of 2004 Mw 9.3 and 2005 Mw 8.7 earthquakes. However, stress altered due to 2004 and 2005 event in the surrounding region can generate earthquakes of magnitude M≤7.5. Central Sumatra & Java has potential for a tsunamigenic earthquake in future. However, the effect of tsunami due to this in India and Sri Lanka may be a limited one as the path of tsunami will be oblique to the rupture zone. Eastern and western parts of the Makran subduction zone of southern Pakistan are potential zones for great earthquakes that can generate tsunamis affecting west coast of India. The eastern part of the Makran zone has produced the 1945 Mw 8.0 earthquake that generated the last major tsunami in the Arabian Sea. Some sectors of the Makran zone are un-ruptured for a long time and can produce large earthquakes in near future. Indus Delta and may be the coasts of

Kutch and Saurashtra are also potential zones for great earthquakes and tsunami. Earthquakes in the southernmost Myanmar and Bangladesh have generated tsunamis in the past. Earthquakes in future also in these regions can possibly generate tsunamis.

5. ACKNOWLEDGEMENT

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Table 1. List of tsunamis generated due to earthquakes/volcanic eruptions that affected Indian region and vicinity in the Indian Ocean

S. N.	Date	Source/ Affected region	Long. °E	Lat. °N	Eq. Mag	Comment	Ref.
1	326 B.C.	Indus delta /Kutch region				Alexander's navy destroyed. Massive sea waves in the Arabian Sea due to large earthquake.	Lisitzin (1974)
2	416 AD	Java-Sumatra				Probably the 416 A.D. Krakatau eruption/explosion/collapse generated a series of catastrophic tsunamis affected Tamilnadu, which must have been much greater than those generated in 1883.	Rastogi & Jaiswal (2006)
3	500 AD	Poompuhar, Tamilnadu (probably due to Krakatau eruption)	79.52	11.12		Poompuhar town was a flourishing ancient town known as Kaveripattinam that was washed away due to tsunami generated probably due to Krakatau eruption	Rastogi & Jaiswal (2006)
4	900 AD	Nagapattinam Tamilnadu (may be from Sunda-Andaman arc)	79.53	10.46		Tsunami waves had washed away the Budhist monastery and several temples and killed hundreds of people. There is evidence of this in Kalaki Krishnamurty's book "Ponniyin Selvan- The Pinacle of Sacrifice".	Rastogi & Jaiswal (2006)
5	1008	Iranian Coast	60	25		Tsunami has been observed in the North Indian Ocean on the Iranian coast from a local earthquake.	Murty et al. (1999)
6	1524	Dabhol, Maharashtra	73.2	17		Tsunami due to a large earthquake caused considerable alarm to the Portugese fleet assembled in the area.	Bendick and Bilham, (1999)
7	May 1668	Samaji – Delta of Indus	68	24		The town of Samawani (or Samaji) sunk into the ground with 30,000 houses during an earthquake.	Oldham (1883)
8	1762.04.02	Bangladesh (Bay of Bengal)	92	22		The earthquake of Bangladesh also caused a tsunami in the Bay of Bengal. The water in the Hoogly River in Kolkata rose by two meters. The rise in the water level at Dhaka was so sudden that	Mathur (1988)

						hundreds of boats capsized and many people were drowned.	
9	1819.06.16	Kutch	71.9	26.6	Mw 7.8	The town of Sindri (26.6N 71.9E) and adjoining country were inundated by a tremendous rush from the ocean, and all submerged, the ground sinking apparently by about 5m	Macmurdo (1821)
10	1842.11.11	N. Bay of Bengal	90	21.5		Due to earthquake near the northern end of Bay of Bengal caused a tsunami by which waters of the distributaries of the Ganges Delta were agitated. Boats were tossed about as if by waves in a squall of wind.	Oldham (1883)
11	1845.06.19	Kutch	68.37	23.6	Mw 7.0	The sea rolled up the Koree mouth of the Indus overflowing the country as far westward as the Goongra river, northward to the vicinity of Veyre, and eastward to the Sindree Lake	Nelson (1846)
12	1847.10.31	Little Nicobar Island	93.667	7.333	Mw 7.5-7.9	Small island of Kondul (7¡13’N, 93¡42’E) near Little Nicobar was inundated by an earthquake whose Mw, magnitude could have been >7.5 (Bilham et al. 2005).	Berninghausen (1966), Heck, (1947)
13	1868.08.19	Andaman Islands	92.73	11.67			Rastogi & Jaiswal (2006)
14	May 1874	Sunderbans (Bangladesh)	89	22		Tsunami struck Sunderbans killing several hundred thousand people. It was result of an earthquake in Bhola district. Earthquake and tsunami both played havoc in vast areas of Sunderbans, 24-Prganas, Midnapore, Barishal, Khulna and Bhola. Even Kolkata felt its impact.	Rastogi & Jaiswal (2006)

15	1881.12.31	W. of Car Nicobar	92.43	8.52	Mw 7.9	Though tsunami run-ups and waves heights were not large; its effects were observed in the Andaman & Nicobar Islands (Port Blair, 1m) and were recorded on the east coast of India (Nagapatinam, 1.2m). Then tsunami struck Chennai, Vishakhapatnam, Mahanadi delta in Orissa and at Pamban in the Gulf of Mannar.	Berninghausen (1966), Ortiz and Bilham (2003)
16	Jan. 1882	Sri Lanka (may be from Indonesia)	81.14	8.34			Berninghausen (1966)
17	1883.08.27	Krakatau (Volcanic Eruption)	105.25	-6.06		Due to Krakatau volcanic eruption of in Indonesia, 35m-high tsunami took a toll of 36,000 lives in western Java and southern Sumatra. Tsunami waves were observed throughout the Indian Ocean, the Pacific Ocean, the American West Coast, South America, and even as far away as the English Channel.	Berninghausen (1966)
18.	1884	W. of Bay of Bengal				A tsunami was noticed at Dublet (mouth of Hoogly River) near Kolkata due to earthquake in the western part of the Bay of Bengal in 1884 that reached up to Port Blair.	Murty et al. (1999)
19.	1935.05.31	Andaman-Nicobar			Mw 7.5	Tsunami in SW Sumatra.	Rastogi & Jaiswal (2006)
20	1935.11.25	Andaman-Nicobar	94	5.5	Ms 6.5		Rastogi & Jaiswal (2006)
21	1941.06.26	Andaman Islands	92.5	12.1	Mw 7.7	Height of the tsunami was reported to be of the order of 0.75 to 1.25	Bilham et al.

						meters. This tsunami was witnessed along the eastern coast of India. It is believed that nearly 5,000 people were killed by the tsunami on the east coast of India.	(2005)
22	1945.11.27	Makran Coast	63.5	25.2	Mw 8.0	More than 4000 people were killed on the Makran Coast by both the earthquake and the tsunami. Max.run up 17m. The height of the tsunami in Mumbai was 2m. A total of 15 persons were washed away in Mumbai.	Murty et al. (1999)
23	1983.11.30	Chagos ridge	72.11	6.85	Mw 7.7	In the lagoon, on Diego Garcia, there was a 1.5-meter rise in tsunami wave height and there was some significant wave damage near the southeastern tip of the island. A 40 cm wave was also recorded at Victoria, Seychelles. There was a large zone of discolored seawater observed 60 - 70 km NNW of Diego Garcia.	Rastogi & Jaiswal (2006), NEIC
24	2004.12.26	Off west coast of N Sumatra and Andaman-Nicobar	95.947	3.307	Mw 9.3	The 2004 Sumatra-Andaman earthquake of magnitude 9.3 generated 30m-high tsunami near the Andaman-Nicobar region. It was the deadliest tsunami killing about 300.000 people in 13 countries situated all around the Indian Ocean. The earthquake produced large landslides that were also cause of generating destructive tsunami.	http://www/bestindia.com/jgsi,17pp. & Rastogi (2005b)
25	2005.03.28	Off west coast of N Sumatra	97.013	2.074	Mw 8.7	2005 tsunami was only locally damaging. A 3-meter tsunami damaged the port and airport on Simeulue. Tsunami runup heights as high as 2 meters were observed on the west coast of Nias and 1 meter at Singkil and Meulaboh, Sumatra.	Rastogi (2005) & NEIC
26	2007.09.12	Off west coast of S Sumatra	101.374	-4.52	Mw 8.4	Killing 9 people and injured few tens, generated relatively small tsunami near epicentral zone.	George, P.-C. (2007),

Abbreviation: MAK - Makran Accretion Zone, MUR – Murray Ridge, OWE – Owen Fracture Zone, CAR – Carlsberg Ridge, CHA – Chagos Archipelago, A & N – Andaman & Nicobar Islands, SUM – Sumatra, NIN – Ninety East Ridge, SUN – Sunda Subduction Zone and JAVA-Java.