Chapter 2 Review of historical seismicity around the world

“An earthquake can occur anywhere, in any season and at any instant of time”.
-Anonymous

2.1 Introduction

Beginning of earthquake is closely related to the origin of the earth and formation of earth surface. Thus the history of the earthquakes is as old as the history of man first time recognized the earthquake. In antiquity, earthquakes were considered an expression of anger or displeasure or curse of Gods on humanity. The Vedas, ancient Indian religious literature (Vedic Sanskrit hymns, 1700-1800 BCE) refer to earthquakes. The principal Veda- the Rigveda quoted several scattered hymns refer to earthquake (Lele et al., 2006). Chinese history contains references to earthquakes as far back as 1800 BCE. First rational explanation of earthquake is found from Greek philosophy. Aristotle (4th Century BCE) discussed nature and origin of earthquakes. In the year 132 CE, the Chinese philosopher Chang Hang devised an artistic earthquake weathercock which was first scientific kind of device. It was indicating the direction of the main impulse due to an earthquake and it could detect earthquakes even not felt locally and this device was reputed highly. Before the invention of the telegraph in 1840, news travelled slowly and knowledge of serious natural disasters was not widely disseminated. The earliest extant compendium of seismicity is a list of 91 earthquakes between 34 CE and 1687 CE, prepared by D. Vincenzo Magnati and first published in 1688 (Heck and Davis, 1946). There seems to have been publishing list of earthquakes locally. At regional level, a well-documented record of earthquakes experienced in Kashmir from 12th Century CE to 1558 CE is available in the Rajatragiji by Kalhan. (Lele et al., 2006). There are number of references since ancient times that earthquakes occurred all around the globe. The purpose of this study is to take brief idea about distribution of major earthquakes and across the globe after scientific revolution and especially instrumental records of earthquake are more reliable with lower uncertainty to evaluate scientific investigations. In this chapter, an overview of distribution, main features and short note on scientific study for all major earthquakes on all major tectonic plates are presented.
2.2 Seismicity around the globe

2.2.1 Evaluation of plate tectonic

By the second half of 20th centuries, ‘continental drift theory’ and ‘theory of plate tectonic’ proposed by Alfred Wegener—a German geologist and meteorologist became generally accepted by the scientific community with extraordinary explanations. Accordingly, gigantic supercontinent which named ‘Pangea’ (also spelled as Pangaea) meaning ‘All-the-land’ was looking like as shown in Figure 2.1 before 200Ma.

![Figure 2.1 Pangea: The earth 200 million years ago.](http://oldintranet.puhinui.school.nz/topics/Volcanoes/TectonicPlates/images/pangea.gif)

200 million years ago all of the present-day continents combined to form a single supercontinent called Pangea.

![Figure 2.2 Development of today’s continents from one supercontinent](http://cassandralegacy.blogspot.in/2012/01/centennial-of-wegeners-continental.html)
Pangea then started to break up into two sub continents called Laurasia and Gondwanaland during Jurassic period and by the end of the Cretaceous period, these continents again separated into smaller land masses that look like today’s continents as shown in Figure 2.2.

The lithosphere is broken up into several parts which are called tectonic plates. These tectonic plates are then defined according to their characteristics and there are seven major and seven minor plates. These tectonic plates are irregularly shaped and are not coinciding with continents. They are not stationary and float in a very complex undefined pattern on the plastic-like layer called the asthenosphere with a velocity of some 2-10 cm/year. These plates move in relation to one another at the plate boundaries. The tectonic plates of the world were mapped in the second half of the 20th century. It is displayed in Figure 2.3 following.

![Figure 2.3 Tectonic plates of the world.](http://earthquake.usgs.gov/learn/topics/plate_tectonics/rift_man.php)
2.2.2 Major plates of the world

There are seven major and seven minor plates comprising the bulk of the seven continents and oceans.

Major plates of the world can be listed below:

1. African Plate
2. Antarctic Plate
3. Indo-Australian Plate, sometimes subdivided into:
   (i) Indian Plate
   (ii) Australian Plate
4. Eurasian Plate
5. North American Plate
6. South American Plate
7. Pacific Plate

2.2.3 Minor plates of the world

There are dozens of smaller plates, the seven largest of which are listed below:

1) Arabian Plate
2) Caribbean Plate
3) Juan de Fuca Plate
4) Cocos Plate
5) Nazca Plate
6) Philippine Sea Plate
7) Scotia Plate

As we can see from the above map that the Arabian plate is an exceptional case and do not comprise significant land area.
2.2.4 Significant earthquakes of the world

Here, we have distribution and details of significant earthquakes of the world along with their main features.

2.2.4.1 Significant earthquake of African plate

![Figure 2.4 Significant earthquakes of African Plate](image)

(1) 1755 Lisbon earthquake

On November 1, 1755 large earthquake of $8.5 < M_w < 9.0$ occurred about 200Km West-South-West of Capes St. Vincent.

- It is, near a submarine plate boundary that separates the African and Eurasian major plates and at Azores-Gibraltar Transform Fault.
- Portugal, Spain, Morroco, Grate Britain and Ireland were most affected countries according to literature available.
- The Great Lisbon earthquake has the largest documented felt area of any shallow earthquake and an estimated magnitude of 8.5–9.0. The associated tsunami ravaged the coast of SW Portugal and the Gulf of Cadiz, with run-up heights reported to have reached 5–15 m. (Gutscher et al. 2006).
- The geometry of the seismogenic zone is obtained from deep crustal studies and can be represented by an east dipping fault plane with mean dimensions of 180 km (N-S) and 210 km (E-W). For 10 m of co-seismic slip resulted an $M_w \sim 8.64$ event and for 20m of slip generated an $M_w \sim 8.8$ earthquake. Thus, for convergence rates...
of about 1 cm/yr, an event of this magnitude could occur every 1000–2000 years. (Gutscher et al. 2006).

- The observation of seiches as far away as Finland, suggest a magnitude approaching 9.0. Precursory phenomena were reported, including turbid waters in Portugal and Spain, falling water level in wells in Spain, and a decrease in water flow in springs and fountains.
- Death toll is approximately 1 lac.

2.2.4.2 Significant earthquakes of Eurasian plate

![Figure 2.5 Significant earthquakes of Eurasian plate](image)

(1) 869 Sanriku-Japan earthquake

On July 9, 869 earthquake occurred at Pacific Ocean, Tōhoku region, Japan of magnitude $M_S \sim 8.6$ or $M_w \sim 9.0$ and it triggered tsunami, named the Jōgan tsunami after the reign of the emperor.

- The earthquake caused over-riding Okhotsk Plate and the subducting Pacific Plate.
- Sediment analysis and hydrodynamic simulation indicate that the tsunami inferred to be triggered by a magnitude 8.3 earthquake spread more than 4 km inland then coast.
- Despite the moderate wave height (~8 m) scale inferred from the numerical model, the extensive deposition of well-sorted arkosic sand suggests that waves of the Jogan tsunami reached inland areas of the Sendai plain (Minoura, 2001).
Matsumoto (1985) studied the Holocene evolution of coastal sequences in northeast Japan, concluded that development of the Sendai plain resulted from the seaward progradation of fluvial systems. He made clear that progradation has continued steadily for the last 5000 years.

Using inversion analysis of geodetic data from 1966 to 1995, El-Fiky and Kato (1999) estimated that the Sendai plain subsides at the rate of 6-7 mm/year. This finding shows the Sendai plain to have been susceptible to vertical displacement.

Casualty recorded was more than 1000.

(2) 1498 Meiō Nankaidō earthquake
On September 1498 earthquake of $M_s \sim 8.6$ occurred at the off coast of Nankai, Japan.

- It is at the subduction of the Philippine Sea Plate below the Eurasian Plate.
- This earthquake triggered large tsunami.
- Casualty reported was approximately 26000-31000.
- The identification and radiocarbon dating of these sandy high-energy flow deposits in several cores suggests that the river mouth closure was initiated by mass sediment transport by a storm surge or tsunami along the Hamana coastline (Fujiwara et al., 2013).
- The same process, of sudden river mouth sealing by tsunami-transported sediments, was recently observed in the northeast of Japan during the great 2011 Sendai tsunami (Uda, T., 2012).
- Historical sources document that after the 1498 Meiō tsunami, the Hamana back-barrier sheltered environment was reconnected to the Pacific Ocean due to breaching of its sand barrier (Fujiwara et al., 2013).

(3) 1707 Hōei earthquake
On October 28, 1707 earthquake of $M_s \sim 8.6$ occurred at the Shikoku region, Japan.

- It is the result of the subduction of the Philippine Sea Plate under the Eurasian Plate.
- Casualty reported was more than 5000.
The 1707 earthquake decreased the normal stress on the dike at 20 km, the proposed depth of a basaltic magma chamber, by 1.06 bars (0.106 MPa). We hypothesize that the stress change and strain generated by the 1707 earthquake triggered the eruption of Mt. Fuji by permitting opening of the dike and ascent of basaltic magma from 20 km into andesitic and deistic magma chambers located at 8 km depth (Chelseys, 2012).

The source rupture area of the new Hōei earthquake source model extends further, to the Hyuga-nada, more than 70 km beyond the currently accepted location at the westernmost end of Shikoku.

The source rupture area of the new Hōei earthquake source model extends further, to the Hyuga-nada, more than 70 km beyond the currently accepted location at the westernmost end of Shikoku (Furumura et al., 2011).

We succeeded in explaining development of the large tsunami from Cape Ashizuri to Hyuga-nada with maximum tsunami heights of 5 m to 10 m that attack along the Pacific coast from the westernmost end of Shikoku to Hyuga-nada. This agrees with the heights of tsunamis observed along the Pacific coast from Cape Ashizuri to Hyuga-nada during the Hōei earthquake (Hatori, 1974, 1985, Murakami, 1996) very consistently.

(4) 1952 Kamchatka earthquakes-Kamchatka
On November 4, 1952 the earthquake occurred at Kamchatka, Russia of the magnitude of $M_w \sim 9.0$.

That was occurred where the Pacific Plate subducts under the Okhotsk Plate at the Kuril-Kamchatka Trench.

The length of the subduction zone fracture was 600 km.

Aftershocks were recorded in an area of approximately 247,000 sq km, at depths of between 40 km and 60 km.

Casualty report was not found.

Johnson inverted tide gauge records from Japan, North America, the Aleutians, and Hawaii for the asperity distribution. The results show two areas of high slip. The average slip is over 3 m, giving a seismic moment estimate of 1551020 Nm or...
$M_w \sim 8.8$. The 20th century seismicity of the 1952 rupture zone shows a strong correlation to the asperity distribution (Johnson, 1999).

- Bath and Benioff studied aftershock epicenters of this earthquake and found that they distributed over an area approximately 1,030 kilometers in length by 240 kilometers in width. They assumed that this distribution represents the active strain zone, the total average strain, average elastic energy and average stress of the rocks before slip were $11.9 \times 10^{-5}$, $1.35 \times 10^2$ ergs/cm$^3$ and 12.6 kg/cm$^2$ respectively (Bath and Benioff, 1958).

Four other earthquakes are displayed on the map of Eurasian plate in Figure 2.5 but they are actually on Pacific plate and hence discussed in respective subsection.

### 2.2.4.3 Significant earthquakes of Indo-Australia plate

![Figure 2.6 Significant earthquakes of Indo-Australia plate](image)

**Figure 2.6 Significant earthquakes of Indo-Australia plate**

**1833 Sumatra earthquake**

The 1833 Sumatra earthquake occurred on November 25, 1833, about 22:00 hours local time, with an estimated magnitude in the range $M_w \sim 8.8$–9.2. It caused a large tsunami that flooded the southwestern coast of the island.

- The island of Sumatra lies on the convergent plate boundary between the Indo-Australian Plate and the Eurasian Plate.
The earthquake shaking lasted 5 minutes in Bengkulu and 3 minutes in Padang, combined with the severity this suggests a very large source rupture. (Natawidjaja et al., 2006).

The region of uplift in 1833 ranges from 2°S to at least 3.2°S and judging from historical report so far shaking and tsunamis, perhaps as far as 5°S (Natawidjaja et al., 2006).

It caused a large tsunami that flooded the southwestern coast of the island. There are no reliable records of the loss of life, with the casualties being described only as 'numerous'.

The magnitude of this event has been estimated using records of uplift taken from coral microatolls (Natawidjaja et al., 2006).

(2) 1938 Banda Sea earthquake

The 1938 Banda Sea earthquake occurred in the Banda Sea region on February 1, 1938, the magnitude of this earthquake was $M_w \approx 8.5$ and was the ninth largest earthquake in the 20th century.

It had an estimated magnitude of 8.5 on the moment magnitude scale, and intensities as high as VII (very strong). It generated Tsunamis of up to 1.5 m but no human lives appear to have been lost.

From a dataset of 17 records at seven stations, we obtain a robust solution, featuring a very large moment of $8.37 \times 10^{28}$ dyne.cm, resulting in a mostly thrust-faulting mechanism of strike: 276°; dip: 63° and slip: 70° (Okal and Reymond, 2003).

The 1938 event took place in a region of sparse seismicity and away from the presumed locations of block boundaries. The deeper than normal focus of the event agrees well with the generally minor level of reported damage, and with the generation of a relatively benign tsunami. (Okal and Reymond, 2003).

(3) 1950 Assam-Tibet earthquake

The 1950 Assam-Tibet earthquake is discussed in detail in section 2.3.4.
(4) **2001 Gujarat earthquake**

The 2001 Gujarat earthquake is discussed in detail in section 2.4.2.

(5) **2004 Indian Ocean earthquake**

The 2004 Indian Ocean earthquake is discussed in detail in section 2.3.4.

(6) **2005 Sumatra earthquake**

The earthquake occurred on 28 March 2005 of Magnitude Mw ~ 8.6. The hypocenter was located at Sumatra below the surface of the Indian Ocean. The 2005 Sumatra earthquake, referred to as the Nias Earthquake by the scientific community.

- The subduction is forcing the Indo-Australian Plate to the south-west under the Eurasian plate's Sunda edge.
- Approximately 1300 people were killed by it, mostly on the island of Nias. The event caused panic in the region, which had been devastated by the massive tsunami triggered by the 2004 Indian Ocean earthquake, but this earthquake generated a relatively small tsunami.
- Effects were felt as far away as Bangkok, Thailand, over 1,000 km away.
- The earthquake lasted for about two minutes. In the twenty-four hours immediately after the event, there were eight major aftershocks, measuring between 5.5 and 6.0.

(7) **2007 Sumatra earthquake**

The magnitude 8.4 and 7.8 southern Sumatra earthquakes of September 12, 2007 occurred as the result of thrust faulting on the boundary between the Australia and Sunda plates.

- At the location of these earthquakes, the Australia plate moves northeast with respect to the Sunda plate at a velocity of about 60 mm/year.
- The September 2007 Sumatra earthquakes were a series of mega thrust earthquakes that struck the Sunda Trench off the coast of Sumatra, Indonesia, three greater than magnitude 7. A series of tsunami bulletins was issued for the area. The most powerful of the series had a magnitude of 8.5, which makes it in the top 20 of the largest earthquakes ever recorded on a seismograph.
A tsunami approximately 1 m high was reported at Padang, Indonesia. A small tsunami, some 15 cm high, was reported at the Cocos Islands. Sumatra was taken off tsunami alert after two hours.

We find that the source of the September 12, 2007 Southern Sumatra earthquake has been characterized by its highest slip values (~10 m) concentrated into a patch 100 km long and 50 km large, located between 20 and 30 km of depth, about 100 km north-west from the epicenter. The occurrence of such a slip amount has been suggested by Nalbant et al. (2005), who indicated that the greatest current seismic threat from the Sunda mega thrust may came from a section overlapped with the source of the September 12, 2007 earthquake, with a slip as great as in 1833 i.e. up to 10 m.

(8) 2012 Aceh, Indonesia earthquake

This earthquake was occurred on April 11, 2012 at Indonesia of the magnitude $M_w \sim 8.6$ and 8.2.

- It had triggered minor tsunami.
- The convergence of Indian and Australian Plates is accommodated by a broad zone of diffuse deformation.
- As part of that deformation, north-south trending fracture zones have been reactivated from the Ninety East Ridge as far east as 97°E.
- Bangladesh, India, Indonesia, Malaysia, Maldives, Singapore, Sri Lanka, Thailand were affected.
- Casualty was very less approx. 10 only.
- This convergence is accommodated by a broad zone of diffuse deformation. As part of that deformation, north-south trending fracture zones have been reactivated from the Ninety East Ridge as far east as 97°E. The earthquake was caused by a strike-slip motion. The earthquake and the largest aftershock had a fault displacement of 21.3 m. The strike-slip nature of the earthquake meant that the movement displaced relatively little seawater and was less likely to cause a tsunami. (Kreemer et al., 2003).
All these earthquakes were consistent with either left-lateral slip on SSW-NNE orientated strike-slip faults, or right-lateral slip on WNW-ESE orientated strike-slip faults, both compatible with the direction of convergence. A back projection analysis of data collected by Hi-net, an observation network in Japan, found a complex pattern of four conjugate faults. There was a strong correlation between the fault rupture pattern and the distribution of the aftershocks (Wang et al. 2012).

These earthquakes have a complex rupture process. The rupture of these earthquakes occurred on multiple, almost orthogonal faults. This is rare in a single earthquake. This earthquake had an overall relatively slow rupture speed, although the speed was above the S-wave velocity in some fault segments (Wang et al., 2012).

2.2.4.4 Significant earthquake of Pacific plate

![Figure 2.7 Significant earthquakes of Pacific plate](image)

(1) 1700 Cascadia earthquake
The earthquake of magnitude 8.7–9.2 (estimated) occurred on January 26, 1700 at Pacific Ocean, USA and Canada.

- The earthquake involved the Juan de Fuca Plate underlying the Pacific Ocean.
- The length of the fault rupture was about 1,000 kilometers (620 miles) with an average slip of 20 m (22 yards). This earthquake, the largest known to have
occurred in the ‘lower 48’ United States, rocked Cascadia, a region 600 miles long that includes northern California, Oregon, Washington, and southern British Columbia (Witter, 2003).

- The earthquake set off a tsunami that not only struck Cascadia's Pacific coast but also crossed the Pacific Ocean to Japan, where it damaged coastal villages. Written records of the damage in Japan pinpoint the earthquake to the evening of January 26, 1700.

(2) 1923 Kamchatka earthquake
The earthquake occurred on February 3, 1923 of magnitude $M_w \sim 8.5$ at Kamchatka, Russia.

- That was occurred where the Pacific Plate subducts under the Okhotsk Plate at the Kuril-Kamchatka Trench.
- The length of the subduction zone fracture was 600 km. Aftershocks were recorded in an area of approximately 247,000 sq km at the depths of 40 to 60 km.
- A severe and locally damaging tsunami generated on Kamchatka by a magnitude 8.2 earthquake struck the Hawaiian Islands at 1:00 pm local time. Property damage from these waves was estimated at $8$ million to $10$ million.
- The highest wave on Hawaii of 3.5 m above mean sea level was reported.
- Triggered an 8 m tsunami that caused considerable damage in Kamchatka. The tsunami was still 6 meters high when it reached Hawaii.

(3) 1963 Kuril Islands earthquake
On October 13, 1963 earthquake occurred at Kuril Islands, Russia of the magnitude of $M_w \sim 8.5$ and was followed by an $M_w \sim 7.8$ event seven days later.

- Both earthquakes triggered tsunamis.
- It is the Pacific Plate is being subducted beneath the Eurasian Plate.
- No casualty record found. One person injured at Waikiki by a tsunami with a measured wave height of 34 cm at Honolulu, Hawaii. One parking lot was flooded at Nawiliwili, Hawaii by a tsunami with a measured wave height of 88 cm.
The seismic moment release of the main shock determined from the P waves is less than one-half the surface wave moment of $70 \times 10^{27}$ dyne.cm. Body wave modeling of the largest foreshock (October 12, 1963; $M_s = 6.7$) indicates source duration of 12 s. (Beck Susan, 1987).

(4) 1965 Rat Islands, Alaska earthquake

The earthquake occurred on February 4, 1965 of magnitude $M_w \sim 8.7$ at Rat Islands, Alaska, USA.

- The Rat Islands form part of the Aleutian Islands, a chain of volcanic islands forming an island arc that results from the subduction of the Pacific Plate beneath the North American Plate.
- This plate boundary, the Alaska-Aleutian megathrust, has been the location of many megathrust earthquakes.
- It had caused tsunami.
- This earthquake generated a tsunami reported to be about 10.7m high on Shemya Island. Loss caused by flooding on Amchitka Island was estimated at about $10,000.$
- The earthquake was associated with a 600 km long rupture along the plate boundary, based on the distribution of aftershocks (Beck and Christensen, 1991).
- The main shock was followed by an earthquake of magnitude 7.6 nearly two months later that triggered a small tsunami. This was not an aftershock, but a normal fault event within the outer rise of the subducting plate, triggered by the earlier event. (Abe, 1972).
- On the basis of the radiation patterns and the amplitudes of the great circle Rayleigh and Love waves, the earthquake is found to have the following characteristics: fault plane dip, 18°; fault plane dip direction, N19°E; rupture propagation direction, N51°W; rupture propagation velocity, 4.0 km/sec; fault length, 500 km; moment, $1.4 \times 10^{29}$ dyne.cm; stress drop, 30 bars; and average dislocation, 2.5 meters (Francis and Kanamori, 1973).
(5) Tohoku, Japan 2011 earthquake

An earthquake of magnitude 9.0 occurred at Pacific Ocean near the east coast of Honshu, Tohoku region, Japan, as a result of thrust faulting on or near the subduction zone interface plate boundary between the Pacific and North American plates.

- The epicenter is approximately 70 km east of the Oshika Peninsula of Tōhoku and the hypocenter at an underwater depth of approximately 30 km. (Japan Meteorological Agency).
- It was the most powerful known earthquake ever to have hit Japan, and the fifth most powerful earthquake in the world since modern record-keeping began in 1900.
- The earthquake triggered powerful tsunami waves that reached heights of up to 40.5 m in Miyako in Tōhoku's Iwate Prefecture which, in the Sendai area, travelled up to 10 km inland (USGS).
- This earthquake occurred where the Pacific Plate is subducting under the plate beneath northern Honshu which moves at a rate of 8 cm/year to 9 cm/year.
- The 2011 $M_w \approx 9.0$ Tohoku earthquake caused an unprecedented level of crustal deformation in eastern parts of Japan. The event also induced seismic activity in the surrounding area, including some volcanic regions, located between 150 and 200 km from the rupture area, experienced subsidence coincident with the Tohoku earthquake. The volcanic regions subsided by 5 cm to 15 cm, forming elliptical depressions with horizontal dimensions of up to 15 km to 20 km (Youichiro and Fukushima, 2013).
- A high coupling coefficient is estimated even near the trench that can act as the source of the large tsunami of the present earthquake. The averaged seismic coupling of 0.5–0.8 in the $M \sim 9$ earthquake’s source area and the seismic moment of the earthquake suggests that the slip deficit for the $M \sim 9$ earthquake was accumulated over a period of 260–880 years, consistent with the recurrence interval of such great earthquakes from tsunami deposit data (Uchida and Matsuzawa, 2011).
2.2.4.5 Significant earthquakes of North American plate

![Figure 2.8 Significant earthquakes of North American plate](image)

(1) **1946 Aleutian Islands earthquake**

On April 1, 1946 earthquake occurred at Aleutian Islands, Alaska, USA of magnitude of 8.6

- Pacific-wide tsunami followed this earthquake.
- Casualty recorded was 165.
- This major earthquake caused only minor damage to buildings on Unimak Island, but it generated a tsunami that devasting the lighthouse and swept away its five occupants. The height of the wave at the lighthouse was estimated at about 35 meters. Tsunami damage also occurred at Dutch Harbor and Ikatan Island in the Aleutian Islands, on the west coasts of North and South America, and in Hawaii. At Hilo, Hawaii, the tsunami took 159 lives and caused $26 million loss to property. The tsunami caused one death in California. ([http://earthquake.usgs.gov/earthquakes/states/events/1946_04_01.php](http://earthquake.usgs.gov/earthquakes/states/events/1946_04_01.php)).
- During the quake, a large section of seafloor was uplifted along the fault where the quake occurred, producing a large, Pacific-wide tectonic tsunami. The most detailed and well documented accounts of the 1946 Aleutian tsunami come from Scotch Cap, located on Unimak Island, and the Hawaiian Islands (Kanamori, 1972).

(2) **1957 Andrean of Islands earthquake**

The earthquake occurred on March 9, 1957 at Andreanof Islands, Alaska, USA of magnitude of $M_w \sim 8.6$. 
USA, Aleutian Islands & Hawaii were affected.

It also caused a tsunami that reached a height of 16 m and caused around $5,000,000 in damage in Hawaii, destroying two villages on Oahu and two bridges in the Aleutian region. More than 300 aftershocks were reported along the southern edge of the Aleutians from Unimak Island to Amchitka Pass. (http://earthquake.usgs.gov/earthquakes/states/events/1957_03_09.php).

It is considered as the third largest earthquake of the century with longest aftershock zone of any earthquake ever recorded i.e. 1200 km.

Johnson et al. (1994) estimated seismic moment released as $88 \times 10^{20}$ N.m. Using the tsunami waveforms, they estimated source area by backward propagation and tsunami area is smaller than the aftershock zone and is about 850 km long. Further they found that slip was highest in the western half near the epicenter and little slip occurred in the eastern half from tsunami waveform inversion for the slip distribution.

Casualty record was not found.

2.2.4.6 Significant earthquake of South American plate

Figure 2.9 Significant earthquakes of South American plate

(1) 1575 Valdivia earthquake

The earthquake occurred on December 16, 1575 at 14:30 hours local time at Valdivia, Chile of the magnitude 8.5 (estimated).
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- Casualty record was not found.
- The 1575 Valdivia earthquake was an earthquake in Chile that caused the subsequent flood of Valdivia much like the 1960 Valdivia earthquake caused the ensuing Ríñihuazo flooding.
- Pedro Marino de Lobera, who was corregidor of Valdivia by that time, wrote that the waters of the river opened like the Red Sea, one part flowing upstream and one downstream. Mariño de Lobera also evacuated the city until the dam at Laguna de Anigua (nowadays Rinihue lake) burst. At that moment he wrote that, while many Indians died, no Spaniards did, as the settlement of Valdivia was moved temporarily away from the riverside.

(2) **1604 Arica, Chile earthquake**

On November 24, 1604 earthquake occurred at Arica, Chile of the estimated magnitude 8.5.
- No record found for casualty loss.

(3) **1615 Arica earthquake**

On September 16, 1615 earthquake caused at Arica, Chile of the magnitude $M_w \sim 8.8$.
- No record found for casualty.
- The 1615 Arica earthquake was a major earthquake in Arica, Chile. The earthquake caused considerable damage to the infrastructure of the city with the Iglesia Mayor and the city's fort collapsing and the cracks opening on the floor of the royal quicksilver storage.

(4) **1647 Santiago earthquake**

The earthquake occurred on May 13, 1647 at Santiago, Chile of the estimated magnitude 8.5 and is said to have brought virtually every building in the city to the ground.
- Chile lies along the destructive plate boundary between the Nazca Plate and the South American Plate.
- No record found for casualty loss.
(5) 1687 Peru earthquake

On October 20, 1687 earthquake occurred at Lima-Peru of the magnitude of 8.5 (estimated).

➢ The earthquake occurred along the boundary between the Nazca Plate and the South American Plate. The earthquake is likely to be a result of thrust-faulting, caused by the subduction of the Nazca plate beneath the South American plate.

➢ It triggered a tsunami and overall about 5,000 people died.

➢ The earthquake was probably followed by another large event further to the south. (Beck and Nishenko, 1990).

➢ A magnitude of 8.7 has been estimated from tsunami run-up heights and by comparison with the earthquake of 1974 (Okal et al., 2006).

➢ The tsunami was reported in Japan where it produced run-ups of 10s of meters.

(6) 1730 Valparaiso earthquake

The earthquake of the estimated magnitude 8.7 occurred on July 8, 1730 at Valparaiso, Chile.

➢ It triggered a major tsunami and spread more than 1,000 km.

➢ The earthquake took place along the boundary between the Nazca and South American tectonic plates.

➢ The quake was felt from Iquique to Osornoat; Cordoba, Mendoza and San Juan, Argentina.

➢ This event was followed by a large tsunami that affected the region between Valparaíso and Concepción.

➢ The tsunami was observed from Callao, Peru to Valdivia, Chile and also flooded some houses and fields in northeastern Honshu, Japan. Despite the severity of this earthquake and tsunami, there were very few casualties (perhaps as few as 5), primarily because an earthquake at approximately 05:00 UTC along with some other intervening tremors had alerted the residents and caused them to leave their homes.

➢ The tsunami generated by this event damaged about 2/3 of Concepcion and caused some damage at Valparaíso. In addition, it caused damage in a large region that
extended more than 1000 km from Copiapó in the north to Concepción in the south. This earthquake caused severe damage at Coquimbo, Illapel, La Serena, Petorca, Santiago and Valparaíso and some damage occurred at Chillan. (http://earthquake.usgs.gov/earthquakes/world/events/1730_07_08.php).

- We suggest that this event was very similar in size and extent to that of Maule in 27 February 2010 (Udias et al., 2012).

(7) **1751 Concepción earthquake**

On May 24, 1751 earthquake occurred at Concepción, Chile of the magnitude 8.8 (estimated).

- It is one of the strongest and most destructive recorded quakes in Chilean history.
- The 1751 Concepción earthquake was the next largest earthquake of this period and affected a very large region from Santiago to Valdivia, It struck the Central Valley of the country, destroying the cities of Concepción, Chillán, Cauquenes, Curicó and Talca.
- The earthquake began around one o'clock in the morning. According to one chronicle of a resident of Valparaíso and another of a resident of Concepción, the quake lasted about six minutes.
- A series of tsunamis generated some 10 to 40 minutes later.
- The earthquake including a large tsunami that destroyed Concepción and made it necessary to relocate the city. We suggest that this event was very similar in size and extent to that of Maule in 27 February 2010. (Udias et al., 2012).
- Casualty record was 65.

(8) **1822 Valparaíso earthquake**

On November 19, 1822 earthquake occurred at Valparaíso, Chile of the magnitude 8.5 (estimated).

- No record found for casualty loss.
(9) 1835 Concepción earthquake

The earthquake occurred on February 20, 1835 at 15:30 hours local time at Concepción, Chile and has an estimated magnitude of 8.5.

- The earthquake caused between the Nazca Plate and the South American Plate.
- The earthquake triggered a tsunami which caused the destruction of Talcahuano. A total of at least 50 people died from the effects of the earthquake and the tsunami.
- The shaking lasted for two minutes, with gradually increasing intensity. At least 300 aftershocks were noted during the next 12 days. The land was instantly uplifted along parts of the coast, as much as 3 m in places, although this was followed by subsidence in the following days. There were three separate waves reported at Talcahuano, the first of which had a run-up of 7 m. The maximum run-up of 24 m was recorded at Coelemu (Darwin, 1835).

(10) 1868 Arica earthquake

On August 13, 1868 earthquake occurred at Chile of an estimated magnitude between 8.5 and 9.0.

- Intensity of this earthquake was measured XI and it generated tsunami or multiple tsunamis in the Pacific Ocean.
- The earthquake caused as a result of thrust-faulting, caused by the subduction of the Nazca plate beneath the South American plate.
- No record found for casualty loss.
- The historian Dr. J. Y. Polo refers to this shock as one of the strongest that has been verified in Peru since the Conquest. Macroseismic observations indicate that the center of the earthquake was in the port of Arica. Along the coast it caused much havoc, being felt some 1400 km to the northwest (Samanco, Peru) and at an equal distance to the south (Valdivia, Chile). In Bolivia it was felt 224 km away east of La Paz, in the direction of Cochabamba.
- Within this area there was heavy destruction at Arica, Tacna, Moquegua, Ilo, Torata, and Iquique; the city of Arequipa was in ruins.
The first wave reached a height of twelve meters, and completely eradicated the harbor of Arica, carrying away on its backwash everything it met in its path. The flux and reflux lasted some 40 minutes. There was a series of strong currents. The backwash of the sea razed a large part of the Peruvian coast, killing 30 people at Chala, about 100 at Arica, and 200 at Iquique. The agitation of the ocean reached as far as California, Hawaii, Yokohama, the Philippines, Sydney, and New Zealand. It is reported that the earth opened up in various places, spewing out muddy water. The Headland at Arica was fractured, likewise the hills of La Caldera, next to the baths of Yura (Arequipa). About 400 movements or aftershocks were counted up to the 25th of August.

(http://earthquake.usgs.gov/earthquakes/world/events/1868_08_13.php)

(11) 1877 Iquique, Chile earthquake

On May 9, 1877 earthquake occurred at 21.16 hours local time at Iquique, Chile of magnitude of $M_S \sim 8.5-9.0$ (estimated).

- The event caused by faulting within both the subducting and over-riding plates of the Nazca plate beneath the South American plate.
- It has also been estimated to be a 9 magnitude earthquake. It had a maximum felt intensity of XI (Extreme) on the Mercalli intensity scale and triggered a devastating tsunami (Delouis et al., 2009).
- Coastal regions of Peru and Chile lie above the convergent boundary, where the Nazca Plate is being subducted beneath the South American Plate along the line of the Peru-Chile Trench. The rate of convergence across this boundary is measured at about 8 cm per year. This boundary has been the site of many great megathrust earthquakes, in addition to events caused by faulting within both the subducting and over-riding plates (Delouis et al., 2009).
- The shaking lasted for five minutes at Caleta Pabellón de Pica, a coastal town 70 km south of Iquique. The area of felt intensity of VIII on the Mercalli intensity scale or greater, extended from about 50 km south of Arica to just south of Cobija. This indicates a rupture length of about 420 km (Comte and Pardo, 1991).
This earthquake produced a 24 meter tsunami that caused extensive damage along the Peru-Chile coast. It was observed throughout the Pacific Basin including Samoa, New Zealand, Australia, Japan, Mexico and California. The tsunami was observed at all the islands of the Hawaiian archipelago. The tsunami caused fatalities in Hawaii and Japan.
(http://earthquake.usgs.gov/earthquakes/world/events/1877_05_10.php)
- A total of 2,541 people died.

(12) 1906 Ecuador-Colombia earthquake

The 1906 Ecuador-Colombia earthquake of magnitude $M_w \sim 8.8$ occurred at 15:36 hours UTC on January 31, off the coast of Ecuador, near Esmeraldas.

- The earthquake occurred along the boundary between the Nazca Plate and the South American Plate.
- The rupture zone for this earthquake was 500–600 km long, and encompassed those for the earthquakes of 1942 ($M_w = 7.8$), 1958 ($M_w = 7.7$) and 1979 ($M_w = 8.2$). The lack of overlap between the three more recent events suggests the presence of minor barriers to rupture propagation along the plate boundary (Kanamoi and McNally, 1982; Mendoza and Dewey, 1984).
- Three events of 1942 ($M_w = 7.8$), 1958 ($M_w = 7.7$) and 1979 ($M_w = 8.2$) ruptured the same area of the plate boundary overall, they released only a small fraction of the energy of the 1906 earthquake (White et al., 2003).
- It triggered a tsunami. The maximum recorded run-up height was 5m in Tumaco, Colombia. At Hilo, Hawaii a 1.8 m run-up height was recorded for this event.
- Approximately 500 to 1500 people died.

(13) 1922 Vallenar earthquake

On November 10, 1922 earthquake occurred at 04:32 hours UTC at Vallenar, Atacama Region, Chile with the magnitude of $M_w \sim 8.5$. 
The earthquake took place along the boundary between the Nazca Plate and South American Plates, at a location where they converge at a rate of seventy mm a year. (http://earthquake.usgs.gov/earthquakes/world/events/1922_11_11.php)

The length of the plate boundary that ruptured during the earthquake is estimated to be 390 km. (Shoa, 1996).

It triggered a destructive tsunami that caused significant damage to the coast of Chile and was observed as far away as Australia.

It produced a 9-m local tsunami that inundated parts of several Chilean cities and killed more than 100 people. It was recorded with 0.2 m at San Diego and 0.3 m at San Francisco. (Landers and Patricia, 1989).

The epicenter of the earthquake was well inland and the tsunami may have been caused by a submarine slide triggered by the shaking (Gutenberg, 1939).

(14) 1960 Valdivia earthquake

The most powerful earthquake ever recorded of moment magnitude $M_w \sim 9.5$ occurred at 15:11 hours local time on May 22, 1960 at Valdivia, Chile.

The earthquake was a megathrust earthquake resulting from the release of mechanical stress between the subducting Nazca Plate and the South American Plate, on the Peru-Chile Trench.

The focus was relatively shallow at 33 km (21 miles), considering that earthquakes in northern Chile and Argentina may reach depths of 70 km. Subduction zones are known to produce the strongest earthquakes on earth, as their particular structure allows more stress to build up before energy is released.

The 1960 Chilean earthquake swarm was a series of strong earthquakes that affected Chile between 21 May and 6 June 1960. The first was the Concepción earthquake, and the strongest was the Valdivia earthquake. The first Concepción earthquake was at 06:02 hours UTC-4 on 21 May 1960. Its epicenter was near Curanilahue. The Valdivia earthquake occurred at 15:11 hours UTC on 22nd May, and affected all of Chile between Talca and Chiloé Island.
The earthquake’s rupture zone was 800 km long, stretching from Arauco (37°S) to Chiloé Archipelago (43°S). The rupture velocity has been estimated as 3.5 km per second (Kanamori and Cipar, 1974).

The earthquake triggered numerous landslides, mainly in the steep glacial valleys of the southern Andes. Within the Andes, most landslides occurred on forested mountain slopes around the Liquiñe-Ofqui Fault.

It triggered tsunami affected southern Chile, Hawaii, Japan, the Philippines, eastern New Zealand, southeast Australia, and the Aleutian Islands in Alaska.

Some localized tsunamis severely battered the Chilean coast, with waves up to 25 m. The main tsunami crossed the Pacific Ocean at a speed of several hundred km/h and devastated Hilo, Hawaii, killing 61 people (Gates et al., 2009) and death toll recorded as 2230 to 6000.

(15) 2010 Chile earthquake

The earthquake occurred on February 27, 2010 at 03:34 hours local time at Chile with the magnitude of $M_w \sim 8.8$ with intense shaking lasting for about three minutes.

It occurred at boundary between the Nazca Plate and South American Plates. This earthquake was characterized by a thrust-faulting focal mechanism, caused by the subduction of the Nazca plate beneath the South American Tectonic Plates. The segment of the fault zone which ruptured in this earthquake was estimated to be over 700 km long with a displacement of almost 10 m. The fault rupture of this earthquake is largely offshore, exceeded 100 km in width and extended nearly 500 km parallel to the coast. In the vicinity of the 2010 earthquake, damaging earthquakes were reported in 1751, near Concepcion; further to the north in 1730. (http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010tfan/summary).

The maximum recorded peak ground acceleration was at Concepcion, with a value of 0.65g (6.38 m/s²).

The earthquake triggered a tsunami which devastated several coastal towns in south-central Chile and damaged the port at Talcahuano. Some 30 minutes after the first shock, consecutive tsunamis hit coastal towns, among which Constitución
suffered the hardest damage. Subsequently, tsunami amplitude of up to 2.6 m high was recorded in the sea at Valparaíso. Chile and Argentina were the most affected. 

- 525 people died and 25 missing.

2.3 Seismicity over India

2.3.1 Indian minor plate

Indian subcontinent is within the Indo-Australian Plate. The Indian Plate is today a part of Indo-Australian plate, one of the seven major tectonic plates of the world. About 55 to 50 million years ago it fused with the adjacent Australian Plate. It includes most of South Asia and a large part of Indian Ocean. (Heirzler, 1977). In the late Cretaceous about 90 million years ago, during splitting off Gondwana Indian Plate split from Madagascar. It began moving North, at about 20 cm per year and is believed to have begun colliding with Asia (Kind, 2007). In 2012, paleomagnetic data from the Greater Himalaya was used to propose two collisions to reconcile the discrepancy between the amount of crustal shortening in the Himalaya ~ 1300 km and the amount of convergence between India and Asia ~ 3600 km (Hinsbergen, 2012). They proposed a continental fragment of northern Gondwana rifted from India, traveled northward, and initiated the "soft collision" between the Greater Himalaya and Asia at ~ 50 Ma. This was followed by the "hard collision" between India and Asia occurred at ~ 25 Ma. Subduction of the resulting ocean basin that formed between the Greater Himalayan fragment and India explains the apparent discrepancy between the crustal shortening estimates in the Himalaya and paleomagnetic data from India and Asia. Kumar et al. (2007) suggested that the reason the Indian Plate moved so quickly is that it is only half as thick (100 km) as the other plate. The collision with the Eurasian Plate along the boundary between India and Nepal formed the orogenic belt that created the Tibetan Plateau and the Himalaya Mountains, as sediment bunched up like earth before a plow. The Indian sub-continent is currently moving northward at about 50 mm/year and colliding with the Eurasian Plate. The collision with Asia began in the Middle Eocene era about 50-55 Ma and formation of Himalaya can be shown in Figure 2.10.
Figure 2.10 Plate tectonic movement of India northwards into the Eurasian Plate.
(http://pubs.usgs.gov/gip/dynamic/himalaya.html)

**Major plates of India are listed below:**
- Bhandara Craton, (India)
- Bundelkand Craton, (India)
- Dharwar Craton, (India)
- Indian Craton (India)
- Singhbhum Craton (India)

These cratons are shown in Figure 2.11.
2.3.2 Seismic zoning of India

Seismic zoning map of India was first produced by Tandon (1956) showing three zones of severe, moderate and minor hazard associated with earthquakes. This map was based on a broad concept of earthquake distribution and geotectonics. The work in seismic zoning in India was started by Indian Standard Institute now Bureau of Indian Standard during the year 1960. The first seismic zoning map was included in the code IS: 1893-1962. A significant progress has been made since then both in seismic zoning and instrumental monitoring of seismicity. The seismic zoning map was revised by Bureau of Indian
Standard (IS) again in 2002 with only four zones viz., Zone-II, -III, -IV and -V on the basis of various scientific inputs from a number of agencies including earthquake data supplied by IMD, (IS:1893-2002, part-I). Of these, zone V is rated as the most seismically active region, while zone II is the least. The Modified Mercalli (MM) intensity, which measures the impact of the earthquakes on the surface of the earth, broadly associated with various zones is listed in the Table 2.1 and shown in the Figure 2.12.

<table>
<thead>
<tr>
<th>Seismic Zone</th>
<th>Intensity on MM scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>II (Low intensity zone)</td>
<td>VI (or less)</td>
</tr>
<tr>
<td>III (Moderate intensity zone)</td>
<td>VII</td>
</tr>
<tr>
<td>IV (Severe intensity zone)</td>
<td>VIII</td>
</tr>
<tr>
<td>V (Very severe intensity zone)</td>
<td>IX (and above)</td>
</tr>
</tbody>
</table>

(Source : IS 1893-2002)

Figure 2.12 Map of seismic zonation of India.
Seismic zonation map of a country is a guide to the seismic status of a region and its susceptibility to earthquakes. As shown in Figure 2.12, a large area of India is under Zone V and threatened to damage from severe earthquakes. Zone V is seismically the most active region where earthquakes of magnitude 8 or more could occur. It should be realized that in the case of shield type earthquakes, historic data are insufficient to define zones because recurrence intervals are much longer than the recorded human history. This may often give a false sense of security. Occurrence of the damaging earthquake at Latur, falling in Zone I is a typical example of this situation.

2.3.3 Overview of seismo-tectonic structure of India

Out of total area of India, 55% area is earthquake prone which had faced many earthquakes of varying intensities in the recent past. We can divide India in to three major parts according to seismic activity i.e. the region having high sensitivity to earthquakes, the region having moderate sensitivity to earthquakes and the region having low sensitivity to earthquakes. India broadly consists of three distinct geological units namely-

1. The Himalaya-Arakan Yoma-Andaman Nicobar Island Arc
2. The Indo-Gangetic plain and
3. The Indian shield.

These units can be mapped approximately as shown in the Figure 2.13. While seismotectonic map of India and fault map of India are shown in Figure 2.14 and Figure 2.15
Chapter 2 Review of historical seismicity around the world

Figure 2.13 Geological units of India.

Figure 2.14 Seismo-tectonic map of India
(http://www.earthcrust.org/science/transects/india.html)
It is now well established that Himalayas are a result of collision between the Indian and the Eurasian plates about 50-60 Ma (Valdiya, 2001). The current penetrating rate of the Indian plate into the Eurasian plate is estimated to be 45 mm/year (Bilham, 2004). Due to this continuous under-thrusting of the Indian plate beneath the Eurasian plate, stresses are...
increasing and accumulating progressively in the Himalayas. This makes the Himalayas seismically very active. The 2,500 km long Himalayan mountain chain is convex southwards and embodies big bulges and knee-bends at the ends (Valdiya 2001). The width of this unit extending from Kashmir to Arunachal Pradesh varies from 250 km to 300 km. In the northeast, the Himalaya takes a bend and meets the Indo-Burmese arc. This eastern extremity of the Himalaya is known as the Assam syntaxis. Similarly, the turning point of the Himalayan mountain system in the north-western region is known as the Hazara syntaxis, where the northwest end of the Himalaya meets the Pamir-Hindukush region. The structure and tectonics of these two syntaxis zones are complex and largely unknown (Chandra 1978). Moreover the geology at the two syntaxis zones is quite different. These syntaxis zones are also the locations of high stress concentrations and intense seismic activity. The Chaman fault in the west and Sagaing fault in the east cut the Himalayan mountain chain at its two extremities. These faults are further linked too much longer and fundamental faults of the Indian Ocean and they act as links in transmitting the movements of the oceanic faults to the Indian plate.

2.3.3.1 Himalaya-Arakan Yoma-Andaman Nicobar Island Arc Unit

(A) The Himalaya region

As per geologists the Himalayan part is more sensitive to earthquakes because of the fact that it is the youngest mountain range only 1-2.5 crore years old and the youngest mountain ranges are quite prone to the appearance of earthquakes. Thus the Himalayan frontal arc is one of the most seismically active regions of the world. The Himalayan mountain range is the result of the collision of Indian and Eurasian plates, some 40 million years ago. The plate collision process gave rise to several active faults in the Himalayan region, namely the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Himalayan Frontal Thrust (Valdiya, 1976). The location of these faults as per the Seismotectonic Atlas of India (GSI, 2000) is shown in Figure 2.15. The Indus Tsangpo Suture Zone (ITSZ) is considered to be the plate boundary where the Tethys Ocean was consumed by the subduction process. The Main Karakuram Thrust (MKT) marks the southern boundary of the Hindu Kush and the Karakuram. The curvilinear ITSZ and MCT are traced to the south of MKT. The Main Mantle Thrust (MMT) in the Hazara syntaxis is
the western extension of the MCT. The Chaman fault joins the Herat fault and the two bend eastward and split into the Karakuram and the Altayan Tagh fault systems in the Pamir region. The Balochistan arc comprising of Sulaiman and the Kirthar ranges are aligned in a north-south direction. The fault plane solutions in Himalayas have thrust solutions with nodal planes dipping toward the north, indicating under thrusting of the Indian plate along the entire Himalayan region.

(B) North East Indian region

North East India (NEI) is considered as one of the most intense seismic regions in the world. This part of India has an extremely complex tectonic and geologic set up. Most of the earthquakes in NEI are caused due to the South–North and the West–East movement of the Indian plate (Chen and Molnar, 1990). The most striking feature in this region is that the Himalaya takes a sharp bend along the Assam syntaxis and continues in a broadly North-South arcuate direction to the east of Burma and joins the Andaman arc giving rise to a complex plate boundary. Another important geomorphologic feature of NEI is the Brahmaputra River which runs almost parallel to the MBT along the Assam valley and suddenly takes a 900 turn to run parallel to the Dhubri fault. The Shillong plateau and Mikir hills are considered as fragment of Peninsular Shield which moved to the east along the Dauki fault. Due to its proximity to Himalayas and Burmese arc, the earthquakes in the Shillong Plateau and Assam valley area may be referred to as plate boundary earthquakes (Kayal, 2008). The seismic activity in this region is very high compared to the shield area of other part of peninsular India.

Northeastern India and the adjoining areas fall in the intense seismic belt of the world. Out of 5 great earthquakes experienced by India during the past, 3 events fall in this region including the 1934 Bihar-Nepal earthquake. Besides, 11 large earthquakes ($M > 7$) occurred in this region during the period from 1869 to 1947. Of these 5 belonged to the Indo-Myanmar subduction zone, four in Meghalaya Plateau and Mikir Hills areas, 1 in the Siang fracture zone of the eastern Himalaya and one in the northeastern corner of Bengal Basin in Bangladesh.
(C) The Andaman-Sumatra-Sunda region

The Andaman-Sumatra-Sunda arc is 5000 km long from Burma to Sumatra and Java to Australia defines the boundary between the Indo-Australian and Eurasian plates (Fitch, 1970; Curray et al., 1979). The under thrusting of the Indian plate in northeast direction beneath the Andaman-Nicobar Islands can be observed in the focal mechanism solutions of earthquakes of this region. The nature of convergence in the Andaman-Sunda arc is of oceanic type, where as in the Indo-Burmese arc, it is continental type (Kayal, 2008). This region is highly active and falls in the zone of most severe seismic hazard. The Andaman-Sunda arc has produced great earthquakes in the past which have generated damaging tsunamis.

The bathymetry of the Andaman and Nicobar islands were first surveyed in 1770 by Captain Ritchie, and more accurately in 1789 by Captain Blair. Their interiors were explored by a scientific expedition in 1857 that also mapped the Barren and Narcondam volcanoes. The history of damaging earthquakes follows semi-continuous colonial occupation in the mid of 18th century by the Danes 1756-68 (Canning et al., 1858), Moravian Baptists (1768–1787), and Austrians (1778–1781). The region has been characterized by minor microseismicity in the past century and it is possible that aseismic processes accommodate reverse-slip on this part of the plate boundary.

2.3.3.2 Indo-Gangetic plain region

The Indo-Gangetic plain also known as the Himalayan fore-deep lies in between the Indian shield and the Himalayas. To the South of the Himalayan zone and running parallel it is the indo-gangetic zone. The formation of Aravali hills in Indo-Gangetic plain is related to tectonic movements before 2500 BCE (Rajendran and Rajendran, 2002) which changed the drainage pattern of the Northwest India drastically (Valdiya, 2002). The Vedic River Saraswati which flowed from the Himalayas to the present day Rann-of-Kutch in the Holocene period got desiccated due to tectonic activities in the Indo-Gangetic plain. This East-West tectonic basin is characterized by several hidden faults and ridges in the basement of the Ganga basin (Gansser, 1974; Valdiya, 1976). The Delhi-Haridwar ridge
which is demarcated by a pair of faults is the continuation of the Aravalli Mountain into the Himalaya through Haridwar. Similarly Faizabad ridge and Munger-Saharsa ridge denotes the prolongation of the Bundelkhand and Satpura massifs. All the ridges are bounded by faults and are in tectonic continuation from the Indian shield. The North-South Dhubri fault in Northeast India separates the North Bengal basin from Shillong plateau. These faults have oblique and transverse alignment across the Himalayan tectonic trend. Gansser (1974) pointed out that Gangetic plain is not sediment filled fore-deep, but it represents the depressed part of the peninsular shield in which several hidden faults exist. The earthquake activity in the Gangetic plain is broadly associated with strike-slip faulting (Gupta, 2006). The Gangetic plain is moderately seismic when compared to the Himalaya (Quittmeyer and Jacob 1979). Most of the earthquakes striking this zone are of moderate intensity of 6 to 6.5 on Richter scale. Therefore this zone is called the zone of comparative intensity. The earthquakes along the foothill are of medium to high intensity. However, the earthquakes of this zone are more harmful due to high density of population in this area.

2.3.3.3 Peninsular shield India
Peninsular India constitutes one of the largest Precambrian shield areas of the world. The Indo-Gangetic alluvium Plain (IGAP) separates the Himalaya to the North and the peninsular shield to the South. The Indo-Eurasian collision resulted in the flexure of the Indian plate. The flexural stresses along with the northwest compressive stress of collision are responsible for sporadic earthquake occurrences within the Indian plate (Bilham et al., 2008). The great structural disturbances during the geological past resulted in the development of local zones of weakness along which crustal adjustments are likely to take place.

The Peninsular shield India is made up of three main cratonic regions namely The Aravalli, the Dharwar and the Singhbhum which are separated by Proterozoic rifts and mobile belts. The major prominent rifts that separate the southern and northern blocks of the shield are the Narmada-Son-Lineament (NSL) and the Tapi Lineament (TL), together called Son-Narmada-Tapi lineament (SONATA) which is an ENE-WSW trending zone and runs across the Indian shield from west coast to east coast. This rift zone of about 1600 km in
length separating the northern and southern blocks of the Indian shield is a region of
moderate seismic activity with infrequent earthquakes. In Southern India, sporadic and
low-level seismicity is observed along the old shear zones. The faults associated with the
Godavari Graben namely, the Kaddam Fault and the Gundlakamma Fault near Ongole on
the coast trending NW-SE are regarded to be moderately active in Peninsular India. These
faults separate the Singhbum and the Dharwar protocontinents. The other rift basins are the
Kutch, Cambay, Godavari, Cuddapa etc. in which the prominent rift zone in Peninsular
India is the Kutch rift located at the northwest margin of the Indian shield. The formation
of Kutch, Cambay and Narmada rift basins in Peninsular India is mainly attributed to the
reactivation of Precambrian structures during the rifting of Gondwanaland in the early
Jurassic or late Triassic period. The structural trend of the Kutch rift basin is controlled by
a number of E-W faults. The Kutch region is bounded by the south-dipping Nagar Parkar
fault in the north and the north-dipping Kathiawar fault in the south. The other major faults
in the region are the E-W trending Allah Bund fault, Island Belt fault, Kutch Mainland
Fault (KMF), Kathiawar Fault, Nagar Parkar Fault and Katrol Hill Fault. Among these, the
Allah Bund Fault, KMF and Katrol Hill Fault are active and have been associated with
devastating earthquakes in the past. Apart from the Kutch and the SONATA rifts and
Godavari Graben, the Cambay Graben, the West Coast Zone, the Cuddapah Basin, and the
parts of southern India are known areas of significant seismic activity. Earthquakes in
Peninsular India can be classified into rift and non-rift events. The Koyna \( (M \sim 6.5, 1967) \)
and the Killari \( (M \sim 6.3, 1993) \) earthquakes were non-rift events where as the Jabalpur
\( (M \sim 6, 1999) \) and the Kutch \( (M \sim 7.7, 2001) \) earthquakes were rift events. Based on the
occurrence of earthquakes, it is observed that the hazard in Peninsular India is less severe
than in the Himalayan region, but the damages caused due to intraplate events are
generally very high. These events are also felt over a much larger area than the Himalayan
earthquakes \( \text{(Singh et al., 2004; Kayal, 2008)} \).

The peninsular shield India earthquakes can be further classified in two groups-
(a) Earthquakes over Kutch region
(b) Earthquakes over Southern peninsular India region.
2.3.4 Significant earthquakes of India.

GSI prepared maps of earthquakes of magnitude $> 5.0$ from the instrumental time to 2002 which is presented here in Figure 2.16 and map of all significant earthquakes including historical earthquakes of $M_w \geq 4.0$, total 38860 earthquakes is shown in Figure 2.17 to provide a brief idea about distribution of earthquakes all around India. Significant earthquakes of India in terms of magnitude or casualty or damage caused occurred over Indian sub-continental are reviewed briefly with their respective features in following subsequence. The sequence follows the order in accordance with seismotectonics of Indian sub-Continental discussed above i.e. first Himalayan region, NE India region, Andaman and adjoining region and finally peninsular shield Indian region. Total 20 significant earthquakes from 1847 CE have been discussed in this subsection.

Figure 2.16 Seismicity of the Indian sub-continent, 1964-2002 (M > 5.0, Source: GSI).
Figure 2.17 Historic Seismicity in and around Indian sub-continent. 
(Total 38860 earthquakes of $M_w \geq 4.0$, Source: GSI)

In the following, Figure 2.18 represents map of 20 significant earthquakes of India.
2.18 Significant earthquakes of India.

(1) 1905 Kangra earthquake

1905 Kangra earthquake was a major earthquake that occurred in the Kangra Balley and the Kangra region of Himachal Pradesh in India on 4 April 1905. Main features of this earthquake are listed below. The earthquake measured 7.8 on the surface wave magnitude scale and the calculated epicenter of the earthquake lies within the zone of
thrust along the front of the Himalayas formed by the continuing collision of the Indian plate into the Eurasian plate.

- Death toll estimated more than 20,000 people. Apart from this most buildings in towns of Kangra, Mcleodgani and Dharmshala were destroyed.
- Although this earthquake is one of the most severe event known in the western Himalaya, it has the largest death toll and is the first to have occurred since the development of instrumental seismology.
- Gutenberg and Richter published a magnitude of $M_s \sim 8$ for the 1905 event and Richter characterized it further as one of the four great Himalayan earthquakes to have occurred in the past 200 years.
- Seeber and Armbruster (1981) suggested that the rupture area appropriate for a $M_s \sim 7.8$ lies in the range $100 \times 120 \text{ km}^2$ to $80 \times 50 \text{ km}^2$ with 3–8 m of average slip and can be interpreted the earthquake to have ruptured a $280 \times 100 \text{ km}^2$ area when combined with the inferred rupture areas of the 1897, 1934 and 1950 earthquakes, which implies that rupture area experienced by half of the 2000 km long Himalayan arc.
- This quake was caused by thrusts, collision of the Indian plate into the Eurasian plate.

(2) 1930 Dhubri earthquake

The 1930 Dhubri earthquake occurred on July 3, 1930 at 03:23 local time near Dhubri, India (then British India). It had a magnitude of $M_s \sim 7.1$.

- From the isoseismic map the depth was suggested to be about ~60 km.
- Most of the buildings were damaged in Dhubri and the surrounding areas.
- This earthquake did not cause any fatalities.
- The maximal intensity was IX on the Rossi-Forel scale near Dhubri.

(3) 1991 Uttarkashi earthquake

The 1991 Uttarkashi earthquake occurred on 20 October, 1991 in the Uttarkashi region of the Uttarakhand province of India, which measured $M_w \sim 6.8$, killed over a thousand people and caused extensive damage to property.
The quake occurred within the main thrust system of the Himalayas.

- The body wave magnitude of the earthquake was 6.6 and the fault plane solution indicates reverse faulting. The hypocentre was located at a focal depth of about 12 km between the Chail and Jutogh Thrusts but movement propagated southward along the Jamak–Gangori Fault (JGF) and Dunda fault (DF) which are developed as blind faults related to the growing Uttarkashi antiform (Thakur and S.Kumar, 1994).

- A 30-meter deep crack was noted in the Uttarkashi area (USGS report).

- The stress drop for the Uttarkashi and the Chamoli earthquakes is computed as 77 and 29 bars, respectively. (Joshi Anand, 2006).

(4) 1999 Chamoli earthquake

The 1999 Chamoli earthquake occurred on 29 March 1999 in the Chamoli district in the province of Uttar Pradesh (now in Uttarakhand) in India. The earthquake was the strongest to hit the foothills of the Himalayas in more than ninety years.

- The magnitude of the earthquake was 6.8 on the Richter scale and it lasted for forty seconds. The epicenter was located near Gopeshwar and the maximum intensity on MSK scale was VIII. Estimated focal depth was 21 km. USGS estimate of the focal depth is 12 km.

- Approximately 103 people died in the earthquake. Apart from the Chamoli district, the quake also affected five other districts of Uttar Pradesh viz. Rudraprayag, Tehri Garhwal, Bageshwar, Uttarkashi and Pauri Garhwal (all are in Uttarakhand now). Among these, Chamoli and Rudraprayag were the most affected districts. Officials from Pakistan reported that the quake was also felt in Lahore and Gujranwala. The earthquake was also felt in the Nanda Devi mountain region, in Kanpur, Shimla, Delhi, Dehradun, Haridwar, Saharanpur, Moradabad, Bijnor, Meerut, Gaziabad and Srinagar and in the Baitadi district, Dadeldhura district, Darchla district and Kanchapur district in Mahakali zone in Nepal.

- The Himalaya Range has been undergoing crustal shortening along the 2,400 km long northern edge of the Indian Plate which resulted in the formation of several
thrust planes including the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT).

- The estimated seismic moment \( M_o \) for the Chamoli earthquake using strong motion data comes out to be in the range \( 6.94 \times 10^{25} \) dyne.cm to \( 12.4 \times 10^{25} \) dyne.cm. The circular source radius using Brune’s formula is in the range 1.98 km to 2.96 km. The stress drops for this event varies from 2091 bars to 3984 bars. The maximum peak ground acceleration of 352.83 cm/sec\(^2\) was recorded for this event at Gopeshwar. (Pandey Y. et al., 2001).

(5) 1869 Cachar (Silchar) earthquake

On 10th of January 1869 Sunday a large earthquake struck in parts of lower Assam of the magnitude assigned varies from 7.3 to 7.5 having its epicenter on the Kopili fault zone and 9.4 km North of Kumbhir (Assam) and hypocentral depth estimated was of 50 km.

- The earthquake was distinctly felt from Patna in the west to northern Burma in the east; in the south it was felt up to locations south of Calcutta and Chittagong; in the north from Darjeeling to Dibrugarh.

- The impact of the shock was felt over 6,50,000 square kilometres. There was heavy damage in the towns of Cherrapunji, Silchar, Shillong and Sylhet and also in Manipur. Fissures opened on the banks of the Surma river and sand vents threw up great amounts of sand and water.

- The most remarkable feature is that it created large fissures on the surface and sinking of ground over large area. The epicentral tract was 30-45 km long and 5-6 km wide lying on the northern border of the Jaintia Hills.

- This is the first earthquake in India for which Geological Survey of India carried out field investigations. Sir Thomas Oldham carried out the investigations.

(6) 1897 Assam earthquake

The earthquake occurred on June 12, 1897 in Assam an estimated magnitude \( M_w \) of 8.7 estimated 14 km away ESE of Sangsik of Meghalaya. From European seismograms
Richter calculated a magnitude of $M_s \approx 8.7$ although retrospective calibration of these same records yields $M_s = 8.0 \pm 0.1$.

- After the detailed investigation of this event Oldham (1899) enunciated the theory that the earthquake was caused by north dipping thrust plane measuring 160 km in length and 80 km in width at a depth of 8 km to 14 km and dipping towards north.

- Geodetic observations indicate that the rupture extended up to 35 km into the crust and might have even cut its base, which in this region, lies at a depth of 43-46 km.

- The northern edge of the Shillong Plateau rose violently more than 11 m during rupture of a buried, 110 km long, reverse fault, dipping steeply away from the Himalaya. The stress drop implied by the rupture geometry and the prodigious fault slip of 18±7 m, explains observed epicentral accelerations exceeding 1g vertically and surface velocities exceeding 3 m/s. Earthquake fountains, some 4 feet high, were reported from Dhubri. Shaking from the event was felt across India, as far as Ahmedabad and Peshawar. Seiches were also observed in Myanmar. This was felt from Burma to New Delhi. Numerous buildings in the neighboring country of Bhutan were heavily damaged.

- It was for the first time during this earthquake, accelerations exceeding 1g were identified as responsible for propelling objects into the air. The great Assam Earthquake of 1897 ($8 < M < 8.1$) is the largest known Indian intraplate earthquake (Bilham et al., 2001).

- It raised the northern edge of the Shillong Plateau by more than 10 m, resulting in the destruction of structures over much of the plateau and surrounding areas (Ambraseys and Bilham, 2003).

- Considering the size of the earthquake, the mortality rate was not that high, with about 1500 casualties, but property damage was very heavy. Landslides were reported all across the Garo Hills. The towns of Dhubri, Goalpara,

- Guwahati and Coach Bihar in Assam and West Bengal were heavily damaged.
(7) **1934 Bihar earthquake**

On January 15, 1934 the earthquake was struck at Bihar with the magnitude of 8.1 at around 02:13 hours local time. The epicenter for this event was located in the eastern Nepal about 240 km away from Kathmandu.

- The 1934 Bihar-Nepal earthquake was believed to rupture a 200 km to 300 km long segment to the east of Kathmandu. The dimensions of the rupture are probably about 100 km North-South (Pandey and Molnar, 1988).
- The 2000 km-long Himalayan mega thrust (MFT/MHT) is generally believed to have been the source of this earthquake.
- The maximum Mercalli Intensity was estimated about XI.
- Extreme damage (X) in the Sitamarhi-Madhubani, India area, where most buildings tilted or sank up to 1 m into the thick alluvium. In Sitamarhi, not a single house was left standing.
- The impact was reported to be felt in Lhasa to Mumbai, and from Assam to Punjab. The earthquake was so severe that in Kolkata, (around 650 km from epicenter) many buildings were damaged and the tower of St. Paul Cathedral collapsed.
- 1934 Bihar-Nepal $M \sim 8.1$ approximately 30,000 people were said to have died. Munger and Muzaffarpur were completely destroyed.
- One noteworthy phenomenon of this earthquake was that sand and water vents appeared throughout the central vents of earthquake area. The ground around these sand fissures subsided, causing more damage.
- Extensive liquefaction of the ground took place over a length of 300 km called the Slump Belt during 1934 Bihar-Nepal earthquake.

(8) **1943 - Near Hojai (Assam), India**

On 23rd October 1943 the earthquake took place at Hojai (Assam) with the magnitude of $M_S \sim 7.2$ at around 22.53 hours of local time at 13.6 km east of Hojai in Assam.

- Based on this account it is possible that the MM intensity near Dimapur was VIII to IX. As this earthquake occurred during the height of World War II when the threat of Japanese aggression on the eastern border of British India was extremely high, much information is not known about this earthquake.
(9) 1950 - Arunachal Pradesh, India, $M_w \sim 8.7$

On August 15, 1950 the earthquake occurred at 20.7 km Northwest of Tajobum (Arunachal Pradesh), India of the magnitude of $M_S \sim 8.7$.

- This earthquake is often referred to as the “Assam Earthquake of 1950” or “Independence Day earthquake” and it was the 6th largest earthquake of the 20th century.
- There were fissures in the earth, from which water and sand was emitted and represented liquefaction due to intense ground shaking.
- This earthquake was caused due to a slip on the Jiali and Po Chu Faults in southern Xizang, along the border with northeast India. The fault plane mechanisms for this event indicates strike-slip faulting (Ben-Menahem et al. 1974) with one of the planes striking NW. Surface faulting is thought to have also occurred as a result of the quake. A recent fault plane solution by Chen & Molnar (1977) suggested a plane dipping NW with a slip in the dip direction of the plane. This event yielded both dextral slip along NW nodal plane and also thrust events (Nandy, 2001).
- It was felt throughout north-eastern India and in many parts of eastern India. It was also felt throughout Bangladesh, Bhutan and Myanmar.
- Damage occurred in the entire region as far as Kolkata. It was felt across a wide area of the subcontinent, over an area totaling 4.5 million square miles and approximately 1500 casualty reported due to this earthquake.

(10) 1988 Nepal earthquake

The earthquake took place on August 21, 1988 with the magnitude of $M_w \sim 6.8$. The earthquake struck in two installments of 10 seconds and 15 seconds each.

- Maximum intensity was VIII.
- Liquefaction observed in a 5,500 sq km area of southern Nepal.
- Felt in large parts of northern India from Delhi to the Burma border and in much of Bangladesh.
- Particularly in the Darbhanga-Madhubani-Saharsa area. Damage in the Gangtok area, Sikkim and in the Darjiling area of India were badly affected.
Casualty was reported 1467 persons and injuring more than 16,000. Nepal and east region of India were affected. Seven hundred twenty-one people killed, 6,553 injured and 64,470 buildings damaged in eastern Nepal, including the Kathmandu Valley.

(11) 2011 Sikkim earthquake
The earthquake was struck on 18 September 2011 around 18:10 hours local time at the Kanchenjunga Conservation Area, Sikkim-India of the magnitude $M_w \sim 6.9$.
- The region is known for seismic activity between the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT).
- More than 300 landslides occurred all over the state and disturbed the road connectivity to major towns like Mangan, Chungthang, and Lachung and even NH31A, main route connecting Sikkim and West Bengal.
- It had triggered land sliding in the Himalayan region. The earthquake was felt across northeastern India, Nepal, Bhutan, Bangladesh and southern Tibet.
- At least 111 people killed in the event.

(12) 1847 Nicobar Earthquake
On 31 October 1847 an earthquake occurred to west of Nicobar island.
- The first of the three large historical earthquakes in the Andaman and Nicobar region for which information available occurred in 1847.
- No original account of the 1847 earthquake survives and all secondary accounts appear to derive from Hochstetter's. The 5week period of felt aftershocks suggest that its magnitude may have $7.5 < M < 7.9$.
- It occurred between the times of the Danish and British occupations and in the absence of further information, a precise location or mechanism is speculative.
- Although it may have occurred on the strike-slip Andaman fault to the west of the Nicobars, we know of no earthquakes exceeding $M_w \sim 7.2$ on this transform fault and it is probable that its size may signify that it occurred on a reverse fault west of, or beneath the islands (Bilham et al., 2005).
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(13) 1881 Car Nicobar Earthquake

On 31 Dec 1881, an earthquake occurred at Car Nicobar Islands. Data for the study of this earthquake were compiled by Oldham (1884), who believed the earthquake occurred on the locus of these two cities beneath the Bay of Bengal (400 km west of the Andaman Islands).

- The earthquake is calculated to have occurred near and west of Car Nicobar with two reverse slip ruptures. The larger measured 150x60 km, and dipped 25°E with a slip of 2.7 m equivalent to a $M_w \sim 7.9$ earthquake (Ortiz and Bilham, 2003).
- The location of the 1881 rupture was sufficiently close to Car Nicobar to have tilted the island, raising its western edge 50 cm relative to its eastern shore. The tsunami resulted in the flooding of stilt houses to the base of their floors.

(14) 1941 Andaman Islands earthquake

On 26 June 1941 the earthquake took place with the magnitude of $M_w \sim 7.7$ to 8.1.

- The 1941 earthquake is listed in Gutenberg and Richter (1965) as $M_s \sim 8.1$ and appears even larger in some catalogs, but Pacheco and Sykes (1992) assign it $M_w \sim 7.7$.
- Slip was less than 3 m on a dip rupture of less than 50 km wide and 150 km long.
- The preliminary aftershock location available to this study suggests that rupture may have extended from 250 km North to 50 km South of the mainshock. Subsidence near and north of Port Blair is consistent with the rupture terminating near the western shoreline of the Andaman Islands.
- Andaman and Nicobar Islands, India and Sri Lanka were mostly affected.
- There may have been damage and deaths in Bangladesh, Myanmar and Thailand due to the tsunami.
- The tsunami generated by the 1941 earthquake is stated to have caused much loss of life along the east coast of India and approx. 7,000 people were possibly killed by the earthquake and tsunami (Murthy and Rafiq, 1991).
(15) **2004 Indian Ocean earthquake**

The earthquake struck on December 26, 2004 at under Indian Ocean with a magnitude of $M_w \sim 9.1–9.3$.

- It is the third largest earthquake ever recorded on a seismograph. The earthquake had the longest duration of faulting ever observed, between 8.3 and 10 minutes. It caused the entire planet to vibrate as much as 1cm.
- The earthquake was caused when the Indian Plate was subducted by the Burma Plate.
- It triggered a series of devastating tsunamis, inundating coastal communities with waves up to 30 m high. The resulting tsunami was given various names, including the ‘2004 Indian Ocean tsunami’, ‘South Asian tsunami’, ‘Indonesian tsunami’, and the ‘Boxing Day tsunami’.
- It was one of the deadliest natural disasters in recorded history, killing over 230,000-280,000 people.
- Indonesia was the hardest-hit country, followed by Sri Lanka, India, and Thailand. Bangladesh, Malaysia, Myanmar, Singapore and the Maldives were also affected.
- Subsidence of the east coast of Car in preliminary damage reports (Malek, 2005) appears to be of order 1-2 m, with possible minor uplift (<1 m) of its western shore.
- In conflict with evidence for 1m of subsidence, a preliminary estimate of 25 cm of co-seismic subsidence is reported following GPS occupation of a point near Port Blair by the Survey of India, Dehra Dun, soon after the earthquake.
- A specific analysis reveals that seismic moment magnitude is close to 9.1 (seismic moment equal to $5.6 \times 10^{22}$ N.m). Moment release analysis along the Sumatra–Andaman trench shows two main slip episodes; One next to the northern extremity of Sumatra (20 m slip) and the other one along the Nicobar Islands (10 m slip), with a global extent of 1150 km to 1200 km.
- Total duration imaged by Rayleigh waves is 580 sec and no activity of the fault is found in the time scale between 600 sec to 2000 sec. In the hypothesis of even longer timescale slip, this phenomenon would be of the order of 10%–20% of the global moment and likely restricted to the Andaman Islands. (Martin Vallée, 2007).
On the basis of simple 2-D elastic deformation in a half-space (Savage, 1983) the slip of 15-23m in the Nicobar Islands and 5-10m in the Andaman Islands.

Slip from 3°N to 9°N was ~ 20 m according to seismic moment estimates (Park et al., 2005) and dislocation models constrained by subsidence estimates near Nicobar Island, consistent with the generation of the catastrophic tsunami that damaged remote coastlines. Aftershocks suggest that it propagated 1300 km from an epicentral region at 3.3°N northwards with a duration of ~ 10 minutes corresponding to an average propagation velocity of 2.1 km/s (Park et al., 2005).

Tsunami run-up on Sumatra and in Thailand locally exceeded 10 m with a death toll of almost 230,000 in the epicentral region, and approximately 70,000 on the distant shorelines of seven nations Sri Lanka, Myanmar, Malaysia, Bangladesh, the Maldives, Kenya, and Somalia. The tsunami's reach extended to the Arctic Ocean via both Pacific and Atlantic pathways. Local peak-to-peak amplitudes of 1 m were recorded on the Pacific coast of Mexico due to focusing of the wave by the East Pacific rise (Ortiz, 2005).

16) 1819 Rann of Kutch earthquake
This earthquake is described under section 3.3 of Chapter 3.

17) 2001 Bhuj, Gujarat earthquake
This earthquake is described under section 3.3 of Chapter 3.

18) 1967 Koynanagar Earthquake
On 11 December 11, 1967 the earthquake hit near the site of Koyna dam of the 6.5 magnitude occurred in and around Koynanagar town in Maharashtra, India.

- The earthquake claimed at least 180 human lives and injured over 1500 people.
- Some geologists believe that the earthquake was due to reservoir-triggered seismic activity.
- The earthquake claimed at least 180 human lives and injured over 1500 people. The earthquake also damaged more than 80% of the houses in Koyana Nagar Township. There have been several earthquakes of smaller magnitude there since 1967.
- The deadly earthquake had caused a 10-15 cm fissure in the ground which spread over a length of 25 km.
(19) **1993 Latur earthquake**

The Latur earthquake of magnitude $M_w \sim 6.4$ struck at Latur of Maharashtra, India at 03:56 hours local on September 30, 1993 and approximately 20,000 people died whilst another 30,000 were injured. Total 52 villages were demolished.

- It was an intraplate earthquake. The earthquake's focus was around 12 km deep relatively shallow causing shock waves to cause more damage.
- Because India does not lie on a plate boundary there was some debate as to what caused the earthquake. One suggestion is the existence of fault webs. The Indian sub-continent crumples as it pushes against Asia and pressure is released. It is possible that this pressure is released along fault lines. Another argument is that reservoir construction along the Terna was responsible for increasing pressure on fault lines.
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(20) **1997 Jabalpur earthquake**

The 1997 Jabalpur earthquake of Magnitude $M_w \sim 6.0$ occurred on May 22, 1997 in Jabalpur district of Madhya Pradesh, India. The epicenter of the earthquake was located at Koshamghat village.

- According to geologist Dr V. Subramanyan, former professor at the Indian Institute of Technology Bombay (IIT Bombay), the quake was caused due to the presence of Narmada Fault.
- Casualty was recorded approximately 39.
2.4 Seismicity over Gujarat province

2.4.1 Geology and seismo-tectonics of Gujarat region

Geologically, Gujarat region exhibits a variety of rock types of different ages. The Aravalli mountain range ~ 2500 Ma (Rajendran and Rajendran, 2002), one of the oldest mountain range passes through the Northeast part of the region. About 60% area of the region is occupied by Deccan basalt in South Gujarat, major part of Saurashtra and districts of Sabarkantha and Panchmahals. While sedimentary rocks belonging to Jurassic and Cretaceous age cover part of Kutch, Surendranagar, parts of Sabarkantha and districts of Vadodara, Narmada and Bharuch. The coastal tracks of Kutch and Saurashtra are exposed by Tertiary rocks. The central Gujarat and part of North Gujarat are covered by alluvium brought by westerly flowing rivers.

Tectonically, the history of this region begins with the formation of three major systems namely Kutch, Cambay and Narmada basins and major West coast fault at the time of separation and northward movement of Indian plate from the Gondawana land (Biswas, 1992). Thus, according to literature available and analysis carried out in this thesis, the Gujarat region can be classified broadly in three zones namely, Kutch zone, Saurashtra zone and Gujarat mainland zone in view of seismic activity observed in the region from historical time to the present day. The geodynamic processes of the Kutch region are complicated and were formed due to the rifting along E-W Delhi trend during early Jurassic period and continued until the early Cretaceous (Biswas, 1987; Karanth et al., 2001; Kayal et al., 2002). The Kutch rift zone is bounded by two major faults namely, the Nagar-Parkar Fault (NPF) in the North and North Kathiawar Fault (NKF) in the South. There are three main uplifts in Kutch basin from North to South, they are Island Belt Uplift (IBU), Wagad Uplift (WU) and Kutch Mainland Uplift (KMU). These uplifts are controlled by major faults namely Island Belt Fault (IBF), North Wagad Fault (NWF), South Wagad Fault (SWF) and Kutch Mainland Fault (KMF) trending in the E-W direction (Biswas, 1987; Karanth et al., 2001). Saurashtra region is a horst which is surrounded by rift Grabens and exhibits volcanotectonic characteristics in the central, southern and northern regions (Biswas, 1987). The Aravalli trend continues across Cambay Graben into Saurashtra, forming the southwesterly plunging Saurashtra area. The Son-Narmada trend
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extends across Cambay Graben and continues in the southern part of Saurashtra. The faults and lineaments are mainly aligned parallel to the major tectonic features in ENE directions. The fault along the southeastern coast and Kim fault trends parallel to Son-Narmada rift. The mainland region of Gujarat consists of two rift zones, namely Cambay rift zone and Narmada rift zone. The Cambay Graben was formed due to upliftment of Saurashtra block during the Late Cretaceous. Narmada rift zone is bounded by two fault systems namely Narmada-Son fault (NSF) in the North and the Satpura fault (SF) in the South. The Satpura belt is characterized by several parallel ENE-WSW striking strike-slip faults with associated conjugate faults and rifts.

2.4.2 Significant earthquakes of Gujarat region

Significant earthquakes in terms of casualty and damage occurred in Kutch region are discussed under section 3.3 of Chapter 3.