SPATIO-TEMPORAL EVALUATION OF LONG-TERM EARTHQUAKE EVENTS AND ITS CONTRIBUTION IN GENESIS OF *TSUNAMI* IN THE INDIAN OCEAN

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ABSTRACT:
A very high magnitude earthquake (9.1 MW) triggered a devastating *Tsunami* in the Indian Ocean on 26th December 2004. The epicentre was located at 3.3° N, 95.8° E with a focal depth of ~ 30 km. The impacts of Tsunami were felt as far away in Somalia, Tanzania and Kenya along the east coast of Africa. Considering the role of earthquake, in the present study the spatio-temporal analysis of long term (1901 to 2019) earthquake events was performed, which recorded by USGS to understand the genesis of *Tsunami* (2004) in the Indian Ocean. The study exhibited that the maximum frequency of earthquake was observed between the ranges of 4 *MW* to 6 *MW* on the Richter scale during 2001 – 2010. There was only one earthquake event >8 *MW* on the Richter scale (26th December 2004 having depth 30 Km) in the Indian Ocean recorded during 1901 - 2019. The study exhibited that the maximum earthquake was observed between 30-40 km below the surface, and primarily of moderate to low magnitudes. The proximity analysis along the major fault line indicates that the maximum earthquakes were in the buffer of 200 km from fault line in Bay of Bengal. The decadal variation of earthquake exhibits that the maximum number of earthquake events (8427 events) were triggered during the year 2001-2010, whereas during the year 2004, the total 902 earthquake events >4 *MW* was recorded. The study indicates that the earthquakes >7 *MW* (on Richter scale) and depth below 30 km (shallow earthquake) are primarily responsible to major *Tsunami* events in the Indian Ocean. The very high magnitude (>9 *MW* on the Richter scale) and shallow depth (~ 30 km) are the major cause of 2004 Tsunami and its high level of damage. There were very low frequency (10 – 15 events) of earthquake occurred having magnitude >7 and depth < 30 km.

1. INTRODUCTION

Tsunami, often incorrectly called tidal waves, is a series of waves with a long wavelength and period (time between crests) (Mathur and Udani, 2015). Since 1750, the Indian Ocean has not experienced a natural disaster of such magnitude, with enormous consequences for the region's environment (Sirikulchayanon et al., 2008). On 26th December 2004, an earthquake of 9.1 *MW* occurred at 0:58:53 GMT in Indian Ocean. The epicentre of earthquake was located at 3.3 N, 95.8 E with a focal depth of approximately 30 km (Lavigne et al., 2013), which triggered a massive Tsunami in the coastal areas of Indian Ocean. Around 280,000 people were killed in South Asia, Southeast Asia, and East Africa (Lavigne et al., 2013). The vertical offset of the ocean floor by 7 to 10 meters on 26th December 2004, Sumatra earthquake displaced massive volumes of water, resulting in a destructive *Tsunami*. Because of the north-south direction of the fault line, the *Tsunami* was the strongest in the east-west direction. The wave height in deep water (open ocean) was measured through satellites to be approximately 60 cm, while traveling at a speed of 500 to 800 km/hr. The velocity decreased to only tens of kilometres per hour in shallow water near the shoreline, depending on the local bathymetry. This, however, resulted in large and destructive waves that reached run-up heights of 20 to 30 meters in Banda Aceh (Saatcioglu et al., 2005). The distribution of aftershocks (U.S. Geological Survey[1]) suggests that the rupture extended over a distance of 1500 km (measured parallel to the arc), but seismic inversions for this event are non-unique and cannot resolve many details of slip, especially along the northern portion of the rupture (Ammon et al. 2005). Furthermore, considering that slip north of ~9°N appears to have generated little or no seismic radiation (Lay et al. 2005; Ammon et al. 2005), seismic inversions will only provide a minimum constraint on the extent and amount of slip, and geodetic inversions will be required to provide a maximum (and perhaps more accurate) constraint. However, inversions of the sparse geodetic data that were available prior to this study provided only limited constraints on the amount and distribution of slip (Subarya et al. 2006). Since as per current research knowledge there is no established methods to detect the tsunami being generated due to earthquake or landslide. The phenomenon of tsunami is mainly generated undersea disturbance due to earthquake or landslide or activity near the coast or in the ocean and displace few kilometres to >1000 km apart from epicentre. The earthquakes mainly occurs in the region having a high tectonic subduction zones along with tectonic plate boundaries and high seismicity in a regions, caused due to collision of tectonic plates. When a disturbance happens the ocean, the ocean floor rise or falls and effects on water above it and as the water moves up and down, seeking to regain its balance, a tsunami is born. (Borrero, 2005; Kanamori and Kikuchi, 1993; Pelayo and Wiens, 1990; Tsuboi, 2000).

The earthquake of 26th December 2004 occurred due to slip on the subduction interface between the Indo- Australian plate and the Burma microplate below Andaman and Nicobar Islands and Aceh province, Sumatra. The Indian plate has been moving north-east at a rate of approximately 60 mm/year, subduction under the overriding Burma microplate. The epicentre of the quake was about 155 km west of Sumatra and about 255 km south-east of Banda Aceh, Indonesia (Saatcioglu et al., 2005). Along the Java Trench to the southeast of Sumatra, the Australian plate sub ducts beneath the Sunda Shelf in a direction nearly orthogonal to the trench and at a rate of about 63 mm/year. (Bock, 2003; Michel et al., 2001). Along Sumatra the direction of convergence becomes increasingly oblique towards the north-west and the relative plate slip is partitioned into nearly perpendicular thrusting at the trench and trench-parallel, right-lateral slip at the Sumatran fault (SF) (Fitch, 1972). The strength of a Tsunami depends upon the magnitude of earthquakes occur in the Ocean. There are a number

[1] http://neic.usgs.gov/neis/poster/2004/20041226.html

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of earthquakes occurring in the earth's crust but their magnitude is very low to trigger a Tsunami.

2. STUDY AREA

In the present study, the North Indian Ocean comprising the parts of Bay of Bengal was considered as study area. The territory is about 150 km north of Aceh in Indonesia and separated from Thailand and Myanmar by the Andaman Sea. In this region, the group of Andaman and Nicobar Islands was located, which is a Union territory of India comprising 572 islands of which 37 are inhabited, are a group of islands at the juncture of the Bay of Bengal and Andaman Sea. There are 572 islands in the territory having an area of 8,249 km^2. Of these, about 38 are permanently inhabited. The islands extend from 6° to 14° North latitudes and from 92° to 94° East longitude. The Andaman and Nicobar Islands have a tropical rainforest canopy, made of a mixed flora with elements from Indian, Myanmar, Malaysian and endemic floral strains. So far, about 2,200 varieties of plants have been recorded, out of which 200 are endemic and 1,300 do not occur in mainland India. As of 2011 Census of India, the population of the Union Territory of Andaman and Nicobar Islands was 379,944, of which 202,330 (53.25%) were male and 177,614 (46.75%) were female.

3. METHODOLOGY

This study aims to analyse the earthquakes events, which is obtained from USGS earthquake portal[2]. Earthquakes of different intensities were plotted in the GIS environment where the events were analysed with reference to its spatio-temporal occurrences, decadal occurrences, magnitude, depth of occurrences, proximity to major fault line near the Andaman and Nicobar Islands. Fault line has been taken from and proximity analysis at various proximity *viz.*, >5 km, 5-10 km, 10-50 km, 50-100 km, and >100 km from major fault line. The earthquake events of occurred during 2004 was analysed with reference to the earthquake events of a century (1901 to 2019).

4. RESULTS AND DISCUSSION

The earthquakes occurred during 1901 to 2019 was analysed in GIS environment showing its magnitude and its depth. The maximum number of earthquakes was observed in the range of 4-5 *MW* on Richter scale (*figure 1)*. Usually, it takes an earthquake with a Richter magnitude exceeding 7.5 *MW* to produce a destructive tsunami at specific depth. The earthquakes in this range is of very low intensity. Maximum frequency of earthquake magnitude occurs in the range of 5-6 *MW* in 2004, which releases low amounts of energy to trigger *Tsunami* (*figure 2*). Earthquake magnitude more than 8 is observed in 2004, which triggered a massive *Tsunami* near Sumatra Island (*figure 2*). The energy released during this earthquake is sufficient to trigger a devastating tsunami. Scatterplots provides better understanding of the frequency of earthquakes occurred from 1901 to 2019. The maximum earthquake belongs to less than 6 magnitudes on the Richter scale. A very few Earthquakes belong to above 8 magnitudes on the Richter scale. An increase in the trend of earthquake event was witnessed from the scatterplot (*Figure 4*). Since the number of events of earthquakes was increased during the post 1960s, but the magnitude trend was observed decreasing, means earthquake event occurring with less magnitude. This may be attributed to the movement of oceanic plate at various intensity leading to earthquake of varied intensity/ magnitude. From 1901-2010, the depth of the maximum earthquake located between 10-

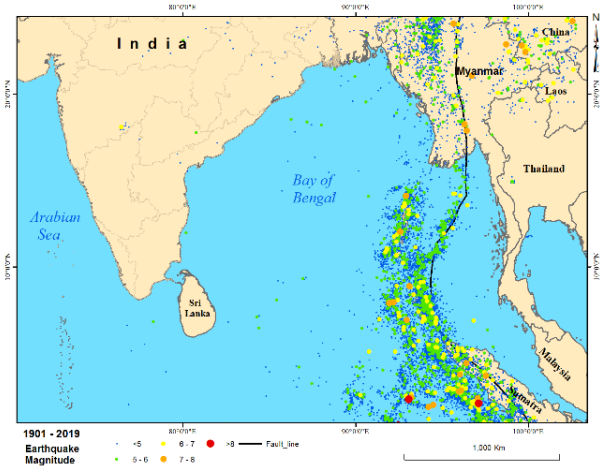

Figure 1. Spatio-temporal distribution of earthquake based on its magnitude during 1901 to 2019

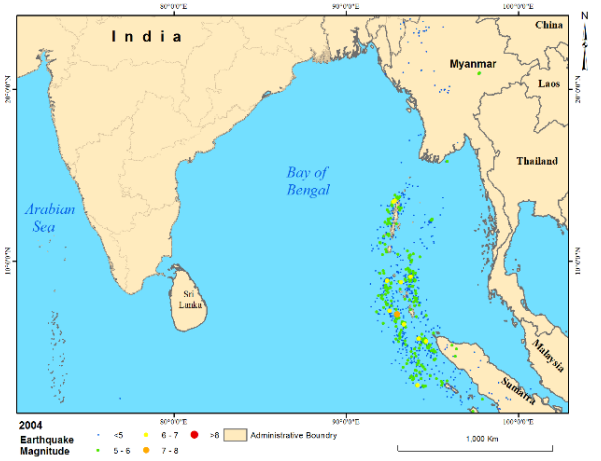

Figure 2. Spatio-temporal distribution of earthquake based on its magnitude during 2004 in Indian Ocean

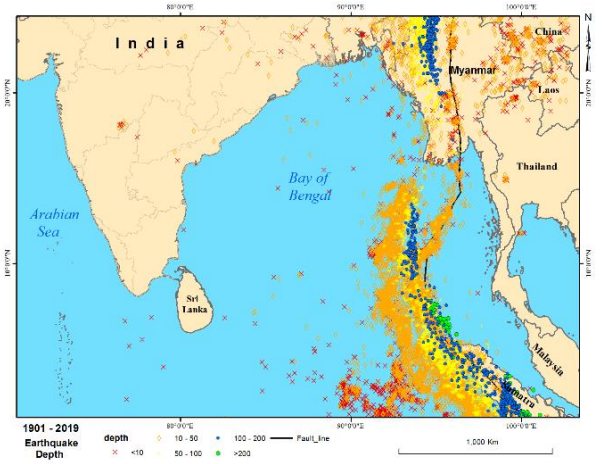

Figure 2. Spatio-temporal distribution of earthquake based on depth to hypocentre during 1901 – 2019

[2] http://earthquake.usgs.gov/

50 km range (*figure 3*) and having magnitude between 4.0 and 6.0. The study exhibited that the nearer the depth of earthquake, the higher the devastation. Increase in distance of surface from the focus, decrease in the impacts of the earthquake on the surface. Earthquake magnitude >4 was analysed from 1901 to 2019 with a sum of occurrence of earthquake in decadal time scale. As per USGS, very less number of earthquakes was recorded till 1970s. The least event of earthquakes captured was one in 1901 -1910 followed by 4 events in 1911-20, 12 events in 1921-30, 15 events between 1931-40 as well as in 1941-50 and 50 events in 1961-70.

The highest number (8427 events) of earthquake events occurred was during 2001-10 followed by 3581 events during 2011-18 (March), 1232 events in 1991-2000, 1164 events in 1981-90 and 509 events in 1971-80 in Indian ocean. In year 2004, 902 events of earthquake triggered, which shows a huge number of earthquakes. The less number of events captured till 1970s may be attributed to limitation of observation, recording station, methods *etc*. The maximum frequency of earthquake events was recorded at the depth between 10 to 50 km in the year 2004. It is difficult to conclude the magnitude of an earthquake on the basis of its depth (*figure 5*). The correlation analysis of magnitude and depth of the earthquake events (1901-2019) exhibits that the more occurrence of earthquake with higher magnitude (>7 *MW*) at the shallow depth (<50 km).

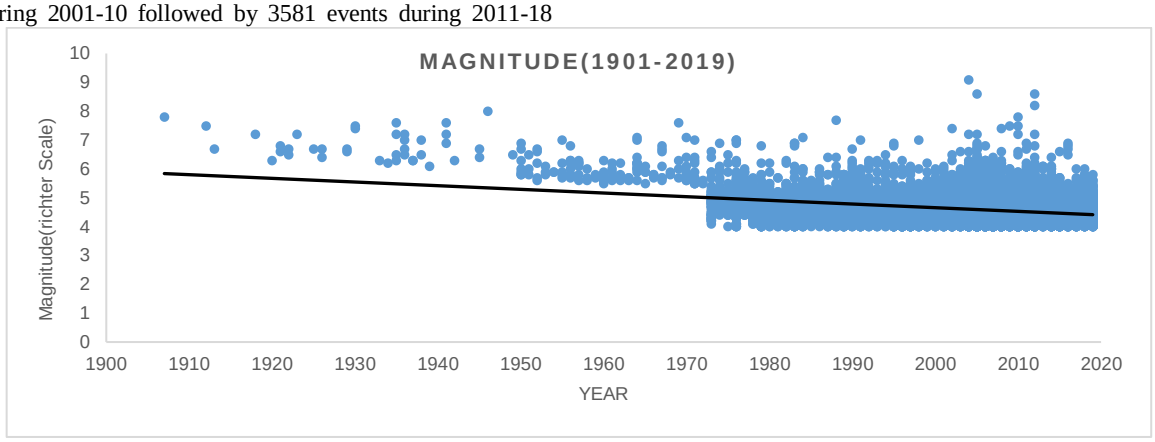

Figure 3. Trend of number of Earthquake from year 1901 - 2019

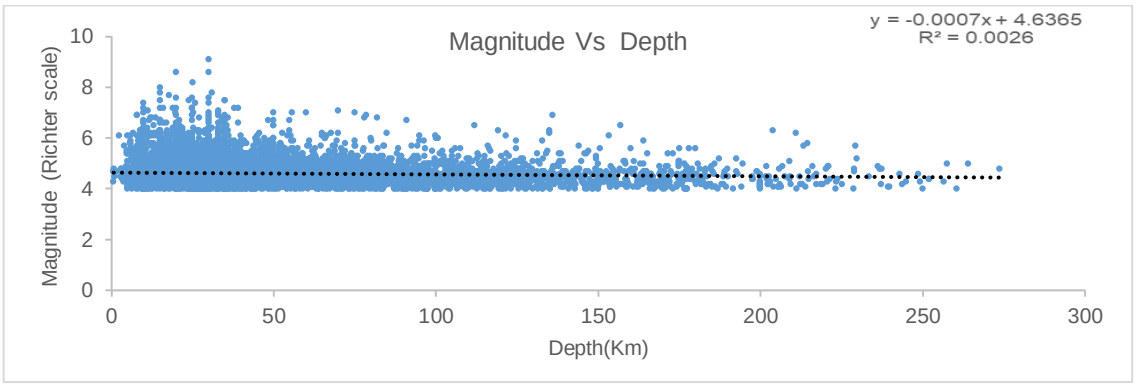

Figure 4. Correlation Map of Magnitude v/s Depth

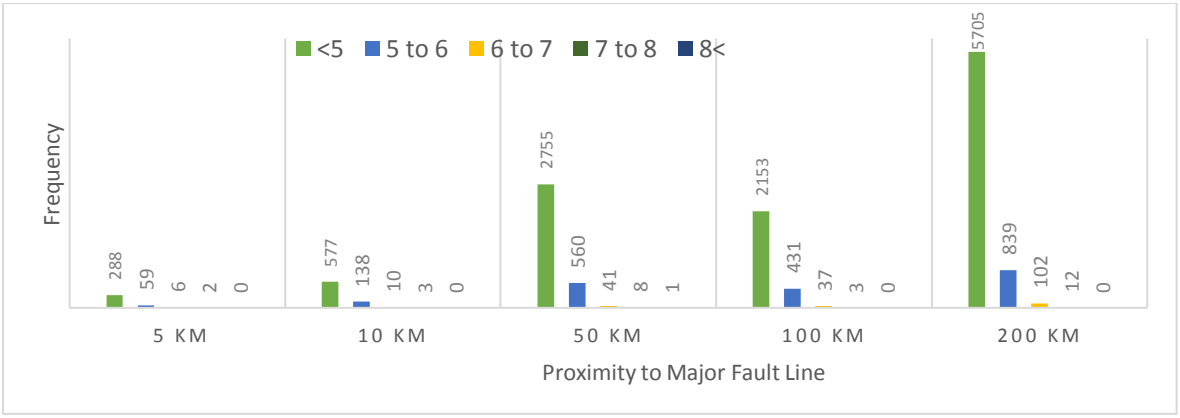

Figure 5. Number of earthquake events in the proximity of major fault line

Year	Events of Earthquake with Frequency (*MW*>4)
1901-1910	1
1911-1920	4
1921-1930	12
1931-1940	15
1941-1950	15
1951-1960	45
1961-1970	50
1971-1980	509
1981-1990	1164
1991-2000	1232
2001-2010	8427
2011-2019	3581
Year	**Frequency (*MW*>4)**
2004	902

Table 1. Number of Earthquake Events in different decade between 1901 - 2019 and year 2004

The depth of the earthquake events were analysed with reference to its depth. The study exhibits that the most events of earthquake occurred between 30 - 40 km vertical depth *i.e.,* 7126 events, followed by 2379 events in 10 - 20 km vertical depth, 1958 events at 20 - 30 km depth and 1278 events >100 km depth. Least events of earthquake (163 events) was occurred at <10 Km vertical depth followed by 464 events at 80 - 100 km vertical depth and 659 events at 60 - 80 km vertical depth. It is to note that in 2004, the most number of events *i.e.,* 455 events occurred at 30 - 40 km depth followed by 192 events at 20 - 30 km vertical depth and 94 events at 10 - 20 km vertical depth. Least event was recorded (10 events) at < 10 km vertical depth followed by 21 events at 80 - 100 km vertical depth, 27 events at 60 - 80 km depth, and 30 events at more than 100 km depth and 73 events at 40 - 60 km vertical depth. Here all events are the recorded occurrence events of earthquakes events.

The proximity analysis (<5 km, 5-10 km, 10-50km, 50-100 km and 100-200 km) of earthquakes events along the major fault line was performed during the period 1901-2019 to deduce the geography of earthquake events in the Indian Ocean (*Figure 5, Figure 6*). The study exhibited that the maximum number of earthquakes events of <4 *MW* was observed within the proximity of 100-200 km from the major fault line. Further, a decreasing trend in the frequency of earthquakes of 5 to 8 magnitude was observed (*Figure 6*). The maximum number of earthquakes were observed in the proximity of 100-200 km zone from the fault line. Only one earthquake event was observed having magnitude >8 in the proximity of 50-100 km from the major fault line.

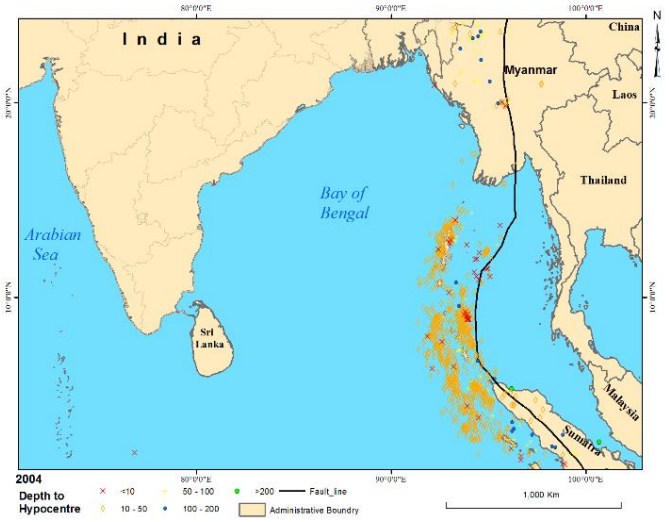

Figure 6. Depth to Hypocentre

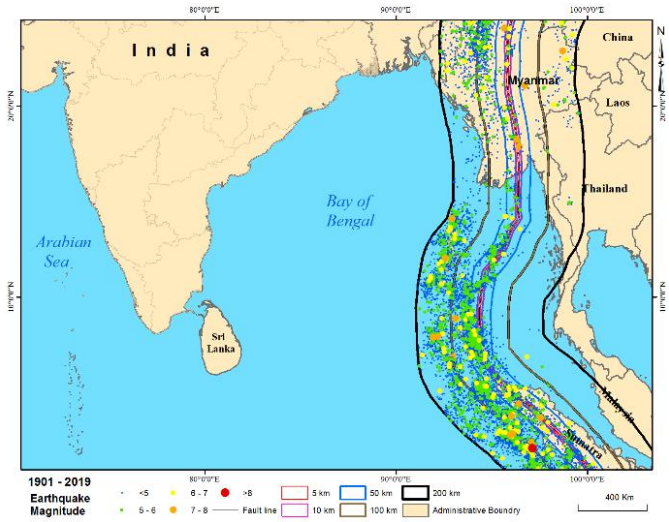

Figure 7. Earthquake events based on magnitude with in the proximity of major fault line in Indian Ocean

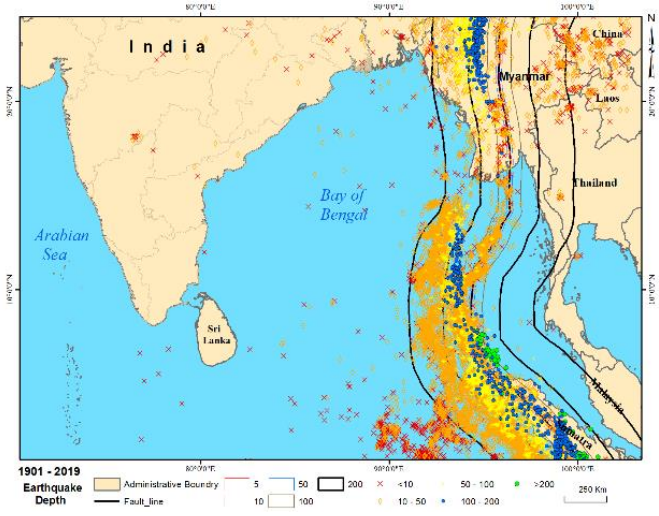

Figure 8. Proximity analysis based on depth to hypocentre along the major fault line

Analysing the USGS based earthquake events occurred in Indian ocean based on its various characteristics, it is concluded that earthquake exceeding with magnitude 7.5 occurring near the ocean surface or <50 km depth triggers the devastating tsunami. The same result has been reported by various studies done on various regions around the globe (Annaka et al., 2007; Fujii et al., 2011; Satake, 1994; Satake et al., 1996; Tanioka and Sataka, 1996; Tomazevic, 1999). As per Global Historical Tsunami Database (GHTD) about 85% - 89% of tsunami are generated by large earthquakes or landslide.

5. CONCLUSION

The study concludes that the maximum number of earthquake events having 4 to 6 *MW* on the Richter scale has been occurring along the fault line does not contribute in the genesis of *Tsunami*. The earthquakes (>7.5 *MW*) observed are mainly responsible for the formation of destructive *Tsunami* in the Indian Ocean. It is to note that there are very less frequency of earthquake events, which had magnitude >7.5 on the Richter scale. Generally, earthquake of higher magnitude (>7.5) primarily at shallow depth (<50 km) trigger the devastating Tsunami. The proximity analysis along the major fault line concludes that the maximum earthquakes occur in the proximity of 200 km along the fault line. It is to mark that since 2004 (> 9.1 *MW*), no significant earthquake event was recorded of such high magnitude. The region is tectonically activated and frequency of high magnitude earthquake events was observed post 1960 periods, primarily during 2001-10. Although, earthquake of *MW* >8 occurred at the depth below 200 km which does not conclude Tsunami eventually. In future work, subsidence and upliftment of earth's surface due to earthquake generated Tsunami using SAR offset tracking (Lal et al., 2018; Sun et al., 2017) or interferometry approach (Fornaro and Pascazio, 2014; Massonnet et al., 1993) may be considered for better understanding of deformation occurred during 2004 earthquake and *Tsunami*.

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