

Interactions and Seismicity of Indian Tectonic Plate with its Neighboring Plates: An Overview

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Abstract Understanding earthquakes and its prediction is most challenging tasks. Even though the earthquakes have been understood clearly, the prediction of earthquakes would take more time to come into reality. For this, collection of earthquake data and its interpretation plays a vital role. Its importance continues for few more decades in understanding the various aspects of earth structure and tectonic plate interactions. India, the second largest populous country of the world has experienced and is continuing to experience both inter and intra plate earthquakes, claiming life loss as well as damage to built environment. Apart from earthquakes, India has also experienced Tsunamis in both the directions; eastern tsunamis from Sumatra and western tsunamis from Makran. In this paper using past earthquake data, Indian plate interactions with its neighboring major (Eurasia, Africa & Australia) and minor plates (Arabia, Burmese & Sunda plate) have been understood. Upon clearly observing seven interactions, it is clear that interaction types, their lengths and thickness of plate play a great role in the occurrence of major to great earthquakes.

Keywords *Crustal Thickness; Earthquake Data; Plate Interaction Types; Interaction Lengths*

1. Introduction

Earthquakes accompany many changes in the earth from the smallest to the largest of the events. They are ideal for trying to understand dynamic patterns in the earth. As the most part earthquake phenomena is simple and discrete events which will objectively signal the stress vectors, motions, and shifts in the vast tectonic plates of the earth's crust. The patterns in earthquake activity directly provide an objective method to describe how plates are moving. Earthquakes can be classified based on their magnitude and focal depths.

Seismic stations of worldwide network records the various earthquakes occurring every day across the globe. These recorded earthquake data are analyzed with the help of computers. The data of geographical location and magnitude of all these detected earthquakes is used to plot the maps at the regional level. As a result, the details of present plate motion are always under observation. Figure 1

show the epicentral locations of earthquakes which have been recorded from 1900 to 2013, which also shows the plate tectonic boundaries on the globe. Figure 1 strongly suggests that the majority of these earthquakes are focused on the plate tectonic boundaries. Then, it becomes very important to develop a proper plate tectonic boundary model which prescribes interaction type and its behavior at the boundary.

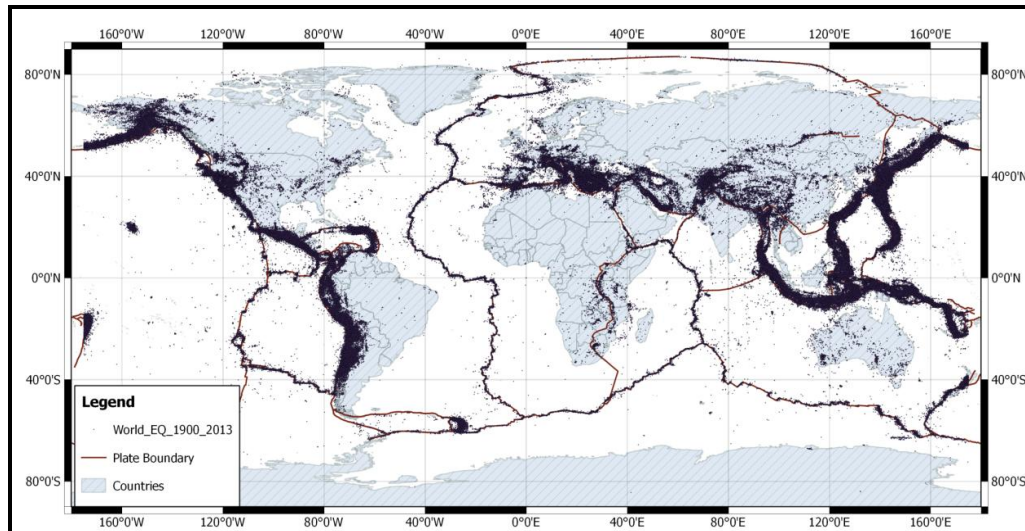


Figure 1: World Earthquake Epicenters from 1900–2013
(Earthquake Data: NCEDC)

Many plate tectonic boundary models have been presented but there are no standard references that are generally accepted on these locations across globe (Peter, 2003). Minster and Jordan (1978); DeMets et al., (1990) (NUVEL-I); Zoback (1992) have published boundaries of large plate models as part of their world stress Map. Gordon (1995) has incorporated the distinction of plates from deforming zones. The Paleo-Oceanographic mapping project undertaken at the University of Texas has shaped a rough set of plate boundaries of large plates and mid-ocean spreading ridges. Muller et al., (1997) has published a map pertaining to the boundaries and also have gridded the oceanic lithosphere age with the help of digital models. An in-detail map of plate boundaries (working set) is maintained at a site by plate's project team, Institute of Geophysics (University of Texas) (Peter, 2003). A good number of studies have been conducted in the past four decades in order to study the fundamental changes in global tectonic process. Many new models have been introduced with the help of evolving data. This study focuses on Indian plate and its interactions with neighboring plates.

The plate tectonic boundary model (PB2002) by Peter Bird (2003) as shown in the Figure 2 is a revised version of the previous model PB1999 that was used in Bird et al., (2002). The digitized boundaries created by POMP have the leading basis for model PB2002. Which has a set of digitized boundaries created by POMP (Muller et al., 1997).

Peter Bird (2003) has described the whole global plates consisting of 14 large plates and 38 smaller plates equating to a total of 52 plates. In this, Arabia, Australia, Eurasia and India plates are considered to be larger plates and Sunda, Burma and Somalia are considered to be smaller plates. This study does not include reasons in differentiating larger or smaller plates, but it deals with their interaction with neighboring plates.

Peter Bird (2003) has divided plate tectonic interactions into seven classes viz Continental Convergent Boundary (CCB), Continental Transform Fault (CTF), Continental Rift Boundary (CRB), Oceanic Spreading Ridge (OSR), Oceanic Transform Fault (OTF), Oceanic Convergent Boundary

(OCB) and Subduction Zone (SZ) as represented in Figure 2 for whole global plates. Figure 2 show that Indian tectonic plate is undergoing all seven types of interactions.

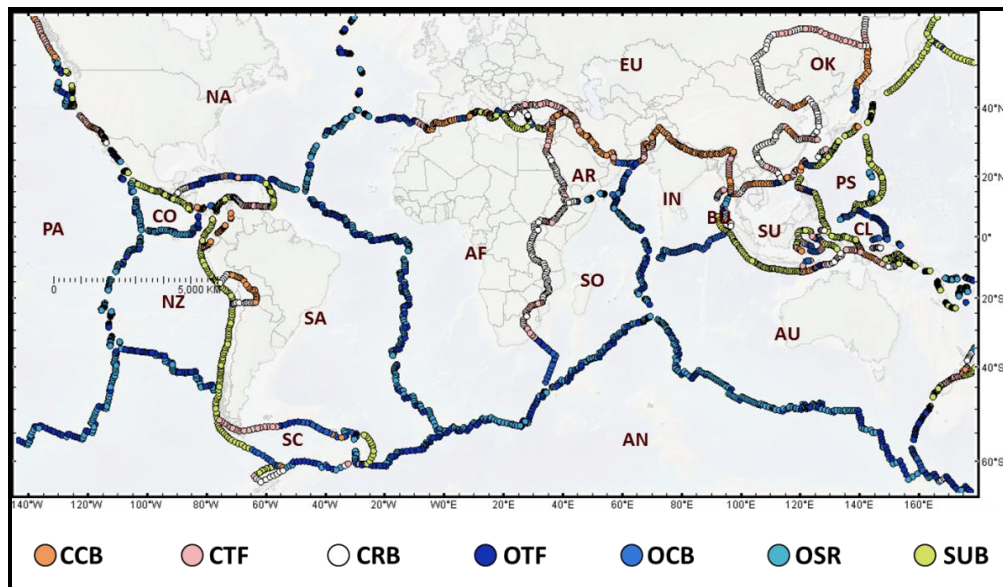


Figure 2: World Tectonic Plates with Interaction Types
(Data: Peter Bird, 2003)

2. Great Earthquakes and Plate Junctions

Large earthquakes over a magnitude of eight are called “great earthquakes”. They have found to occur at an average gap of one and half years. Researchers believe that these great earthquakes occur in order to release stresses over a large area that are tectonic in nature. Figure 3 shows the epicentral locations of the great earthquakes occurred during 1900–2013.

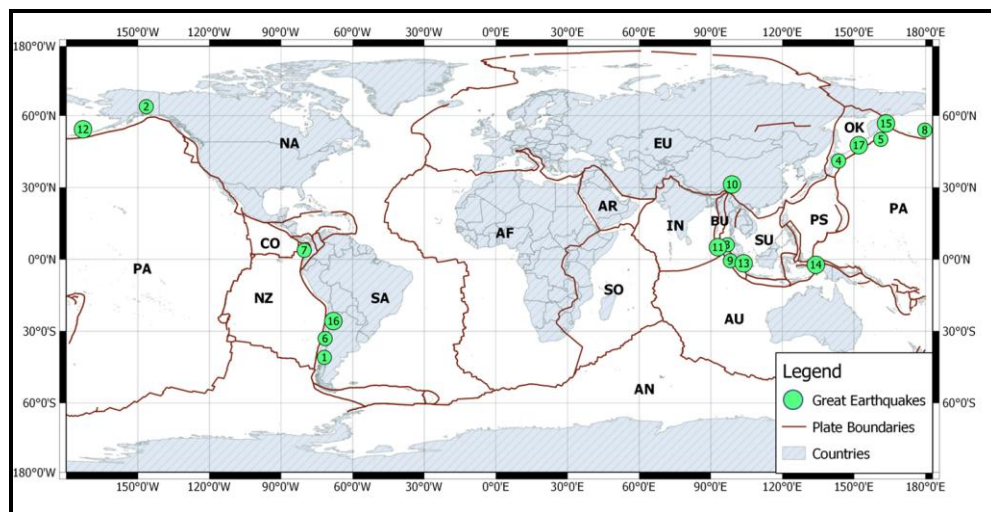


Figure 3: Epicentral Locations of Great Earthquakes of the World 1900–2013
(Source: USGS)

Table 1: List of the 17 Largest Earthquakes in the World Since 1900, their Locations Close to Plate Junctions, and the Plates Associated with Each Earthquake. AN, Antarctica; AU, Australia; BU, Burma; CA, Caribbean; CO, Cocos; EU, Eurasia; IN, India; NA, North America; NZ, Nazca; OK: Okhotsk; PA, Pacific; PS, Philippine Sea; SA, South America; SU, Sunda
(Source: USGS)

No.	Location	Date	M	Lat.	Long.	Reference	Associated Plates
1.	Chile	1960 05 22	9.5	-38.29	-73.05	Kanamori, 1977	NZ, SA, AN
2.	Prince William Sound, Alaska	1964 03 28	9.2	61.02	-147.65	Kanamori, 1977	PA, NA
3.	Off the West Coast of Northern Sumatra	2004 12 26	9.1	3.30	95.78	Park et al., 2005	IN, BU, AU, SU
4.	Near the East Coast of Honshu, Japan	2011 03 11	9.0	38.322	142.369	PDE	PA, PS, OK
5.	Kamchatka	1952 11 04	9.0	52.76	160.06	Kanamori, 1977	PA,NA,OK
6.	Offshore Maule, Chile	2010 02 27	8.8	-35.846	-72.719	PDE	NZ,SA,AN
7.	Off the Coast of Ecuador	1906 01 31	8.8	1.0	-81.5	Kanamori, 1977	NZ, SA, CO,CA
8.	Rat Islands, Alaska	1965 02 04	8.7	51.21	178.50	Kanamori, 1977	PA, NA
9.	Northern Sumatra, Indonesia	2005 03 28	8.6	2.08	97.01	PDE	IN, BU, AU, SU
10.	Assam - Tibet	1950 08 15	8.6	28.5	96.5	Kanamori, 1977	IN, EU, BU, SU
11.	Off the west coast of northern Sumatra	2012 04 11	8.6	2.311	93.063	PDE	IN, BU, AU, SU
12.	Andreanof Islands, Alaska	1957 03 09	8.6	51.56	-175.39	Johnson et al., 1994	PA, NA,
13.	Southern Sumatra, Indonesia	2007 09 12	8.5	-4.438	101.367	PDE	IN, BU, AU, SU
14.	Banda Sea, Indonesia	1938 02 01	8.5	-5.05	131.62	Okal and Reymond, 2003	AU, SU, PS, PA
15.	Kamchatka	1923 02 03	8.5	54.0	161.0	Kanamori, 1988	PA, NA, OK
16.	Chile-Argentina Border	1922 11 11	8.5	-28.55	-70.50	Kanamori, 1977	NZ,SA,AN
17.	Kuril Islands	1963 10 13	8.5	44.9	149.6	Kanamori, 1977	PA, PS, EU, OK

Table 1 provides the details of all the great earthquakes occurred in different locations (with respective to tectonic plates) of the world. Magnitudes of all these listed great earthquakes were in the range of 8.5 to 9.5. Except for 2, 8 and 12 on the western Aleutian trench, all other great earthquakes have occurred at the multiple-plate junctions. In the first sight, the 1964 Alaskan earthquake (refer to event 2) seems to be a case of two-plate interaction. However, when subduction zone in the western Aleutian trench in the north, and the right lateral strike-slip faulting environment along the San Andreas Fault in east are considered, then it does act like triple junction resulting in the stress to be built. In summary, it can be said that there is a strong correlation between plate junctions/inflexion points and epicentral locations of these earthquakes. Recently there have been few major observations about the correlation between great earthquakes, swarm activity (Kanamori, 1971), subduction process, oceanic plates (Benioff, 1954), focal depth and plate junctions.

Out of the 17 great earthquakes, five great earthquakes have occurred on or in the vicinity of Indian tectonic plates as mentioned in Table 1. Plate junctions which have been responsible for great earthquakes in and around Indian plate are mentioned in the Table 1. IN-BU-AU-SU & IN-BU-EU-SU are known as quadruple plate junctions leading to minor to great earthquakes.

Few major observations about great earthquakes; almost all the great earthquakes have occurred on or nearer to the plate boundaries; they have occurred nearer to the plate junctions (N.P., Rao, 2005); they have occurred at the zones of subduction (Larry Ruff and H., Kanamori, 1980); they have occurred where oceanic plate is subducting under continental plate (Luciana et al., 1988); and all the great earthquakes occurred are shallow in nature.

Indian tectonic plate interactions have led to five great earthquakes in the last 100 years and a few more are expected to occur in the near future at the Himalayan arc and the Burmese arc. A study of its interactions would lead to proper conclusions of great earthquakes and the intervals of their recurrence.

3. Indian Tectonic Setup

The Indian plate is bounded by zones of broadly distributed active deformation. The most widely distributed plate boundary in the world is actively deforming as continental India continues to collide with Eurasia. Beginning at the northern edge of India plate, along the Himalaya Range Front, active deformation extends through Tibet and into China, Mongolia, and as far north as Russia. Along the eastern flank the subduction of the Indian plate under the Burma plate in the Andaman-Nicobar Islands region. To the south the transition between the India plate and the Australian plate is uncertain as seismicity is dispersed over thousands of kilometers and shows no distinct trends that highlight an obviously distinct boundary. Along the western plate boundary, the Central Indian Ridge, the Carlsberg Ridge and Owen Fracture zone discretely separate Indian plate from the Somalian and Arabian plates through a series of spreading centers and transform faults.

Studies of global reconstructions phenomena have suggested that the Indian plate move at a rate of 54 mm/yr (0.054 m/yr) and hence leading to convergence with the Asian plate (DeMets et al., 1994). The interior of Indian tectonic plate have Himalayan mountain belt, Indo-Burmese range, peninsular shield, and Sindhu-Ganga-Brahmaputra alluvial plains.

3.1. Indian Intraplate Deformation

The Indian shield region consists of various complex rift zones and several shear/thrust zones. Indian shield region is categorized as Stable Continental Region (SCR). However, Indian shield region has witnessed several earthquakes of magnitude six or more since 18th Century, some of which were disastrous (Bhatia et al., 1999). The spatial distributions of earthquakes of magnitude 6 and above are shown in the Figure 6 (c). This Intraplate seismicity exists across Central India that might be related to flexure of the plate as it is thrust below Tibet (Bilham et al., 2003).

The Narmada-Son Lineament (NSL) is one of the significant tectonic features of the Indian shield trending ENE-WSW apparently dividing the shield into two sectors, namely northern and southern sectors (Bhatia et al., 1999). This paleo-rift zone (Jain et al., 1995) exhibits high heat levels and strain rates estimated from seismicity that are larger than many stable continental regions (Rao, 2000). This suggests a potential concentration of intraplate deformation or kinematic separation of India into two distinct plates. Thinned and weakened lithosphere formed due to passive-margin normal faulting in the Cretaceous might also have led to the increased seismicity activity in the region (Biswas et al., 2007) and by heating from the plume head is the reason for the late Cretaceous Deccan flood basalts (Chandrasekhar et al., 2009). Ductile creeps occurring at depths from 10 km to 15 km leading to continental flexure, which is a major factor for intraplate tectonism. 285 earthquakes have occurred in the last forty years with varied magnitudes at different focal depths, of which 200 earthquakes have occurred majorly at the focal depths of range between 10 km to 15 km over Indian stable shield (Koyna, Killari and Bhuj earthquakes) (Khan, 2009).

The present day tectonics of the northeastern part of India is complicated because of the interaction between the active north-south convergence along the Himalaya (Seeber et al., 1981) and east-west convergence and folding within the Indoburman ranges deformation apparently evolved from subduction along a nearly east-west trending zone in Tertiary time to its present configuration (Mitchell, 1981). The Shillong plateau in the Northeast India exhibits considerable north-south shortening supported by the existence of large earthquakes such as the great (M_w 8.1) Assam earthquake of 1897 (Bilham and England, 2001). In addition, detailed analysis of moderate earthquakes in the same region is also consistent with the north-south shortening (Angelier and Baruah, 2009). Exhumation rates deduced from low-temperature chronometric data suggest a convergence rate of 13 mm/yr (0.013 m/yr) across the plateau, since 9 Ma (Biswas et al., 2007). GPS

data in the Shillong Plateau region also show contraction with respect to stable India (Banerjee et al., 2008).

Seismic experiments conducted in southern Tibet suggest a crustal thickness of the order of 80 km (Hirn et al., 1984; Zhao et al., 1993; Mitra et al., 2005). For comparison, the crustal thickness of the Indian Shield is estimated at 40–44 km (Saul et al., 2000; Mitra et al., 2005). But from recent studies carried by Kumar et al., (2007) the given thickness of Indian plate is ranging from 80–100 km. In the same paper Kumar et al., (2007) has also mentioned that it is because of its lesser thickness Indian plate has actually moved at a velocity of 180 to 200 mm/yr (0.18 m/yr to 0.20 m/yr) before collision with Eurasian plate.

3.2. Indian Interplate Deformation

Figure 4 shows the tectonic plate boundaries of all the neighboring plates with Indian tectonic plate, whereas Figure 5 shows the type of interaction Indian tectonic plate having with its neighboring plates which are given in seven classes mentioned by Peter Bird (2003). These types of interactions experiencing by Indian plate are compared with the whole global plates. The values are mentioned in Table 2. But in detail, interaction types and their lengths in km are mentioned in Table 3.

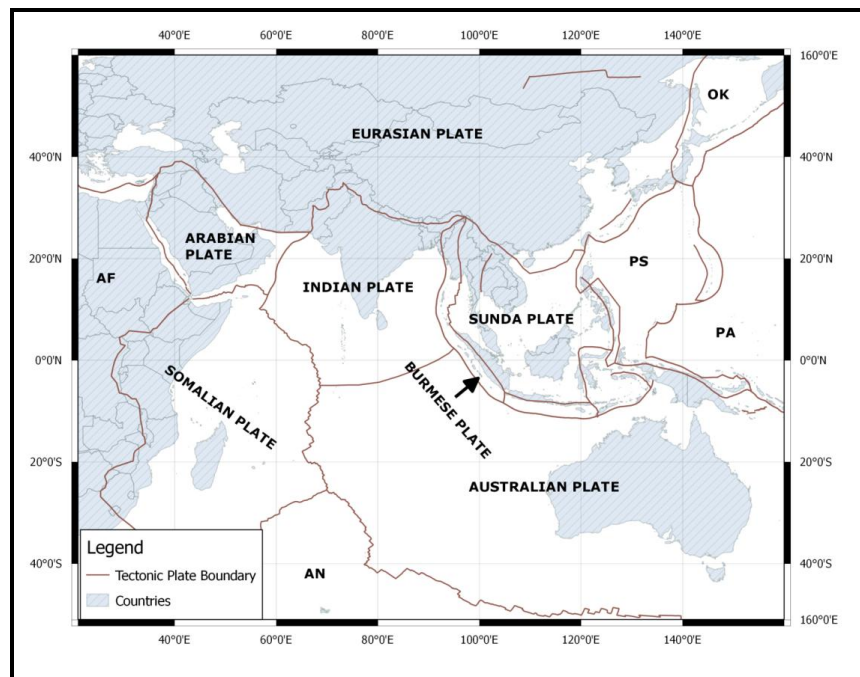


Figure 4: Indian Tectonic Plate with Its Neighbouring Plates

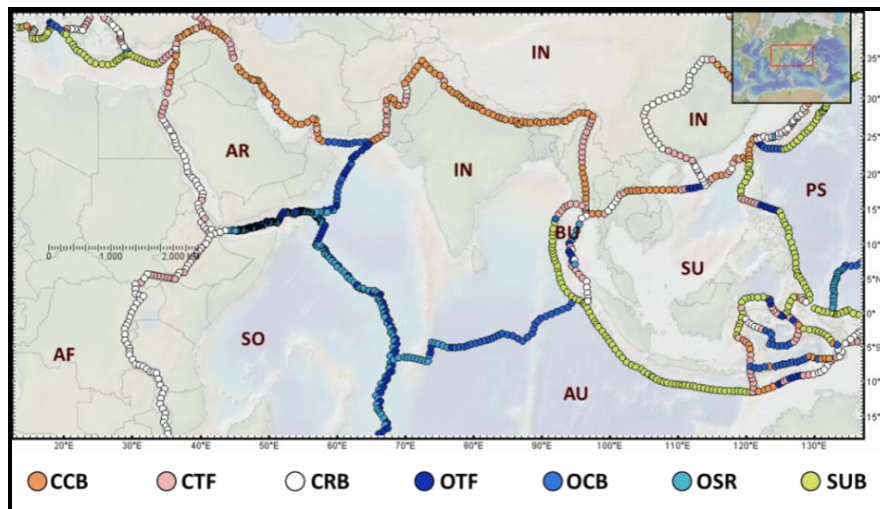


Figure 5: Indian Tectonic Plate with Its Neighboring Plates and Interaction Types
(Data: Peter Bird, 2003)

Table 2: Interaction Type Length of Indian Plate and World Plate Lengths (CCB – Continental Convergent Boundary, CTF – Continental Transform Fault, CRB – Continental Rift Boundary, OSR – Oceanic Spreading Ridge, OTF – Oceanic Transform Fault, OCB – Oceanic Convergent Boundary, SUB – Subduction Zone)

Interaction Class	Total Length (km)	
	INDIA	WORLD
Continental Convergent Boundary (CCB)	4323.9	23003
Continental Transform Fault (CTF)	2086	26132
Continental Rift Boundary (CRB)	126	27472
Oceanic Spreading Ridge (OSR)	3827	67338
Oceanic Transform Fault (OTF)	2257	47783
Oceanic Convergent Boundary (OCB)	3076	17449
Subduction (SUB)	1417	51310

Table 3: Interaction Types and their Lengths in km of Indian Plate and its Neighboring Plates (IN – Indian Tectonic Plate, EU – Eurasian Plate, BU – Burmese Plate, AU – Australia Plate, SO – Somalia Plate)

Interaction Class	IN - EU	IN - BU	IN - AU	IN - SO	IN - AR	Total
CCB	4323.9	- NA -	- NA -	- NA -	- NA -	4323.9
CTF	1586.7	499.4	- NA -	- NA -	- NA -	2086.1
CRB	126.5	- NA -	- NA -	- NA -	- NA -	126.5
OSR	- NA -	- NA -	1058.8	2486.8	281.5	3827.1
OTF	- NA -	- NA -	228.9	1218	810	2256.9
OCB	- NA -	88.8	2309.9	113.4	564.2	3076.3
SUB	- NA -	1416.6	- NA -	- NA -	- NA -	1416.6

(NA – Not Applicable)

Indian plate along with its boundaries and neighboring plates is shown in Figure 6 that also shows the seismic activity from 1900 to 2013. Figure 6(a) gives the seismicity of different magnitudes. A close observation tells that larger magnitude earthquakes are more concentrated on the boundaries than the interior. Similarly Figure 6(b) shows the epicentral locations of all the earthquakes separated on the basis of their focal depths. Most of the earthquakes in the central region of Indian plate have focal depth less than 70 km which are shallow in nature. As we move from southern part to northern part and western part to eastern part, the focal depth is increasing, which also indicates that the plate thickness is increasing at the northern and southern boundaries. Figure 6(c) shows all the

earthquakes of magnitude more than 6. It can be said that major to great earthquakes are quite common on the boundaries and that the interior part of the Indian plate is seismically active. It is also observed that deep focus earthquakes are limited to Hindu Kush (100-300 km) and Burmese arc (90-150 km) (Mishra et al., 2012).

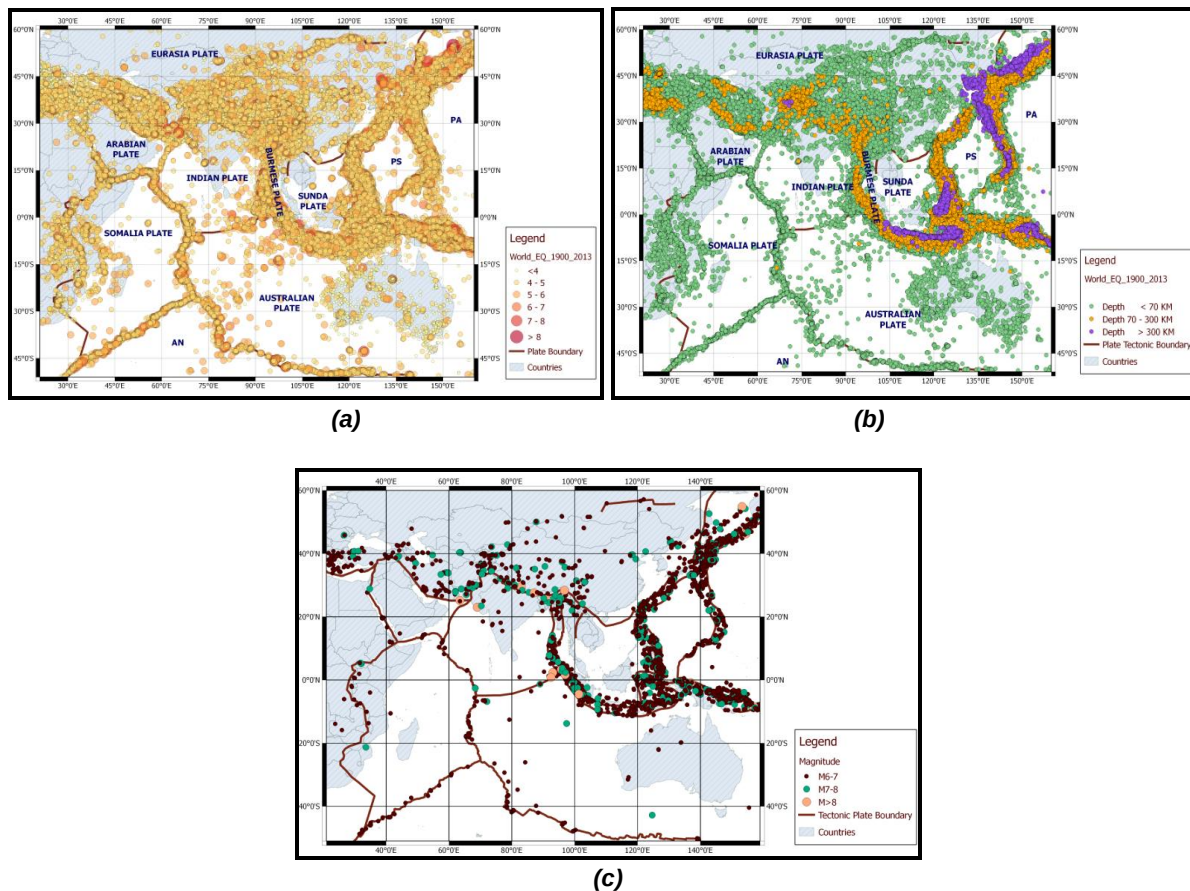


Figure 6: Epicenters in and around Indian Tectonic Plate (a) Figure Shows Epicenters with Different Magnitudes (b) Figure Shows Epicenters with Different Depths (c) Figure Shows Epicenters of Earthquakes Whose Magnitude is Equal or Greater than 6 (Earthquake Data: NCEDC)

In this study, we have divided the whole Indian tectonic plate interactions into six components; boundaries for each component are mentioned in Table 4, where minimum, maximum latitudes and longitudes are given. Figure 4 shows the complete tectonic plate boundaries of Indian and neighboring plates viz., Eurasian, Arabian, Somalian, Australian, Burmese and Sunda plates.

Table 4: Considered Areas for Our Study Detailing Its Location on the Globe

No.	Plate Interactions	Longitude		Latitude	
		Min	Max	Min	Max
1.	Indian – Neighboring Plates	21°0' E	160°0' E	51°0' S	60°0' N
2.	Indian – Eurasian Plate	46°0' E	112°0' E	5°0' N	44°0' N
3.	Indian – Australian Plate	60°0' E	174°0' E	63°0' S	35°0' N
4.	Indian – Arabian Plate	32°0' E	78°0' E	6°0' N	44°0' N
5.	Indian – Sunda Plate	72°0' E	135°0' E	12°0' S	36°0' N
6.	Indian – Burmese Plate	75°0' E	105°0' E	15°0' S	30°0' N
7.	Indian – Somalian Plate	22°0' E	86°0' E	52°0' S	20°0' N

4. Indian Tectonic Plate Boundary Interactions

4.1. Indian-Eurasian Plate

The Indian–Eurasian collision was brought about by the rifting of India from Africa and East Antarctica during the Mesozoic and by its migration northward as the intervening oceanic lithosphere was subducted beneath the Eurasian Plate. The two continents were once separated by the Tethys Sea, which was subducted beneath the southern margins of Eurasia. The Himalayan–Tibetan orogen was created mainly by the collision between Indian and Eurasian over the past 70–50 Myr (Yin & Harrison, 2000). Reconstruction plate motion of Indian plate relative to Eurasian plates has an abrupt decrease in the convergence rate from ~150 mm/yr (0.15m/yr) to 40-50 mm/yr (0.04-0.05 m/yr). Which might probably because of continuous collision (Molnar and Tapponnier, 1975). This movement into each other led to an indent of 3000 km into Eurasia, leading to generation of lateral escape and crustal thickening. This lateral escape and crustal thickening has led to the highest topographic features on earth (Molnar and Tapponnier, 1975). The present convergence rate is absorbed by crustal shortening across the Himalaya, estimated at 19 ± 2.5 mm/yr based on geodetic measurements from central and eastern Nepal (Bettinelli et al., 2006). This convergence has been responsible for any large earthquake along the Himalayan arc in the past and could likely contribute to large earthquakes in the future (Bilham et al., 2001).

The Himalayas covering 20-38° N and 70-98° E is separated into three zones: (i) Central Himalayas (starting from 28-38° N latitude covering till 78-98° E longitude) (ii) Northeast Himalayas (starting from 20-28° N latitude covering till 88-98° E longitude) and (iii) Western Himalayas (starting from 30-38° N latitude covering till 70-78° E longitude) and forms a well-defined arc to the north of Indo-Gangetic plains and extends over a length of nearly 2500 km from west-northwest to east-northeast. Phenomena of tectonics and seismicity of Himalayas has been the area of interest for many researchers for the past few decades.

Continuous movement of Indian plates in North-northeastward led to stress accumulation and hence resulted in active thrusts and faults. These active thrusts and faults are the source for seismicity along the Himalayan arc in high levels (Gupta I.D., 2006). In the Hindu-Kush region the seismicity activity is focused at the depths of 220 km and hence, many large earthquakes have occurred in this region. Presence of vertical tensional axes in intermediate-depth events reflects the detachment of denser oceanic lithosphere from the active buoyant continental lithosphere (Luciana et al., 1988).

The entire Himalayan arc experiences thrust/fault systems. Major thrust/fault systems that span across the entire Himalayan arc from north to south are: the Indus Suture Thrust (IST), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust (HFT), and the seismicity between the MCT and MBT are defined as the Main Himalayan Seismic Belt (MHSB). This belt has witnessed many large ($M > 7.0$) and great earthquakes (M 8.0 and above) (Kayal, 2001). The thrust zones in this region have become the prime areas for the earthquake events. The common crustal depths of these earthquake events were in the range of 20 km. Small earthquakes are very common and localized vertical movement is also evident in this region. Under thrusting of plates in this region is the major source for the seismicity activity. Seismic gaps (Figure 8) i.e. the regions of plate boundary which were not ruptured in the past century are predicted to be active locations for future great earthquakes. The major gaps defined are: Kashmir gap (west of 1905 Kangra earthquake), Central gap (region between the 1905 Kangra earthquake and 1934 Bihar earthquakes), Assam gap (region between the 1934 and 1950 Assam earthquake). The gap in the western most part called as location of complex earthquakes. In the past century, Himalaya belt has experienced various earthquakes of different magnitudes. Four great earthquakes of magnitude exceeding 8 and 10 earthquakes exceeding magnitude 7.5 have occurred in the same period (Bhatia et al., 1999).

Gupta I.D., (2006) stated that the Indo-Gangetic plains experience strains in areas in front of prodding subsurface ridges. These transverse features Himalaya does result in small to moderate magnitude earthquakes in Indo-gangetic plains at Himalayan foothill areas. Many more moderate to great earthquakes are expected to occur in the near future.

Several models are proposed by researchers in the explanation of the detachment surface along the Himalayas. Seeber and Armbruster (1981) provide the models to explain the rupture of the Himalayas at different parts i.e. lower, higher and Tethys Himalaya in terms of 'detachment surface'. Ni and Barazangi (1984) have presented the geometry of seismotectonics of the Himalayan collision zone of the under thrusting Indian plate beneath Indo-Gangetic plains and Himalaya. The steady state tectonic model provided by Seeber and Armbruster (1981) states that MBT and MCT and other thrust are imbrication along the detachment surface merging at the depths with dipping northerly low angle. This steady state tectonic model is also supported by Ni and Barazangi (1984).

As a whole Indian plate and Eurasian plate are interacting in three classes: the largest being the continental convergent of approximate length 4323.9 km (orange dots) which includes complete Himalayan belt, continental transform of length 1586.7 km (pink dots) near north-western part and part of north-eastern which can be seen in the Figure 7(d), continental ridge of length 126.5 km (white dots) in the north western part, which is the least of all seven kinds of interactions.

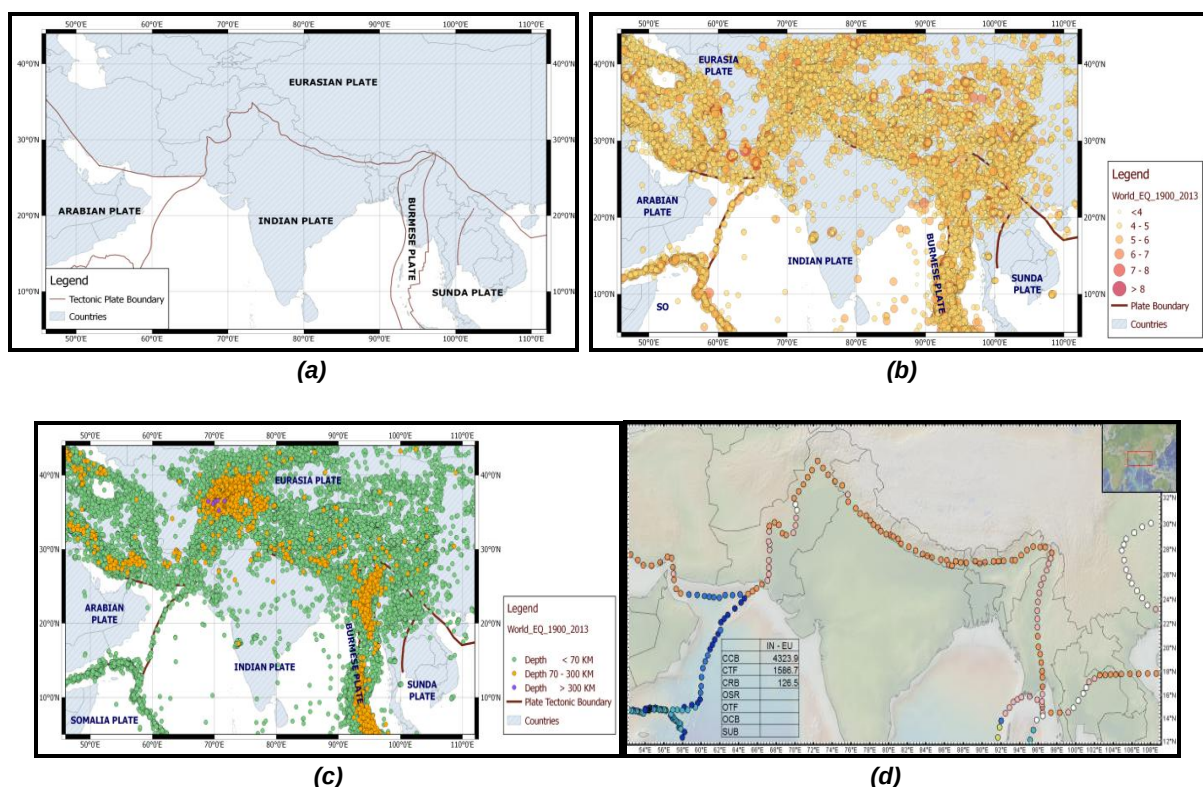


Figure 7: Interaction between Indian Tectonic Plate and Eurasian Plate; a) Tectonic Setup of India and Eurasia Plates; b) Figure Shows Epicenters with Different Magnitudes; c) Figure Shows Epicenters with Different Depths; d) Interaction Class Type (Earthquake Data: NCEDC)

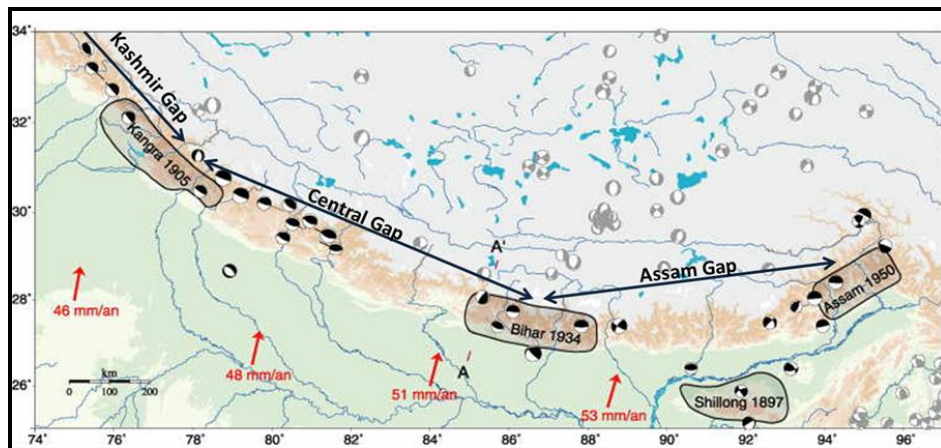


Figure 8: Map Shows Four Major Earthquakes and Seismic Gaps
(Source: Avouac et al., 2001)

4.2. Indian–Arabian Plate

The Indian-Arabian plate motion currently accommodated along the Owen Fracture Zone (OFZ) in the NW Indian Ocean (Fournier M., 2011). Large strike-slip plate boundaries form the OFZ like the San Andreas and are marked by a moderate seismicity (Fournier M, 2011). The OFZ connects with the Dalrymple Trough (Gordon and DeMets, 1989) which intersects the Makran subduction zone at the diffuse triple junction of the Indian, Arabian, and Eurasian plates. The southern extent of the OFZ terminates at the Indian, Arabian, and Somalian triple junction (Edwin, 2011).

It is found that the Arabian plate and the Indian plate move towards northwards at differential rates. The Arabian plate moves faster at a rate of 2 mm/yr to 4 mm/yr (0.002 m/yr to 0.004 m/yr) than the Indian plate as estimated by geodetic (Fournier et al., 2008b) and geological data (DeMets et al., 2010). The rotation of the Arabian with respect to Eurasian is calculated as a convergence along the Makran subduction zone at 23 mm/yr (0.023m/yr) (Reilinger et al., 2006).

The thickness of late Proterozoic Arabian shield varies across the regions. It has an average crustal thickness of 39 km. The crust thins to about 23 km along the Red Sea coast and to about 25 km along the margin of the Gulf of Aqaba. In the northern part, the crustal thickness ranges from 27-33 km and southeastern part of Arabian platform has a thickness ranging between 41-53 km (Al-Damegh et al., 2005).

As a whole Indian plate and Arabian plate are interacting in three classes viz oceanic spreading ridge of length 281.5 km (sky blue dots), oceanic transform of length 810 km (navy blue) and oceanic convergence of length 564 km (dark blue dots) as shown in the Figure 9 (d). Crustal thickness at the IN-AR boundary based on the past earthquake data would be less than 80 km as all the earthquakes occurred in the region are shallow (< 70 km) in nature. But, in the northern part of the Arabian plate which is colliding with the Eurasian plate, the crustal thickness is between 70 km and 300 km which can be seen in Figure 9(c).

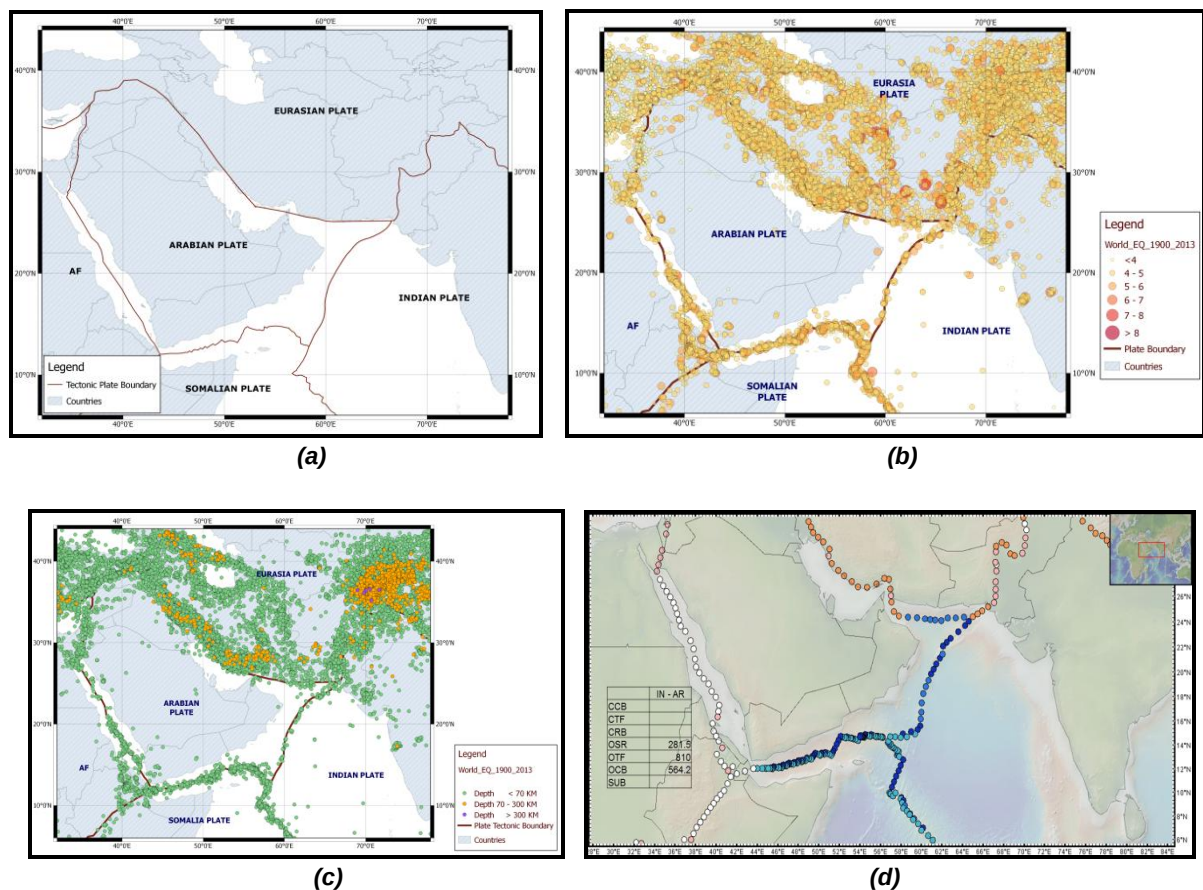


Figure 9: Interaction between Indian Tectonic Plate and Arabian Plate; a) Tectonic Setup of India and Arabian Plates; b) Figure Shows Epicenters with Different Magnitudes; c) Figure Shows Epicenters with Different Depths; d) Interaction Class Type (Earthquake Data: NCEDC)

4.3. Indian–Somalian Plate

The Indian plate is separated from Somalian plate along the mid-ocean ridge which is in the south of the Owen Fracture Zone. This boundary is completely submarine defined by the Carlsberg Ridge and the Central Indian Ridge (Edwin, 2011) highlighted by discrete seismicity. Arabian, Indian and Somalian plate meet at a junction called Aden-Owen-Carlsberg triple junction (Fournier et al., 2010). The motion between Indian and Somalia is important in understanding Indian plate path taken before and after collision with Eurasia (DeMets et al., 2005). At the same time, there has been no change in location for the past 20 Myr as indicated by India-Somalia rotation poles.

From the Figure 10(b), it can be inferred that there would be very less chance of occurrence of major earthquakes in this part of boundary. Except one earthquake remaining all of the earthquakes are of magnitude less than 7. And from Figure 10(c) the approximate crustal thickness at the India-Somalia boundary may lie between 100 and 200 km.

As a whole, the Indian plate and the Somalian plate are interacting in three classes viz oceanic spreading ridge of length 2486.8 km (sky blue dots), oceanic transform of length 1218 km (navy blue) and oceanic convergent of length 113.4 km (dark blue dots) as shown in the Figure 10(d).

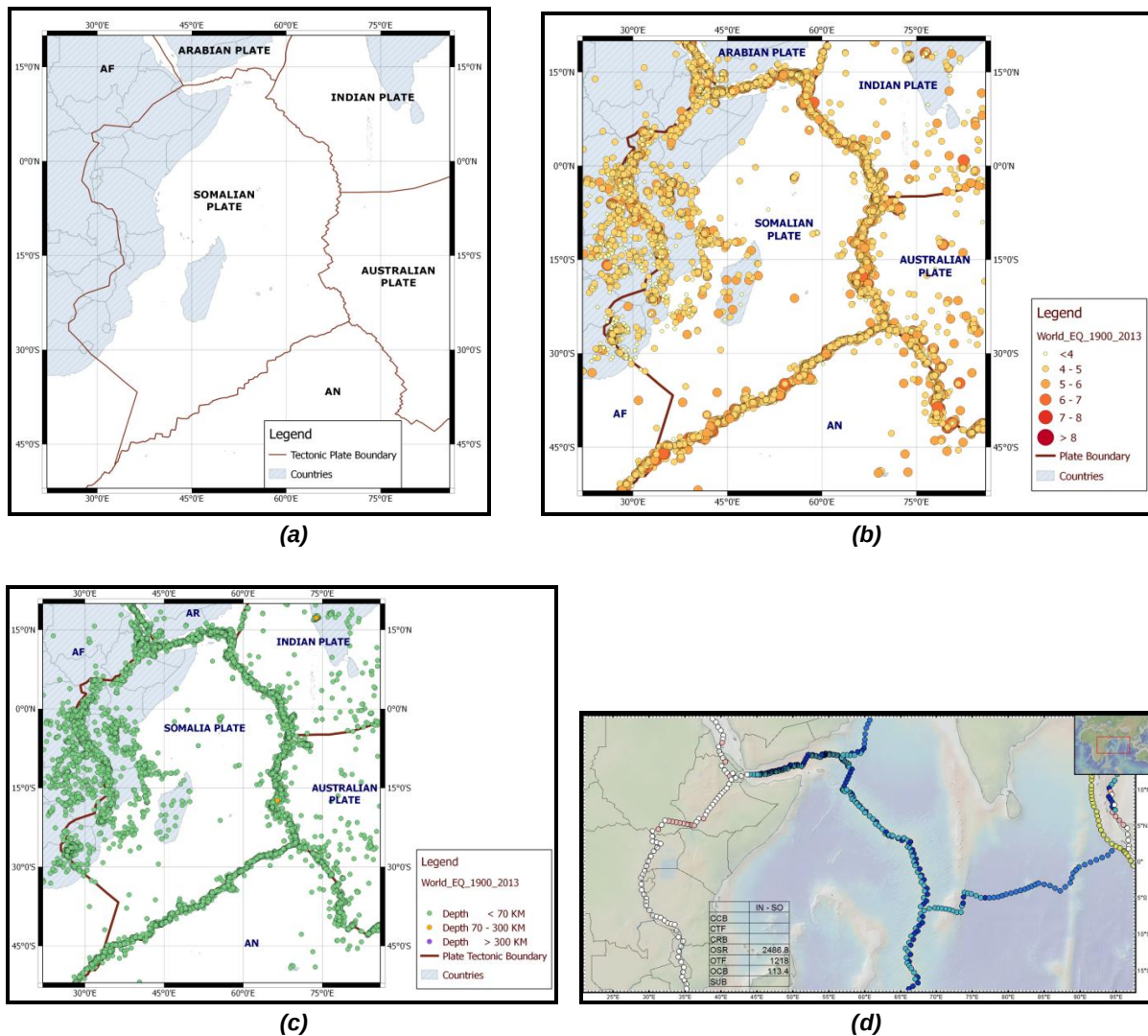


Figure 10: Interaction between Indian Tectonic Plate and Somalian Plate; a) Tectonic Setup of India and Somalian Plates; b) Figure Shows Epicenters with Different Magnitudes; c) Figure Shows Epicenters with Different Depths; d) Interaction Class Type (Earthquake Data: NCEDC)

4.4. Indian–Australian Plate

In the early days of plate tectonics, India and Australia were viewed as forming a single rigid Indo-Australian plate divided from adjacent rigid plates by narrow boundaries (Wilson, 1965; Morgan, 1968). That is during the rifting of Gondawana, both plates formed on the northern side of spreading ridges that separated the northward-drifting continents from Antarctica (Norton and Sclater, 1979). However, the broad zones of seismicity surrounding and within the presumed single plate rapidly led to identification of diffuse plate boundaries (Stein, 2002). And in the central Indian Ocean, Indo-Australian plate is said to be broken into three smaller pieces separated by diffuse boundaries including Capricorn plate between India and Australia plates (Royer and Gordon, 1997, Helen Shen, 2012).

Compressional faults and folds have occurred in the Central Indian Basin south of India and west of the Ninetyeast ridge (NER) (Krishna et al., 2001). In contrast, deformation is mainly by strike-slip faulting in the Wharton Basin to the east of the NER (Deplus, 2001). In the middle of this deformed zone, the NER is a 4500 km volcanic ridge that displays active seismicity in some locations, but the

nature of deformation is unclear because geophysical data are sparse in the region (Sager et al., 2013). India-Capricorn plate boundary deformation is characterized by East West thrust faults that are spaced in the range of 5-10 km apart and 100-300 km long wavelength folds (Bull and Scrutton, 1992). This deformation does extend across the broad zone to the west side of the NER and began 14-18 Myr ago (Krishna et al., 2009).

Chamot Rooke (2007) states that the earthquakes have occurred in the diffused zone spread across the Central Indian Basin and Wharton basin from $\sim 35^{\circ}$ S to $\sim 7^{\circ}$ N. Very high seismic activity occurs in a band that stretches NE-SW from the Java Trench, across the northern NER, and continues into the Central Indian Basin, south of India. North east thrust faults related to subduction are the major events that are found near the Java trench. In the Central Indian Basin, mixed in earthquakes are observed dominantly by thrust, while other being strike-slip mechanisms are found near the equator (Sager et al., 2013).

The thinnest crust of 25 km occurs in Western Australia and the thickest crust of 61 km occurs in central Australia. The average crustal thickness in Australia is 38.8 km (Clitheroe et al., 2000). Australian plate experiences the subduction at 60 mm/yr (0.060 m/yr) at the western end and 76 mm/yr at the eastern end of the Sumatra coast. It is observed that the subduction rate decreases as one move from eastern end to the western end (Muller et al., 2008).

As a whole Indian plate and Australian plate are interacting in three classes viz oceanic spreading ridge of length 1058.8 km (sky blue dots), oceanic transform of length 228.9 km (navy blue) and oceanic convergence of length 2309.9 km (dark blue dots) that is eastern part of the interaction between AU-IN plates as shown in the Figure 11(d). Crustal thickness at the IN-AU boundary based on the previous earthquake data would be less than 80 km as all the earthquakes occurred in the region are shallow (< 70 km) in nature.

4.5. Indian–Burmese Plate

The Burma-Andaman arc lies on the eastern margin of the Indian plate, along which an oblique convergence between the Indian and Burmese plates has been suggested (Fitch, 1972; Curray et al., 1979). The Burmese arc commences near eastern tip of Himalaya and extends for about 1100 km in north–south direction. The transition between the two arcs is marked by an aseismic zone (Chandra, 1984). The major tectonic features along the arc are the N-S trending Indo-Burman ranges in the north and the Andaman Nicobar ridge in the south. The Sumatran fault system in the southeast, the western Andaman fault and the Sagaing fault, further east, are the features supporting major right lateral movements in this region. The Sagaing fault separates the central low lands from the eastern high lands of Burma and seems to continue into the Andaman sea rift system which is characterized by sea floor spreading and transform faulting (Curray et al., 1979). The presence of the major right lateral strike-slip faults in the east, running parallel to both arcs, has been related to the oblique nature of convergence (Fitch, 1972; Maung, 1987). The development of the two arcs as distinct entities has been attributed by Maung (1987), to the northward drag of the Indo-Burman ranges and the Andaman-Nicobar ridge. According to Kundu and Gahalaut (2013) the Indo-Burmese arc is probably one of the least studied domains as far as plate motion, crustal deformation and earthquake occurrence processes that are concerned.

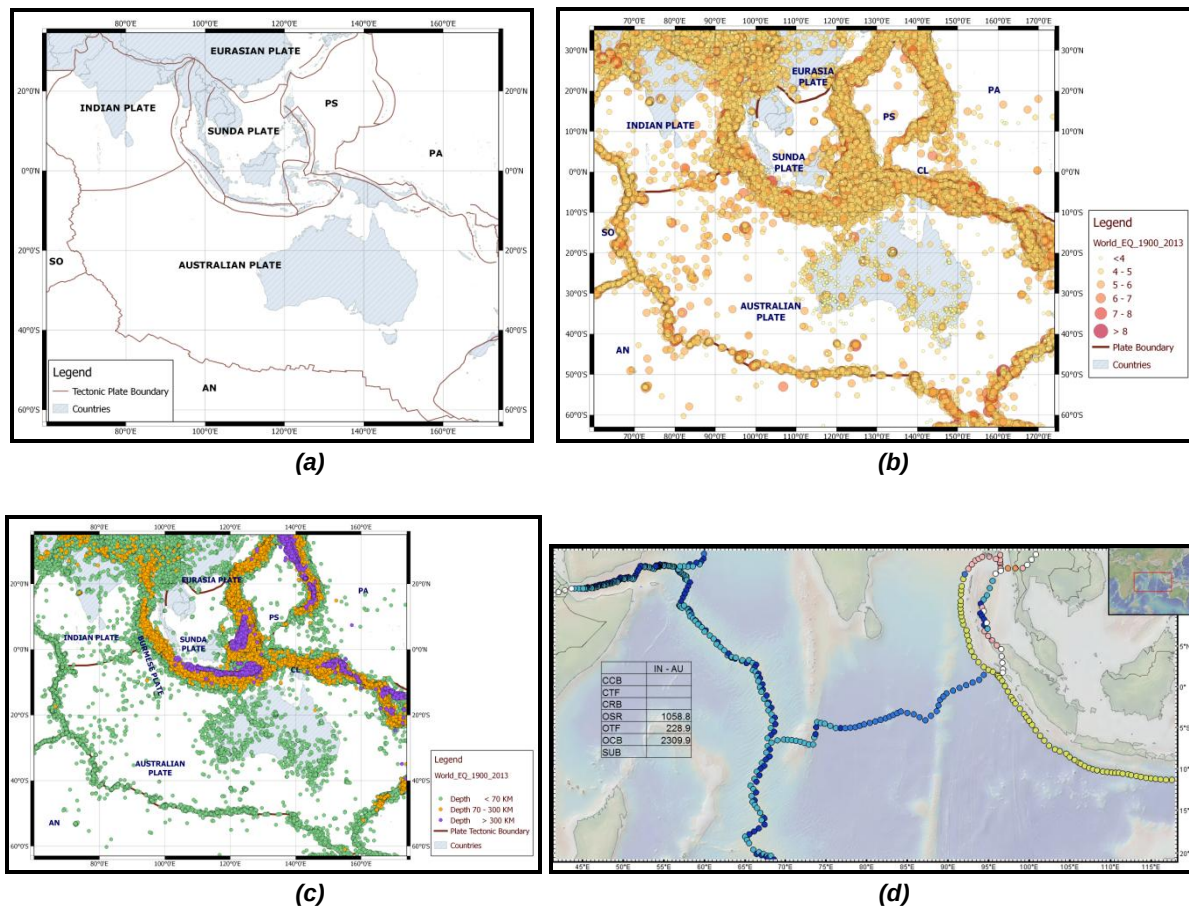


Figure 11: Interaction between Indian tectonic plate and Australian plate; a) Tectonic setup of India and Australian plates; b) Figure shows epicenters with different magnitudes; c) Figure shows epicenters with different depths; d) Interaction class type (Earthquake Data: NCEDC)

The collision pattern of Burmese and Indian plates led to the high seismicity in the Burmese arc. It is found to be decreasing from north to south of Burmese arc as due to migration of plates from north to south direction. The subduction process is said to be still continuing (Gupta I.D., 2006). Deep focus earthquakes at a depth of 200 km are observed to occur at approximately 250 km from Arakan Yoma ranges. Most of these earthquakes originated at Indo-Burmese zone, caused due to thrust fault mechanism. A few of them are due to strike-slip and normal faulting. Thrust faulting is seen to prevail at depths greater than about 70 km, while at shallower depths, strike-slip or normal faulting are occurring quite commonly (Verma, 1976; Rao, N.P., et al., 1999).

As a whole Indian plate and Burmese plate are interacting in three classes viz continental transform fault of length 499.4 km (pink dots), oceanic convergent of length 88.8 km (dark blue) and subduction of length 1416.6 km (green dots) as shown in the Figure 12(d). So we can say that December 26, 2004 great earthquake of magnitude 9.1 is a result of this subduction.

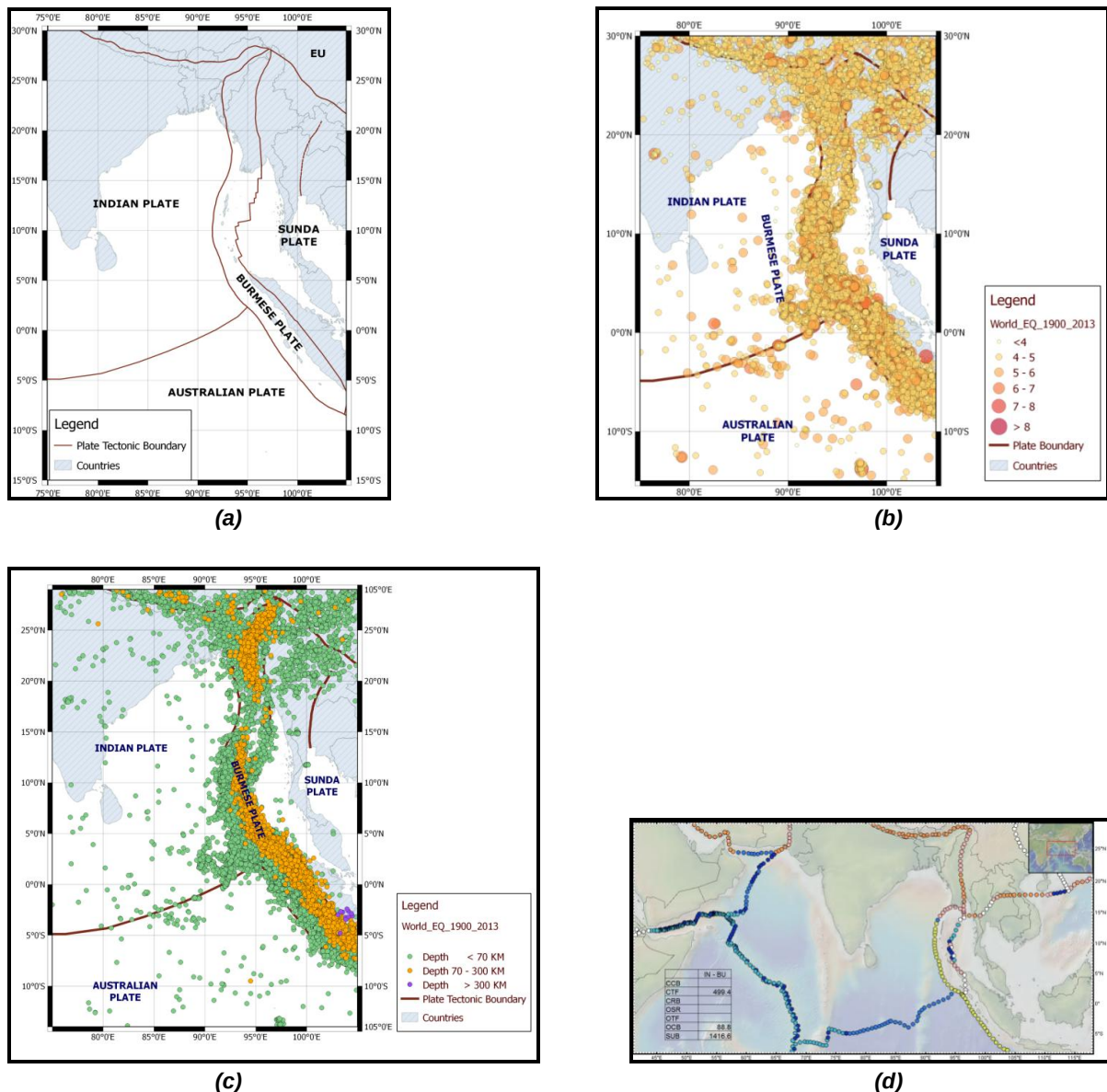


Figure 12: Interaction between Indian Tectonic Plate and Burmese Plate; a) Tectonic Setup of India and Burmese Plates; b) Figure Shows Epicenters with Different Magnitudes; c) Figure Shows Epicenters with Different Depths; d) Interaction Class Type (Earthquake Data: NCEDC)

4.6. Indian-Sunda Plate

The interaction between the Indian plate and Sunda plate is most significant along the Sumatra-Andaman subduction zone, even though Indian plate does not interact with the Sunda plate directly as shown in the Figure 13(a), but its effect is observed in occurrences of earthquakes plotted in Figure 13(b) and Figure 13(c). When Indian-Sunda motion portioned along the mega thrust and the sub-parallel strike slip great Sumatra fault (McCaffrey et al., 2000). The Indian and Sunda land plates abut in Myanmar (Anne et al., 2006). The Sunda plate includes most of southeast Asia, the south China sea, the Malay Peninsula, most of Sumatra, Java, Borneo, and the intervening shallow seas. The very low rate of shallow earthquakes is evidence of its low anelastic strain rates. Sunda plate is separated from the Australia and Philippine Sea plates by subduction zones (Peter, 2003). Geodetic measurements show that the Sunda plate is currently moving eastward with respect to Eurasian plate

(Bock et al., 2003). With respect to Sunda, India moves around 35 mm/yr (0.035 m/yr) NNE (Anne et al., 2006).

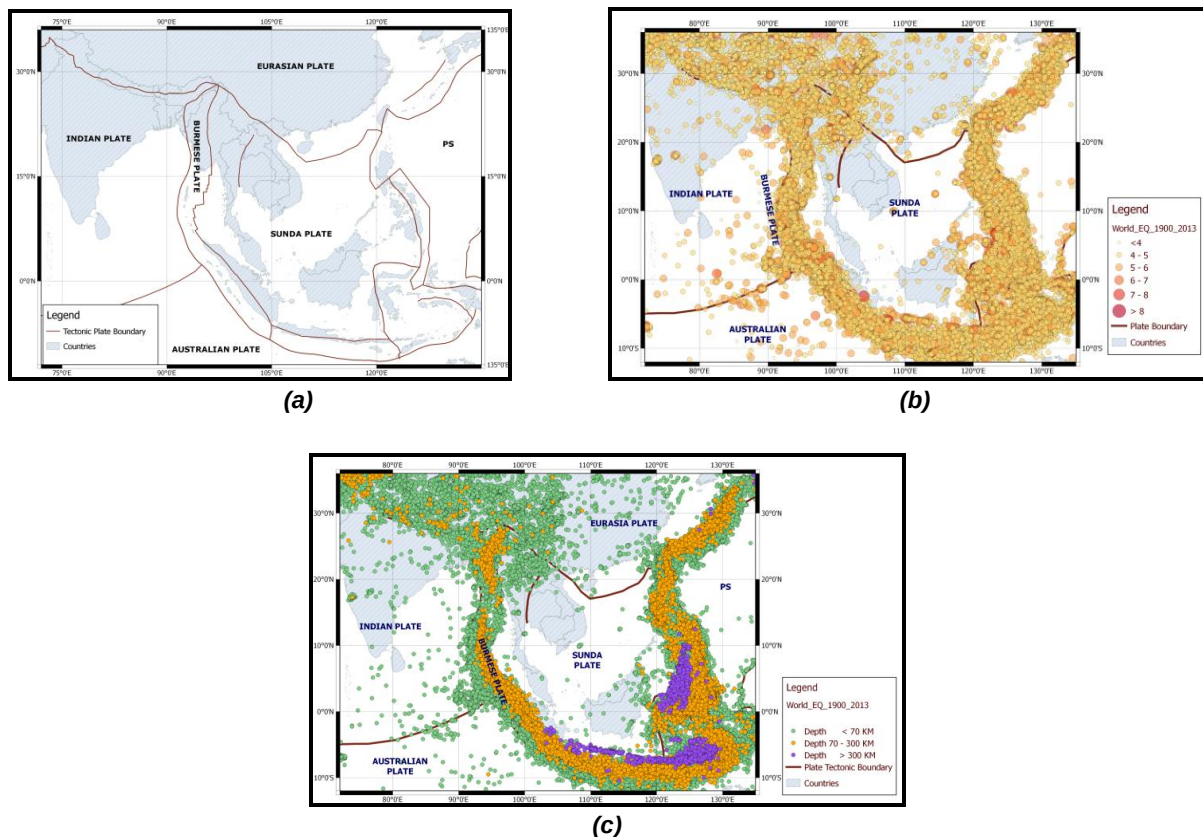


Figure 13: Interaction between Indian Tectonic Plate and Sunda Plate; a) Tectonic Setup of India and Sunda Plates; b) Figure Shows Epicenters with Different Magnitudes; c) Figure Shows Epicenters with Different Depths; (Earthquake Data: NCEDC)

5. Discussion

5.1. Indian Intra-Plate Deformation

As Indian plate is colliding in the northern part and subducting in the eastern part, its high impact is seen in the intraplate deformation which has been leading to minor to great earthquakes. Intraplate deformation in central India could also result from flexure of the Indian plate as it collides with Eurasian plate (Bilham et al., 2003). Once, Indian shield was considered to be a stable continental region. But now it has become seismically active. Given the observed seismicity along the Narmada Son, it is possible that Indian intraplate deformation is concentrated along this lineament. It also suggests that NSL divides Indian subcontinent in to two parts northern India and Southern India.

5.2. Indian Plate Boundary Interactions

The seismicity of the Himalaya arc tectonic belt is associated with the under thrusting of the Indian plate beneath the Eurasian plate (Molnar, 1979). Due to their continental interaction, the upper Indian crust was sheared off into a series of thrust sheets, which were crumpled and folded in the form of Himalaya (Gupta, 2006). Seeber and Armbruster (1981) have explained a tectonic model which postulates the existence of a gently dipping detachment thrust plane at depths ranging from about 20-40 km.

The Indo-Australian plate is unique among the earth's plates in its variety of first-order tectonic features, having a combination of active subduction zones, an extensive mid-ocean ridge system, significant areas of both continent-continent and continent island arc collision, and regions of intraplate oceanic-lithosphere deformation (Coblentz et al., 1998). Based on the observed seismicity the boundary between Australia and India is diffused. The formation of two triple plate junctions IN-AU-SO and IN-AU-BU could lead to future moderate to great earthquakes.

The Indian plate and Burmese plate interaction is the most active seismicity zone which has led to one of the greatest earthquake of the century (26th Dec., 2004, 9.1 M_w) apart from regular minor to major earthquakes. The focal depth variation of earthquakes is found to be between 7 km–300 km.

As compared to other interaction of Indian tectonic plate, interaction with Arabian plate and Somalian plate are not very high seismically active. Even though minor to major earthquakes are observed, they could also be probable reason for generating intraplate earthquakes. Still the reasons for Allah bund and Bhuj earthquake are being understood.

6. Conclusions

Past earthquake data have been very useful in understanding and modeling different plate tectonic models. Mainly three important points can be concluded or derived from the past earthquake data.

- i. Interaction types and their lengths
- ii. Approximate varying thickness of plate inner to boundaries from focal depths
- iii. Location of major to great earthquakes

As for the Indian tectonic plate is considered its interaction with neighboring plates have led to very large seismicity at the boundaries includes North-western, Northern, North-eastern, Eastern and Southern-eastern. With the current understanding if a three dimensional numerical model where all seven plates are interacting is modeled, it will probably give more insights about the locations of future major to great earthquakes. Understanding of this complete tectonic environment will improve as additional seismological and plate motion data accumulate. Stress models may provide further insight into the mechanics of the plate boundaries.

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