

SEISMOTECTONICS OF THE INDIAN SUBCONTINENT AND THE BENGAL FAN

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Abstract

Bengal Fan in the northeastern Indian Ocean is bordered by the Indian mainland on the west, Bengal Foreland basin in the north and the Andaman - Sumatra Islands on the east. Seismicity of the Indian sub-continent and the Bengal Fan is predominantly confined to four major types of tectonic settings. They are i) Extra-Peninsular (Himalayan Region), associated with plate-collision seismicity, ii) Peninsular or the Stable Continental Region (SCR), associated with intra-plate stress related seismicity, iii) Equatorial region of the Central Indian Ocean Basin (CIOB), associated with intraplate crustal deformation and iv) the Andaman Nicobar arc region, with subduction related seismicity .

The extra-Peninsular seismicity is mainly due to the significant concentration of stress around the detachment plane, due to the northward underthrusting of the Indian lithosphere. During the period 1897-2000, five major earthquakes of magnitude greater than 8.0 have occurred in this region. Recent examples of extra-Peninsular seismicity are the Uttarkashi and Chamoli earthquakes, both located in the Garhwal Himalayan region and the 7.6 Mw earthquake that occurred in Pakistan on 8th October, 2005.

Since the last few decades, Peninsular Shield or the Stable Continental Region (SCR) has been experiencing moderate seismicity, which indicates the ongoing tectonic activity or reactivation of existing Precambrian faults in the area. These events are mainly due to strike slip movements at shallow depths (< 5 km) and thrust movements at deeper depths (>5 km) and are the consequence of the continued northward movement of the Indian plate and the resulting accumulation of strain energy. In some cases like Koyna earthquake, the activity is attributed to reservoir induced seismicity. Latur (1993), Jabalpur (1997) and Bhuj (2001) are examples of SCR earthquakes, out of which the Bhuj earthquake was the most disastrous event, unique to SCR.

A broad scale nature of intra-plate deformation, also a consequence of the Indian-Asian plate collision was reported in the equatorial region of the Central Indian Ocean Basin (5° N to 8° S; 70° E to 90° E). This region is associated with anomalous seismicity, high heat-flow along with folded and faulted oceanic basement and sediments. These observations suggest a nascent subduction zone in the Central Indian Ocean Basin (CIOB) formed mainly due to N-S compression acting on the Indian Plate.

Finally we have the convergent margin of significant seismo-tectonics, namely, the Andaman-Sumatra trench at the eastern edge of the Indian plate which is part of the Sunda Arc, extending from the eastern Himalayan syntaxis to the Sunda arc, a zone where the India-Australia plate (or plates) get subducted beneath the south-east Asian plate. This classic plate edge convergent margin or subduction zone, the only one in the Indian Ocean displays seismicity with a distinct eastward dipping Benioff zone with a focal depth of nearly 200 km north of Sumatra. The Andaman-Nicobar part of the trench is mostly associated with earthquakes of moderate magnitude (< 5.0) till recently.

In essence, the seismic hazards of the Indian mainland owe their origin to extra-Peninsular, SCR and subduction related seismicity, with the last one causing major concern at present.

Introduction

The great Sumatra earthquake of 26th December, 2004 (0629 hrs IST) followed by the unique Indian ocean tsunami have added a new dimension to the natural hazard scenario of the country. Hitherto, the coastal region is associated mainly with such hazards like cyclones, storm surges, sediment slumps, coastal erosion, etc. Seismicity associated with compressional tectonics is another hazard in the Indian mainland, including the coastal regions. However, the mega event and the associated aftershocks mostly oriented along the Andaman-Nicobar islands arc indicate the possibility of Andaman-Nicobar area as a significant seismic hazardous zone of the country. In this paper, the seismicity of the Indian mainland, including the Andaman and Nicobar Islands is briefly reviewed.

Fig.1 Tectonic setting and the seismicity of the Indian subcontinent and Bengal Fan. I) Extrapeninsular; II) Stable Continent Region (SCR); III) Central Indian Ocean Basin (CIOB); IV) Andaman-Sumatra subduction zone.

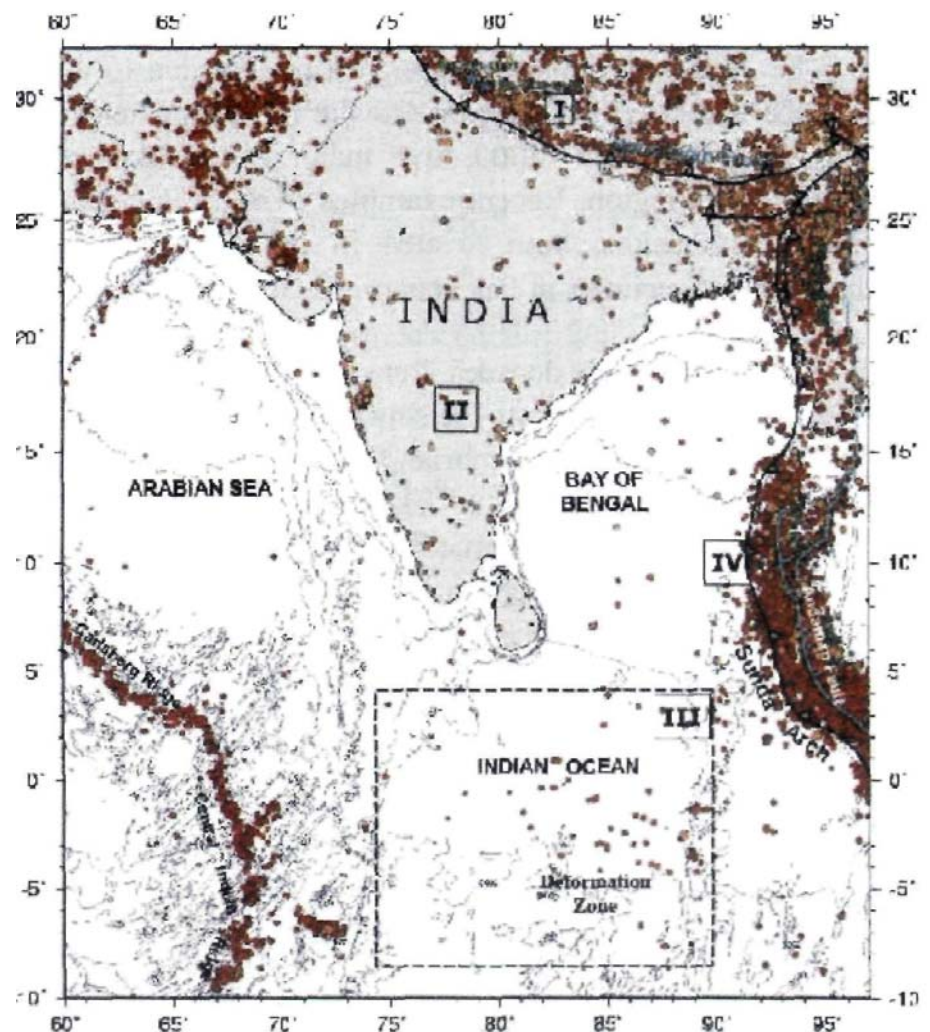
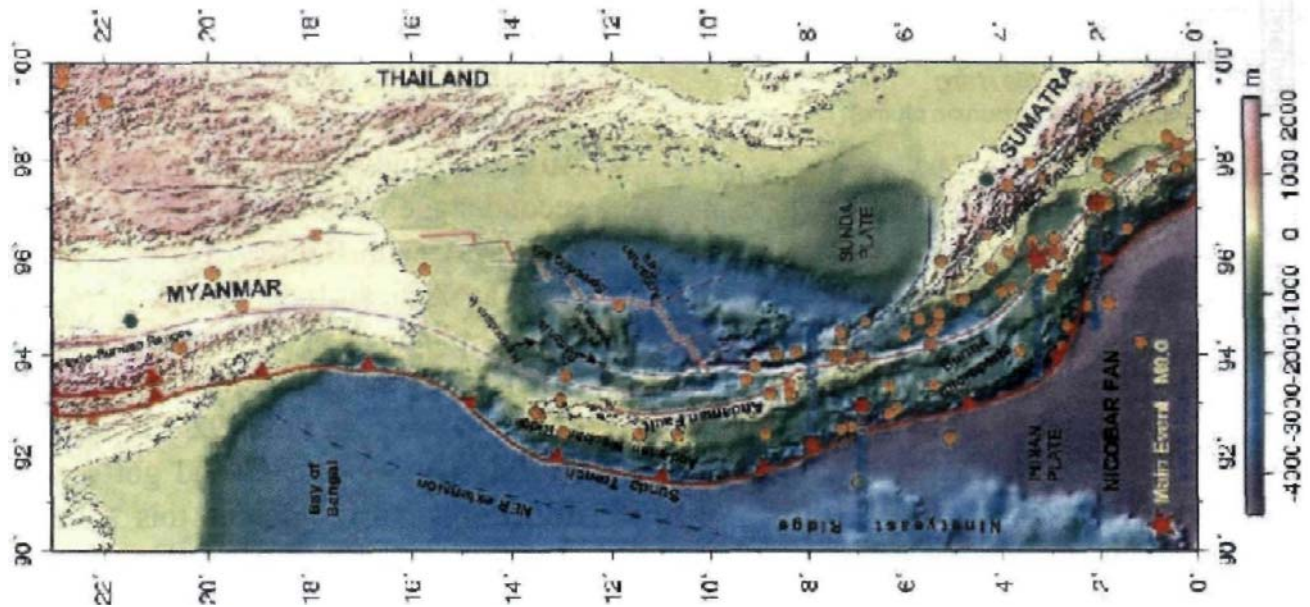


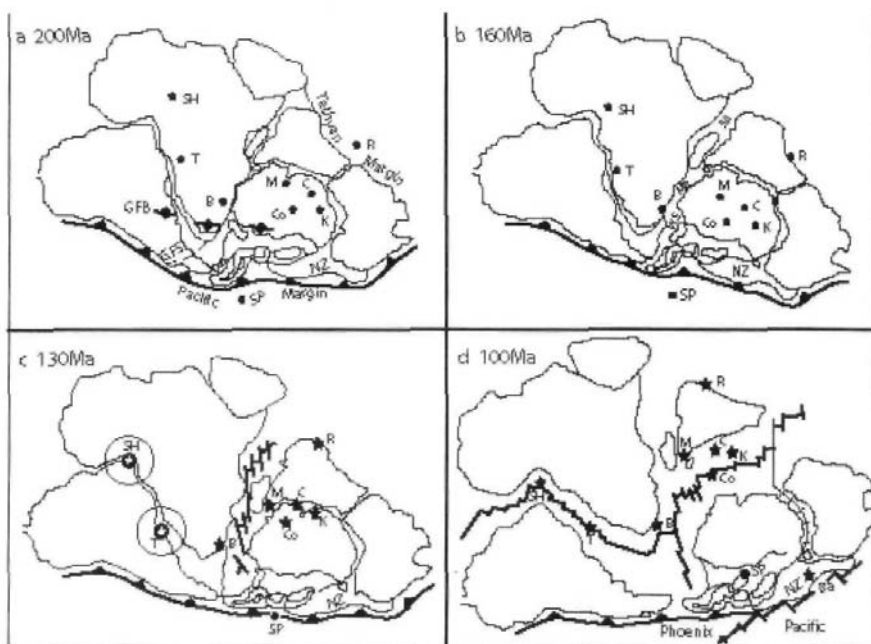
Fig. 2 The Sunda Trench axis: With the location of Great Sumatra Earthquake of 26, December, 2004.



Evolution of Indian Ocean and Bengal Fan

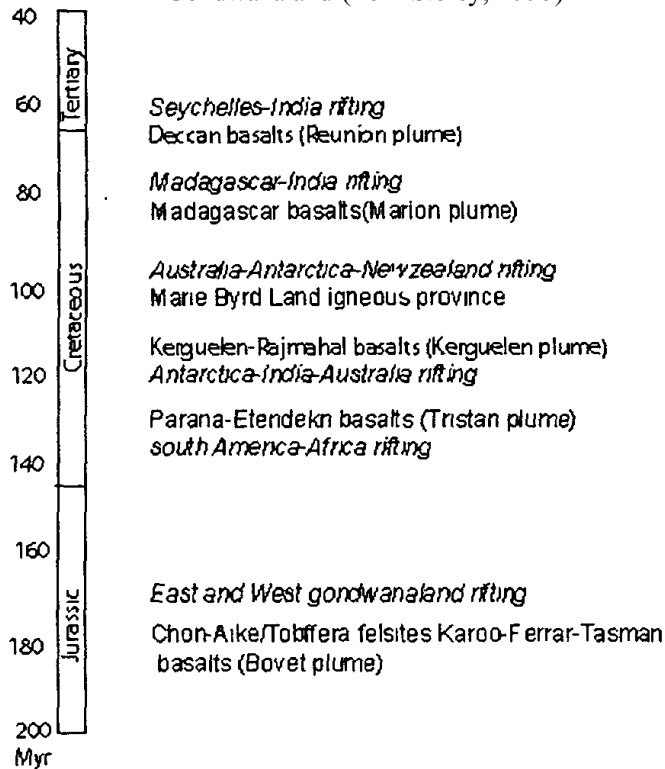
The evolution of Indian Ocean and the present morphology and tectonics of the bordering landmass are a consequence of the breakup of Gondwana land and the spreading across the three oceanic ridges namely, the southwest (SWIR), southeast (SEIR) and the central Indian ridges (CIR). The Indian Ocean covers an area of nearly 74 million sq.km, and is relatively younger than the Pacific and Atlantic Ocean (Ramana *et al*, 2003). There were three main episodes (Fig. 3) in the disintegration of Gondwana mainland (Storey, 1995).

Fig. 3(a) Different stages in the evolution of Indian Ocean since early Jurassic (180Ma) (modified from Storey, 1995)



Abbreviations for plumes are as follows: Ba: Balleny; B: Bouvet; C: Crozet; Co: Conrad; K: Kerguelen; M: Marion; R: Reunion; SH: St Helena; T: Tristan da Cunha; GFS: Gastre Fault System; GFB: Gondwanian fold belt; MB: Mozambique basin; NZ: New Zealand continental block; SB: Somali basin; SP: South Pole; WS: proto-Weddell Sea

Fig. 3(b) Chronology of events in the break up of Gondwanaland (from Storey, 1995)



The initial rifting started in early Jurassic time (180 Ma) when Gondwana divided into eastern and western parts, causing a seaway separating South America and Africa from Antarctica, Australia, India and New Zealand. The second stage occurred in early Cretaceous (130 Ma), with South America separating from an African-India plate and African-Indian plate itself separating from the Antarctica. Finally the third stage occurred in late Cretaceous time (92-100 Ma) when Australia and New Zealand got separated from Antarctica. Around this time only Madagascar and Seychelles separated from India, as the latter migrated northwards away from Africa and Antarctica.

The initial separation of India from Antarctica (130 Ma) is in a NW-SE direction, whereas around late Cretaceous

(90 to 80 Ma), a plate reorganization took place when this orientation changed essentially to N-S. The soft collision between India and Asia might have occurred around 53 Ma (Paleocene-Eocene-Boundary) which resulted in the initiation of Himalayan uplift. The hard continent-continent collision with the Asian landmass, which resulted in the closing of the marginal sea behind the Island Arc, occurred at about 45 Ma (Middle-Eocene). The continued northeastward drift and the associated counter-clockwise rotation of the Indian plate until about 20 Ma was accommodated by two main phases (Biswas and Agarwal, 1992).

- i) By indentation of Asia leading to the consumption of Indian Ocean crust of the remaining Tethyan seaway in the north and in the east followed by its terminal collision with the Indo-Sinian plate during the late Oligocene.
- ii) Followed by tectonic escape of fragments of the Asian plate causing spreading in the South China Sea, the Gulf of Thailand and the margin below the Andaman Sea.

The continued rotation, combined with northeastward drift of the Indian Plate in the Oligocene led to the consumption of oceanic crust between the eastern edge of the Indian Plate at the Indo-Burmese subduction zone. Subduction of Indian plate started along the western Sunda Arc (Curry *et. al*, 1982) following the breakup of Gondwanaland in the early Cretaceous (130 Ma) and the Andaman-Nicobar ridge and the Indo-Burma ranges were uplifted as a sedimentary arc during the Oligocene to late Eocene, consequent to the hard continent collision in the north.

The drift of the Indian plate ever since its breakup from Antarctica is evidenced by traces of hot spots (mantle plumes) presently forming major aseismic ridges in the Indian Ocean, Bengal Fan and Arabian Sea (Duncan and Richards, 1991; Storey, 1995). The Kerguelen plume (90°E Ridge) and the Reunion plume (Chagos-Laccadiv Ridge) are the two examples of such plume trajectories (Fig. 4).

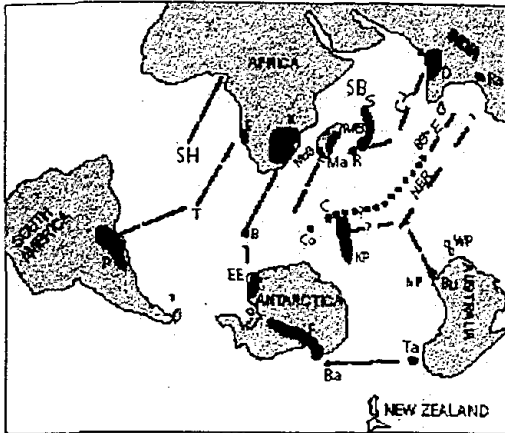


Fig. 4 Trajectories of mantle plumes (hot spots) in the Indian Ocean and south Atlantic (modified from Storey, 1995)

Abbreviations Bu: Bundury; D: Deccan; E: Etendeka; EE: Explora Escarpment; F: Ferrar; K: Karoo; KP: Kerguelen Plateau; Ma: Madagascar; NP: Naturaliste Plateau; P: Parana; Ra: Rajmahal; Ta: Tasmanian; WP: Wallaby Plateau and known hotspots; C-L: Chagos-Laccadive; MB: Mascarene basin; MoB: Mozambique basin; NER: Ninetyeast Ridge; SB: Somali basin; S: Seychelles.

In some cases the initiation of mantle plume activity coincides with the breakup events, for example, the Kerguelen plume (120 Ma) activity coincides with the Antarctica-India-Australia rifting and the Reunion plume (70 Ma) coincides with the separation of Seychelles from India. In a similar way, Marion plume (90 Ma) might coincide with the rifting between Madagascar and India (Storey, 1995). However there are also instances where breakup events are not associated with any plume activity (for example separation between Antarctica & Australia).

In recent years, considerable geophysical data have been collected in the Bengal Fan which resulted in several theories and refined models for the breakup events and to the nature and origin of the aseismic ridges in the Bengal Fan (Ramana *et al.*, 2001), though some complexities still remain in explaining the geodynamics of this region, mainly because of the thick pile of sediments in the northern Bengal Fan, which obscure the tectonics associated with the separation and movement of the Indian plate (Murthy, 1995). These details are not discussed here as it deviates from the scope of the paper.

Extra-peninsular (Himalayan) seismicity

The largest and the most severe earthquakes occur at the boundaries of the Indian plate at the north (Himalayan) and at the east (Andaman- Nicobar Islands).

The Indian plate is subjected to predominantly a NE directed compressional stress, which in consequence has resulted in its northern edge to under thrust Tibet. About 2500 km of post-eocene shortening has been mainly accommodated through crustal stacking along the system of intra-continental thrust and internal deformation of the Indian plate, which resulted in the uplift of Himalayas (Anand, 2000).

The Himalayas at the northern edge of the Indian plate extend over a distance of about 2400 km from the peak of Nanga Prabhat (elevation 8125 m) in the west to the peak of Namcha Barwa (elevation 7755 m) in the east and comprises the most spectacular lofty mountain ranges of the world (Umesh, 1992). It forms a part of the well known Alpide belt extending from Indonesia to Spain. It is believed to be a product of ongoing collision of Indian and Eurasian continents. Most workers have divided the Himalayas into a series of longitudinal tectono-stratigraphic domains (Nath *et al*, 2000) such as,

- | | |
|---------------------|---------------------|
| a) Sub-Himalayan | c) Higher-Himalayan |
| b) Lesser-Himalayan | d) Tethys-Himalayan |

which are separated by major dislocation zones (Fig. 5). The lesser and higher Himalayas are separated by a ductile shear zone called the Main Central Thrust (Nath *et al.*, 2000).

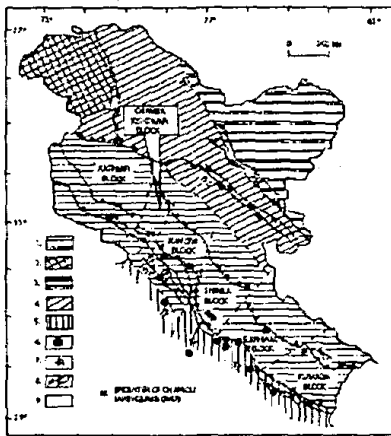


Fig. 5 Tectonostratigraphic domains of the Himalaya. (modified from Narula *et al*, 2000)

1. Main Himalayan Seismic Zone(MHSZ); 2. Kashmir Syntaxial Seismic Zone (KSSZ); 3. High Plateau Seismic Zone (HPSZ); 4. High Himalayan Seismic Zone (HHSZ); 5. Foot Hill Seismic Zone (FHSZ); 6. Specific locations where neotectonic activity has been recorded; 7. Directions of crustal shortening during Quaternary; 8. Suture Zone; 9. Block boundary based on geological/geophysical/tectonic flux attributes. SSZ-Shylok Suture Zone; ISZ-Indus Suture Zone; KF-Karakoram Fault; MCT-Main Central Thrust; MBF-Main Boundary Fault; FHT-Foot Hill Thrust.

The Himalayan range is associated with some of the largest Earthquakes in the world (Tandon, 1992) and accounts for nearly 15% of the yearly Global seismic energy released (Narula *et al*, 2000). Approximately half of the Himalayan arc has ruptured in four great earthquakes in the past 100 years (1897, 1905, 1934 and 1950) (Bilham, 1995).

In the Himalayan collision zone, the stress orientation results in the deformation at the plate boundary (Rajendran *et al*, 1992). The broad region in the Himalaya include the mountain ranges bounded by Sulaiman and Kirthar ranges to the west, Hindukush ranges in the north-west and the Tibetan platue in the north. Towards the east, the Himalaya is bordered by the Arakan Burman ranges. The average crustal thickness under the Himalayas is of the order of 70 km (Gupta and Narain, 1967).

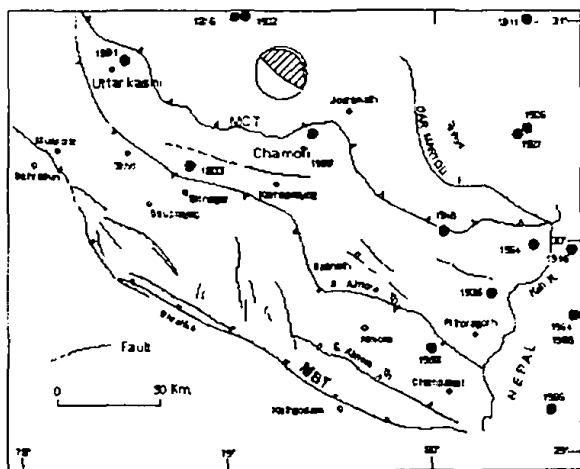
Himalayan seismicity is a consequence of concentration of the stress around the ramp on the detachment plane, due to the underthrusting of the Indian Lithosphere at its collision with the Asian Counterpart (Molnar and Lyon-chen, 1988), a process that is taking place since tens of millions of years. The earliest catastrophic event in the Himalaya occurred in the Garhwal-Kumaon sector in 1803. During the period from 1897-2000 (113 years) fourteen major earthquakes of magnitude greater than 7.5, including 5 great earthquakes of magnitude greater than 8.0 have occurred in the Himalayan-Burma region (Mandal *et al*, 2000). In the last decade

two earthquakes of magnitude greater than 6.0 (the Uttarkashi Earthquake of 1991 and Chamoli Earthquake of 1999) occurred in the Garhwal Himalaya, which represents the central seismic gap area for high magnitude earthquakes of >8.0 (Gupta *et al*, 1995). Both these events with almost identical magnitude of 6.6 and separated by about 80 km are due to the movements along the thrust plane or detachment surface due to the underthrusting of the Indian Lithosphere. The detachment dips at an angle of 2-6° between the lesser Himalayas (southern part) whereas its steepness increases to nearly 15° towards north beneath the higher Himalayan range,

A more recent example of Himalayan seismicity is the occurrence of a 7.6 magnitude earthquake in Pakistan in the early hours of 8th October, 2005, with its epicenter located about 65 km north-east of Islamabad (near Muzafarabad) with a focal depth of nearly 10 km. The loss of human lives due to this catastrophic event is estimated to be nearly 100,000.

The Uttarkashi earthquake of 20th Oct. 1991, 30.7°N, 78.7°E with a magnitude of 6.6, was associated with the Main Central Thrust Zone (MCT) of Himalaya. The focal depth of the event is about 15 km (Mandal *et. al*, 2000) and the quake has claimed nearly 2000 human lives. This event is characteristic of the present day motion of the thrust-fault system. The Chamoli earthquake of 28th March, 1999 with its epicenter at about 30.5°N, 79.4°E and focal depth of about 15km is another example of extra-Peninsular seismicity associated with the Himalayan Orogeny (Mandal *et al*, 2000, Rastogi, 2000, Narula *et al*, 2000) and it has caused 100 deaths approximately. The epicenter zone of the Chamoli earthquake also lies within the boundaries of the main Central Thrust (MCT) and Main Boundary Thrust (MBT) in the lesser Himalayan Zone (Fig. 6).

Fig. 6 Tectonics in the vicinity of Uttarkashi (1991) and Chamoli (1999) earthquakes (after Rastogi, 2000)
 MBT: Main Boundary Thrust MCT: Main Central Thrust.



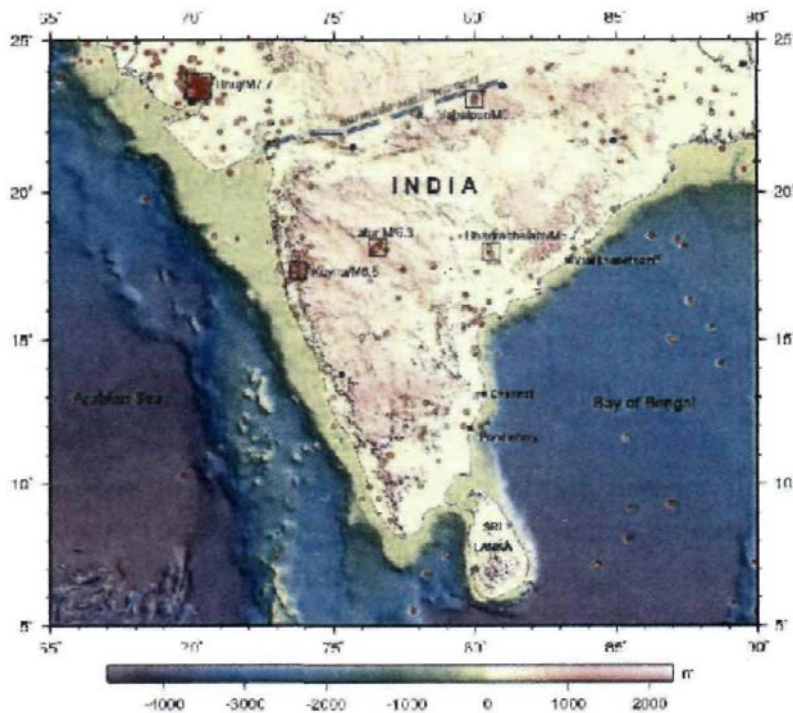
Study of Uttarkashi and Chamoli earthquakes has helped to identify the causative thrust in the Lesser Himalaya and the Frontal thrust area of the Himalaya (Mandal *et al*, 2000). Both these earthquakes nucleated near the ramp (detachment surface) at about 15 km depth, beneath the surface expression of Vaikrita thrust or Main Central Thrust (MCT). An important feature of the Himalayan seismicity is that it is of shallow nature with no volcanism associated (Bilham and Gaur, 2000). In the absence of

heavy down-going slab, that is characteristic of a subduction zone, the forces driving the collision are mainly due to spreading at the mid-oceanic ridges and the basal shear beneath the plate.

Peninsular or stable continental region (SCR) seismicity

During the last four decades, the Peninsular shield (Fig. 7) comprising mostly the Stable Continental Region (SCR) has also experienced moderate seismicity ($< M_w 5.0$), with some disastrous events such as the Latur earthquake of 1993 and Kutch (or Bhuj) earthquake of 2001.

Fig. 7 Seismicity associated with Stable Continent Region (SCR), with location and magnitude of different events.



These SCR earthquakes bear the testimony of ongoing tectonic activity in the Indian shield. These earthquakes can be explained in terms of reactivation of pre-existing faults, triggered mainly by the NNE compression due to movement of Indian plate and also by other local factors like topography, density heterogeneity, etc. (Mandal *et al*, 2000). Some of the typical examples of SCR earthquakes are the Koyna in 1967, Latur in 1993, Jabalpur in 1997 and the Kutch in 2001.

Koyna earthquake:

Earthquakes are reported in the vicinity of Koyna reservoir of Maharashtra for the last four decades (Gupta *et al*, 1969, Rastogi and Mandal, 1999, Mandal *et al*, 2000). Continued seismicity in this region has been explained in terms of loading of Koyna reservoir. Reservoir induced seismicity of significant magnitude ($M_w 6.3$) occurred on 11th Dec, 1967 with a focal depth of about 5 km and the latest event in this region is dated 12th March, 2000 (Mandal *et al*, 2000). Alignment of epicenters in this region shows a southward shift in recent years which were explained as due to the filling of Warna reservoir, located 35 km SSE of the main Koyna reservoir (Gupta *et al*, 1969, Mandal *et al*, 1998, Rastogi and Mandal, 1999). The Koyna-Warna seismic zone is associated with two NNE-SSW left-lateral strike-slip faults and a NW-SE normal fault (near Warna reservoir) along which strain energy gets accumulated due to the northward movement of the Indian plate. Another reason attributed to the Koyna-Warna seismicity is the periodic water level fluctuations in the reservoir, which might be responsible for the nucleation of fracturing process. According to Mandal *et al.*, (2000), the nucleation might be originating first at shallow depths (< 1 km) and then propagate to the base of the seismogenic layer (8-10 km), through the porous and permeable Koyna-Warna fault zone.

Latur earthquake (1993): Another typical SCR earthquake of magnitude 6.2 occurred on 30th Sept. 1993 in Latur area of Maharashtra (Fig.7), with epicenter located at 18°03'N, 76°33'E, that has caused human loss of nearly 10,000: The focal depth of this event is much shallower (3 km), the tremor itself being the result of reactivation of a pre-existing fault that has a previous history of movements. Kayal *et al*, (1995), showed that the region beneath the

epicenter zone of Latur earthquake is associated with strike-slip movement at shallow depths (<5 km) and thrust movement at deeper depth (>5 km). Mandal *et al*, (2000) indicate that the Latur earthquake was caused by an approximately 45°SW dipping thrust at a depth of 3 km. Though attempts were made to attribute reservoir induced seismicity to Latur earthquake also (suggesting percolation from neighboring Makni reservoir), studies by Rastogi (1995) indicate that Latur earthquake can not be classified under Reservoir induced seismicity.

Jabalpur earthquake (1997): This earthquake of moderate magnitude (Mw 5.8) that occurred on 22nd March, 1997 at Jabalpur is located (Fig.8) along the Narmada-Son Lineament, a major tectonic lineament passing through the central part of SCR. It is relatively a deep-focus earthquake of focal depth of 35 km, with the causative source explained as due to the reactivation of the south dipping south Narmada fault near Jabalpur, a part of the major E.W trending Narmada-Son-Lineament. This lineament has a past history of reactivation with an earlier event reported in 1927, namely the Son valley earthquake of magnitude 6.7. Studies on the seismicity of the NS lineament indicate an average recurrence period of 16 years (Rajendran, *et al.*, 1996).

Bhuj (or Kutch or Gujarat) earthquake of 2001: Bhuj (or Kutch) earthquake of 26th Jan 2001, (Mw7.7), occurred in the northwestern edge of the Indian shield (Fig. 7) is the most damaging event in recent years that took nearly 20,000 lives with collapse of homes of the order of 400,000 (Rajendran *et al*, 2001). The epicenter of this Republic Day earthquake (23.6°N, 69.8°E) is located north of the Kutch mainland fault (Gaur 2001). This region lies east of a major plate boundary called the Herat-Chaman plate boundary along which Indian continent slips past northward. Two damaging earthquakes have earlier been reported in this area; the 1819 event (Mw 7.7) and the other in 1956 near Anjar, located south of the Kutch Mainland Fault. The 1819 event was also the result of the reactivation of another fault located north of the Rann of Kutch area, which in fact resulted in the uplift of an 80 km long fault scrap, now called as the Allah Bund, with a relief of 6.5 m (Gaur, 2001).

The Kutch region is underlain by a Mesozoic rift system, the faults associated with it being prone for failure under the Compressional regime. Both the 1819 and 2001 are such reactivation events. Rajendran *et al*, (2001) described the post-seismic field observations and their impact on the mechanism of Kutch earthquake.

Intra-Plate deformation in the equatorial region of CIOB

The equatorial region of the Central Indian Ocean Basin (5°N to 8°S, 80°E to 90°E) is undergoing deformation since late Miocene 7 Ma, as a deviation from the conventional plate tectonic theory, according to which such a deformation should generally occur at the convergent (subduction) and divergent (mid-oceanic ridges) and not in the interior of the plate (Murthy *et al*, 1993, Murthy and Rao, 1992). An extensive study has been carried out during the last two decades over this area (Fig. 8) and the results agree in general that the Indian Plate is currently under a N-S Compression as a result of two mutually opposing forces, the continued spreading across the South East Indian Ridge (SEIR) and the resistance to shortening across the Himalayas at the northern end of the plate (Cochran *et al*, 1987, 1988). Seismic reflection data

(Fig. 9) for example indicate folded and faulted seismic basement and overlying sediments in the deformation zone, reported initially by Eittreim and Ewing (1972) and subsequently by several others (Weissel *et al*, 1980, Geller *et al*, 1983, Levchenko, 1989, Curray and Munasinghe, 1989, Bull, 1990, Bull and Scrutton, 1990, Cochran, 1990, Neprochnov *et al*, 1998, Krishna *et al*, 1998, Gordon *et al*, 1998)

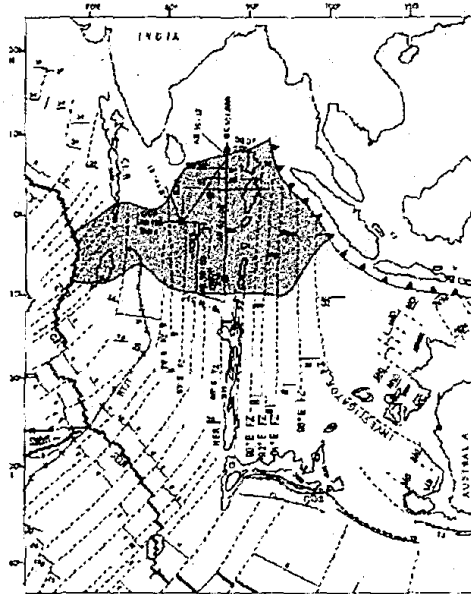
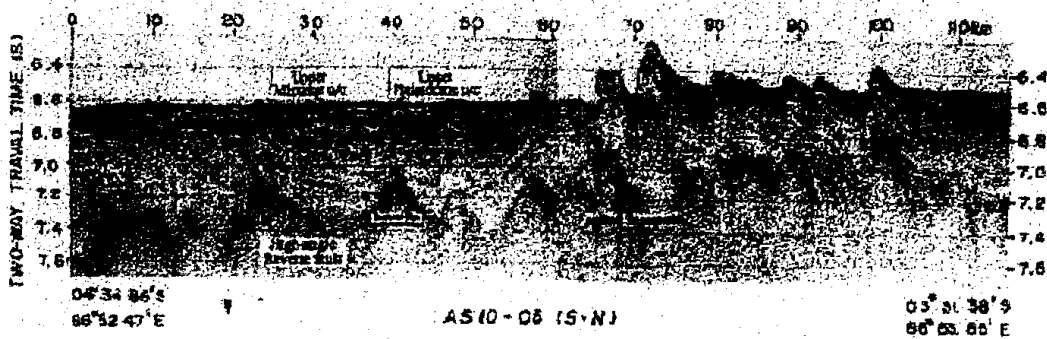


Fig. 8 Intraplate crustal deformation in the Central Indian Ocean Basin (CIOB).

F2 : Fraction zones; ODP: Ocean Drilling Program; SWIR: Southwest Indian Ridge; SEIR: South East Indian Ridge; CIR: Central Indian Ridge; CLR: Chagoas-Laccadiv Ridge; NER: Ninety East Ridge; RTJT: Rodrique Triple Junction Trace; COB: Continent Ocean Boundary; Deformation zone shaded.

Numbers indicate seafloor spreading anomalies; AS, SK are ship tracks, (modified from Gordon *et al*, 1990, Royer *et al*, 1989,1991)

Fig 9 Oceanic basement and sediment section below the upper Miocene.



The boundary are extremely crumpled in the form of tight holds and high angle faults. Termination of lower sediment layers and basement rise indicates pre-determational origin.

Two sets of deformed fabric have been observed; long wavelength (100-300 km), large amplitude (1-2 km) folds are generally observed in the basement and overlying sediments, with short wavelength (25 km) generally occurring over the crest of the large amplitude anticlines. The short wavelength undulations are generally bounded by high angle faults having an azimuth of nearly 100° (Weissel *et al*, 1980). Bull and Scrutton (1990) interpreted these high angle faults as the reactivated normal faults formed at the spreading axis of the SE Indian ridge at which this lithosphere has originated around 60-90 Ma. This part of the deformed crust in the Central Indian Ocean Basin is associated with high seismicity (Stover, 1996; Sykes, 1970 and

Stein and Okal, 1978) with compressional and strike slip earthquakes (Bergman and Solmon, 1985) and high localized heat flow (Weissel *et al*, 1980, Gellar *et al*, 1983).

Studies carried out under the Ocean Drilling Program (ODP Leg 116, Cochran *et al*, 1987, 1988) indicate that the sediments in the deformed block mainly comprise of a sequence of turbidites originating from the apex of the Bengal fan in the north and also from the eastern continental margin of India (ECMI). Curray and Munasinghe (1989) and Gordon *et al*, 1990 reported that the onset of deformation can be correlated over a wide area between the Central Indian Ridge in the west and up to the Java-Sumatra subduction zone in the east. Murthy *et al*, (1993) were of the view that the Bengal Fan turbidites in this region are much older than early Miocene and may stretch as far as the Oligocene (23Ma). They indicated that the major axis of compression is in a NW-SE direction. In an interesting study, Weins *et al*, (1985) and Gordon *et al*, (1998) suggested a diffuse plate boundary in the zone of deformation in the Central Indian Ocean Basin which might separate the rigid Indo-Australian plate into two plates. Though it is believed now that the deformation in the equatorial Indian Ocean is a diffuse plate boundary, there is no consensus about the timing of initiation of motion within the India-Australian plate.

Krishna *et al*, (1998) have made an extensive study of the seismic reflection data of the deformation zone, and proposed periodic deformation in the area, instead of a single phase of Late Miocene (7 Ma) deformation that was reported by earlier workers. According to them the periodic deformation comprises four phases (Fig. 10), the first phase prior to early Miocene when the Oceanic basement in the northeastern Indian Ocean Basin underwent deformation, followed by three stages during Late Miocene (7 Ma), early Pliocene (4 Ma) and Late Pleistocene (0.8 Ma), with a periodicity of 3.5 Ma.

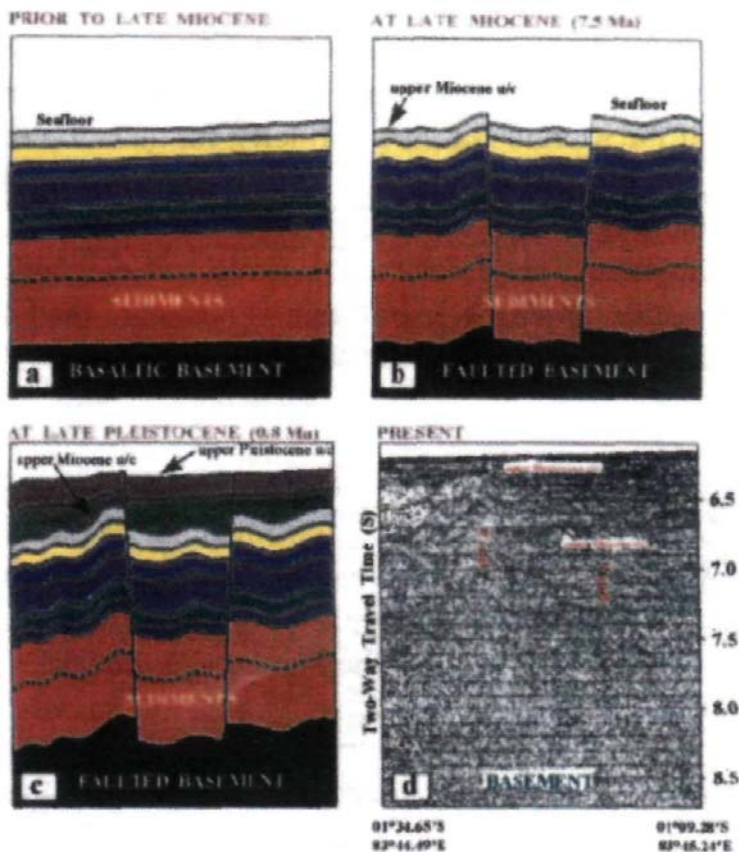


Fig. 10 Conceptual models exhibiting the gradual development of the topography of the upper Miocene unconformity. (after Krishna *et al*, 1998)

The concept of a diffuse plate boundary in the equatorial region of CIOB separating the Indian and Australian plate assumes significance in the context of Sumatra earthquake of 26th December, 2004, since it is now believed that the Australian and Indian plates are moving in opposite direction at the convergent boundary near Sumatra and the oblique convergence of these two plates with reference to the Andaman-Sunda arc is one of the prime reasons for the stress buildup at the plate interface.

Seismicity associated with Andaman-Sumatra Arc

The Andaman-Nicobar arc in the northeastern Indian Ocean defines a nearly 1100 km long active plate margin, where the Pacific Arc system through its continuation into the Sunda arc gradually transits northward along the strike to young fold belts of Burma (Fig. 2). The Andaman-Nicobar arc is part of the Sunda arc of nearly 6000 km that extends from the eastern Himalayan syntaxis in the north through the western Burma, the western Andaman sea, Sumatra and Java and continues into the Banda arc of eastern Indonesia (Curry, 1989). It is a typical example of a convergent or subduction margin where the Indian-Australia plate (or plates) subduct beneath the Eurasian or southeast Asian plate. Active subduction beneath the arc might have started following the breakup of Gondwanaland in Late Cretaceous (130 Ma). The Andaman-Nicobar ridge and the Indo-Burman ranges were uplifted as a sedimentary arc during Oligocene to Eocene, (45-28 Ma); simultaneously with the uplift of the non-volcanic ridge to the southeast along the Sunda arc. Active andisite volcanism occurs all along this arc and seismicity associated with this convergent margin shows a distinct Benioff zone, with variable focal depth of the order of 150-700 km. Deep focus earthquakes originate at a depth of nearly 700 km in the Java part of the trench, whereas the focal depth reduces towards north. Active subduction of the Indian Ocean Lithosphere below the Andaman Arc is primarily documented by (1) an east-dipping Benioff zone down to 200 km (2) Anomalous heat flow, (3) An active volcanic arc (4) Large amplitude gravity anomalies and (5) Correlation of arc-trench bathymetry to morpho- tectonic elements and their underlying seismic zone. Major variations occur around the length of 6000 km arcuate shaped segment of the Sunda Arc. These variations are mainly due to the direction and spread of convergence across the subduction zone, the thickness of the accreted sediments, the age of the lithosphere all along the trench axis, etc. (Curry, 1989).

The Andaman back arc basin behind the Andaman-Nicobar trench is the effect of the oblique convergence of Indo-Australian plate(s) at the Sunda Arc. The Andaman Sea might have started opening approximately in an E-W direction as a typical back arc extensional basin during Oligocene and resulted in the formation of the Mergui Basin, a northerly continuation of the North Sumatra Basin (Fig. 2). According to Curry *et al*, (1982), the entire Central Andaman Basin might have opened in slightly more than 10.8 Ma. However, in a recent study, Kamesh *et al*, (2004) on the basis of swath bathymetry, single channel seismic and magnetic data, suggested that the time of initiation of spreading in the back arc basin is not more than 4 Ma. A two phase opening of Andaman Sea has been described by Khan and Chakraborty (2005) based on seismotectonic evidence.

The volcanoes and volcanic rocks of the Andaman Sea have been studied by several workers (Dasgupta, 1992). Most conspicuous volcanic features in the central Andaman basin are the Barren and Narcondam Islands and the Alcock and Sewell seamounts (Fig. 2). Recent Barren Island Volcanism was initiated in March 1991 and completed by October, 1991. Volcanic activity is also reported from the Barren Islands within few months of the Sumatra earthquake.

The Andaman-Nicobar Sumatra Trench, which is part of the Sunda arc, is the only one convergent margin in the Indian Ocean. Though the seismicity associated with this arc is moderate and does not raise any concern so far, the scenario has significantly changed after the

26th December, 2004, Sumatra earthquake of Mw 9.3. This rupture propagated northwards towards the Nicobar-Andaman Island arc, and to this date as many as few thousand aftershocks were reported after the main event. Apart from the main shock of 26th December, the aftershocks of 28th March, (Mw 8.4) and 24th July, 2005 (Mw 7.3) were felt along the Coastal area of Andhra Pradesh and Tamilnadu margin. The frequency and amplitude of earthquakes in the Andaman and Nicobar belt show significant rise since December, 2004 and thus pose a new seismic hazard for the coastal region of India, though fortunately none of these aftershocks were associated with a Tsunami.

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