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Earthquakes in India: Hazards, Genesis and Mitigation Measures

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1. INTRODUCTION

Earthquake, as its name suggests, means shaking of the ground which is caused by a sudden release of stored elastic energy in the rock mass that had accumulated as strain over time along faults. Seismic waves are generated due to sudden release of energy which extend outward from the point of origin (called "epicenter") like water ripples. The speed of these waves depends on the geologic composition of the materials through which they pass. Earthquakes can occur at a range of depths, and the focal depths (distance below the earth's surface at which accumulated energy is released) from 0 to 70 km are considered *shallow*, from 70 to 300 km are considered *intermediate* and greater than 300 km are considered *deep* (Richter, 1958). Some 50,000 earthquakes occur on an average every year as the earth's tectonic plates shift and adjust, including some of potentially devastating magnitude releasing enormous amounts of energy. Approximately 75% of the world's population live in the areas that were affected at least once by natural disasters namely earthquake, tropical cyclone, flood or drought between 1980 and 2000 (UNDP, 2004). Potential earthquakes often cause considerable causalities and economic damage, coupled with significant hydrologic/hydrogeologic changes (e.g., UNDP, 2004; Allen, 2007; Manga and Wang, 2007). In addition, many secondary hazards/disasters such as landslides, rockfalls, avalanches, tsunamis, etc. are known to occur in the aftermath of an earthquake.

The Himalayan mountain ranges are considered to be the world's youngest fold mountain ranges. The subterranean Himalayas are geologically very active. In a span of 53 years, four earthquakes of magnitude about 8 or more have occurred in this region. The peninsular part of India comprises stable continental crust. Although these regions were considered seismically least active, occasionally they were affected by the earthquakes, which caused great havoc as in the case of Latur earthquake in Maharashtra during 1993 (Seeber et al., 1996). The escalation in population has no effect on the frequency of occurrence of major and great earthquakes, but it does have effect on the fatalities caused by the earthquakes. The total deaths per earthquake appear to be on rise (Fig. 1), and this is particularly true with many developing Asian nations, including India. In developed nations, though the number of deaths per earthquake has come down, it appears to be on the rise in developing nations due to exponential urban growth and poor construction. It is difficult to believe but in the Indian subcontinent, on an average, every year more than 600 people lost their lives due to earthquakes in past 100 years. Thus, it is important to understand the regions of high earthquake risk and dense population and the regions where they overlap. With this view, a brief review of Indian seismicity, genesis and possible mitigation measures is presented in this chapter.

In this review, earthquake occurrence processes and earthquakes that occurred between the eastern and western Syntaxial bends in Assam and Kashmir, respectively have been considered. Thus, in the western region, the regions and the earthquakes that occurred in the Indo-Kohistan Seismic Zone (IKSZ), e.g., the recent 2005 Kashmir earthquake, which appears to be different from the Himalayan detachment earthquakes (Gahalaut, 2008), Hazara arc, Salt Ranges and Chaman fault region are excluded. In the

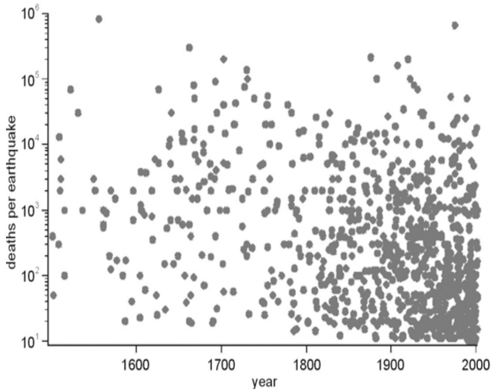

Fig. 1 Global earthquake fatalities since sixteenth century (Bilham, 2004).

eastern region, the regions and earthquakes that occurred in the Indo-Burmese arc and Sagaing fault regions are excluded. Since the focus is on the thrust belt of the Himalayan frontal arc, the regions of Tibet, Hindukush and Pamir are not considered. Thus, a review of some of the major, recent and important earthquakes in the Indian shield region, results of geodetic measurements in the Himalaya and India shield region about the rate and mode of convergence, and discussion on seismic gaps in the Himalayan arc region have been provided in this chapter. Finally, some issues related to the mitigation of seismic hazard and the feasibility of early warning systems are discussed.

2. GENESIS OF EARTHQUAKES

Occurrence of tectonic earthquakes is best explained by the theory of plate tectonics. According to this theory, entire lithosphere (i.e., consisting of crust and upper mantle with total thickness of 100-150 km) around the globe is divided into plates which are in continuous motion with respect to each other. It is the interaction of these plates along their edges which causes earthquakes. These earthquakes are referred to as interplate earthquakes. A few earthquakes occur within the plate interiors due to crustal heterogeneities and internal deformation and they are referred as intraplate earthquakes. Indian plate moves in the northeast direction at a rate of about 5 cm/year (about 1 mm/week) and its interaction with the Eurasian plate has led to the highest Himalayan mountain chain in the world and the highest plateau, i.e., the Tibetan plateau (Fig. 2). It has also led to the occurrence of some great earthquakes in the Himalayan and its contiguous regions. The earthquakes in the Himalayan arc occur due to the underthrusting of Indian plate beneath the Eurasian plate. According to the most acceptable and widely applicable model of underthrusting and earthquake occurrence, the convergence of the Indian and Eurasian plates is accommodated through slip on the detachment (Seeber and Armbruster, 1981). The detachment (also referred to as decollement or the Main Himalayan Thrust, MHT) is the surface between the underthrusting Indian shield rocks and the overlying Himalayan rocks (Fig. 3). The part of the detachment that lies under the Outer and Lesser Himalaya is seismogenic and slips episodically in a stick and slip manner. It accumulates strain during the interseismic period when it is locked, which is released during the infrequent earthquakes through sudden slip on the detachment. The detachment that lies under the Higher and

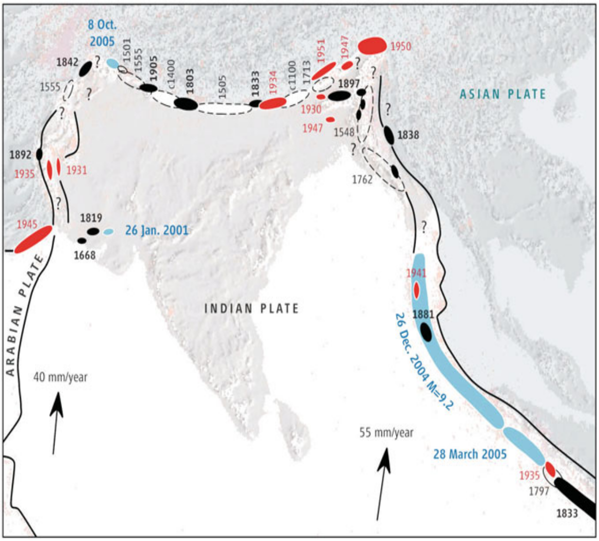

Fig. 2 Great and major earthquakes in the Indian subcontinent (Bilham, 2006). Question marks show the region where either the earthquakes have not occurred in past 200 years or there are no data to support or reject the occurrence of earthquakes.

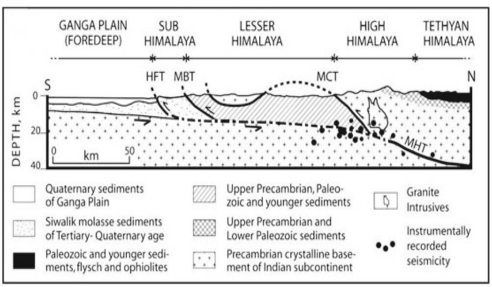

Fig. 3 Generalized north-south section across the Himalaya for the central portion of the Himalayan arc (Seeber and Armbruster, 1981). Figure after Kumar et al. (2006).

Tethys Himalaya slips aseismically and does not contribute to strain accumulation. In this model the major thrusts, namely, the Main Frontal Thrust (MFT), Main Boundary Thrust (MBT), Main Central Thrust (MCT) and Southern Tibet Detachment (STD) are assumed to be listric to the detachment.

The great thrust earthquakes in the Himalaya occur on the seismogenic detachment under the Outer and Lesser Himalaya, whereas the small and moderate earthquakes of the Himalayan seismic belt occur on the downdip part of the seismogenic detachment or on the mid-crustal ramp (Seeber and Armbruster, 1981; Ni and Barazangi, 1986; Molnar, 1990; Pandey et al., 1995, 1999; Gahalaut and Kalpna, 2001). Majority of the earthquakes of the Himalayan seismic belt are of thrust type with slip vectors perpendicular to the Himalayan arc. Further north of the Higher Himalaya, majority of the earthquakes exhibit normal type of motion on north-south oriented planes, while along the major faults, e.g., the Altyn Tagh and Kun-Lun, strike slip motion dominates. Those earthquakes are not included here in this review. Majority of the earthquakes in the Indian shield region occur along the well defined zones, which are referred as the failed rift regions. These are the regions along which rifting within the India plate developed but was immediately aborted as the India plate started moving northward after rifting from Africa and Madagascar. Thus, these regions became weak with heterogeneous intrusive material where many earthquakes of Indian shield region have occurred. Important of such failed rifts are Narmada-Son, Godavari and Kachchh failed rifts. Some of the earthquakes in the Indian shield region are referred as Stable Continental Region (SCR) earthquakes, e.g., the 1993 Killari earthquake. The 1967 Koyna earthquake also falls into that category with a distinction that it was triggered (but not caused) by the reservoir. Some small and moderate magnitude earthquakes occur along the Eastern and Western Ghats, which are linked to deformation in the rift shoulders.

3. REVIEW OF MAJOR EARTHQUAKES IN THE HIMALAYA AND INDIAN SHIELD REGION

The earthquakes in India and worldwide caused an enormous amount of damage to life and property (Table 1). The swiftness with which an earthquake unleashes its energy and the destruction that is left behind in its wake make earthquakes a hazard for mankind. To reduce the hazard from earthquakes, it is imperative that we understand the physics of the processes that occur during earthquakes and to review what happened during the past earthquakes. An earthquake happens when the accumulated strain energy in the earth is released suddenly. A part of the energy released, called fracture energy, is used in mechanical processes other than frictional heating on the fault zone as the rupture propagates; a part of the energy, frictional energy, is dissipated as heat on the fault surface and yet another part, wave energy, moves the particles on the fault generating seismic waves that are felt by people and recorded by instruments all over the world. The only part of the energy released in an earthquake that we have direct access to is the wave energy. Here we review interplate earthquakes of Himalayan region and intraplate earthquakes of Indian shield region.

Table 1. Top ten Indian earthquakes

Date	*Earthquake*	*Magnitude*	*Deaths in India*
16 Jun 1819	Kuchchh	8	1,500
12 Jun 1897	Shillong Plateau	8.7	1,500
04 Apr 1905	Kangra	8	19,000
15 Jan 1934	Nepal-Bihar	8.3	11,000
26 Jun 1941	Andaman	8.1	Thousands
15 Aug 1950	Assam	8.6	1,530
21 Aug 1988	Nepal-Bihar	6.6	1,004
30 Sep 1993	Killari	6.2	7,928
26 Jan 2001	Bhuj	7.7	13,805
26 Dec 2004	Sumatra-Andaman	9.2	10,749
08 Oct 2005	Kashmir	7.4	1,308

India Meteorological Department, www.imd.ernet.in

3.1 Seismicity of the Himalayan Region

The Himalaya is one of the most seismically active regions of the world (Fig. 2). Earthquakes of small, medium and large magnitudes have occurred in the Himalaya since earliest records (Guttenberg and Richter, 1954; Chandra, 1978). The seismicity in Himalaya appears to be nonuniform although major trends have been recognized which consist a belt of events beneath the lesser Himalaya between MCT and MBT (Seeber et al., 1981), which occurred along a huge circular arc, analogous to interplate earthquakes in island arcs.

The occurrence of earthquakes in the Himalayan arc and adjoining regions due to the collision process may be referred as the earthquakes of the Himalayan Continental Plate Margin (HCPM). The HCPM has produced three great earthquakes (1897 Shillong Plateau, 1934 Bihar-Nepal and 1950 Assam) with magnitude larger than 8.0 since the end of the 19th century and nine earthquakes magnitude larger than 7.5 since 1500 including five prehistorical earthquakes. All the great earthquakes of the Himalayan arc are considered to have occurred on the seismogenic detachment under the Outer and Lesser Himalaya (Fig. 3). The moderate sized earthquakes are reported to have occurred at a depth of 10 to 20 km (Seeber et al., 1981; Molnar, 1990) on the Basement Thrust (BT), a more steeply dipping thrust that juxtaposes basement of the Indian shield with the Tethyan slab, the pre-collisional leading edge of the Indian shield (Powell, 1979; Seeber and Armbruster, 1981; Ni and Barazangi, 1986; Molnar, 1990; Pandey et al., 1995, 1999; Gahalaut and Kalpna, 2001). We refer these earthquakes as the earthquakes of Himalayan Seismic Belt (HSB). In recent years, such moderate sized earthquakes which caught attention are 1991 Uttarkashi earthquake (Mw 6.8), and 1999 Chamoli earthquake (Mw 6.6). Both earthquakes occurred on the detachment under the Himalaya. The October 20, 1991 Uttarkashi earthquake affected region in the Garhwal Himalaya lies in the western part of the seismic gap between the rupture zones of 1905 Kangra earthquake and 1934 Bihar-Nepal earthquake. The last strong earthquake of Himalayan seismic belt occurred on March 29, 1999 (Ms 6.6) in the Kumaun-Garhwal Himalaya, and is known as the Chamoli earthquake.

3.1.1 Historical Earthquakes of Himalaya

(1) 1897 Shillong Plateau Earthquake

The great June 12, 1897 earthquake (Ms 8.0) in the Shillong Plateau in north-eastern India having epicenter at 25.7°N and 91.1°E is the largest well-documented intraplate earthquake in India, and probably one of the largest known anywhere (Fig. 1). The Shillong plateau is the only high ground between the Himalaya and the Bay of Bengal of about 250 km long and 80 km wide and about 1500 m above the plains of the Brahamaputra River. This earthquake has not only large magnitude but also caused heavy damage in surrounding district due to extensive liquefaction of the ground. The main event occurred at 17:15 hrs local time (11:09 GMT) and was recorded by 12 primitive seismograph in Europe. Many aftershocks were felt at and around the fault over a wide area through the end of 1898 (Oldham, 1899). Three large aftershocks occurred on successive days which when combined with the main event cause severe destruction in the surrounding region. No precise estimate of loss of lives is available but in spite of its large magnitude and high population density in some parts of epicentral area, it experienced less destruction as compared to the other earthquakes.

The highest intensity areas for this earthquake are Shillong Plateau and northern extension of this unit below the plains of western Assam. According to Seeber and Armbruster (1981), 1897 earthquake rupture was 550 km long with east-west strike and 300 km wide with no significant surface rupture (Oldham, 1899), which was meant to be the strong evidence for a shallow-dipping, detachment-like fault source. Molnar (1987) inferred an east-west extent of the rupture of 200±40 km from the western margin of the Shillong Plateau. A 170×100 km^2 rupture was estimated to have occurred in a predominantly thrust fault dipping north at about 5° having a depth of about 15 km and 23 km below the southern and northern margin of the rupture zone respectively by Gahalaut and Chander (1992). For more than a century it was believed that it occurred on a thrust fault dipping gently on north or some considered it as a Himalayan Basal thrust (Seeber et al., 1981; Molnar, 1987; Molnar and Pandey, 1989; Gahalaut and Chander, 1992) but according to recent analysis of geodetic data acquired in 1860, 1897 and 1936, Bilham and England (2001) recognize that the earthquake occurred on a ESE striking for 110 km, SSW-dipping reverse fault at 57° beneath the northern edge of the central Shillong Plateau with 16±5 m of slip on a fault between 9 and 45 km depth with a rake of 76° and named as Oldham Fault (Figs 4 and 5). They found that the northern edge of Shillong Plateau rose violently more than 11 m during rupture of a buried, 110 km long, reverse fault dipping steeply away from the Himalaya resulting in the destruction of structures over much of Plateau and surrounding areas. This solution is well constrained and consistent with an interpretation advanced by Auden (1949), and by gravity data, which suggest that Shillong Plateau is a horst of Peninsular India thrust up between the Himalaya and the Naga Hills (Auden, 1949). Ambrasys and Bilham (2003) confirmed that the rupture is inferred to have extended from 9 km to more than 30 km depth on a 100 km long SSE steeply-dipping reverse fault that slipped 15 m. They proposed a moment magnitude of this earthquake as 8.1. Surface faulting was found by Oldham (1899) in northwest part of the Shillong Plateau running for a distance of at least 19 km along the Chedrang fault, a north-south secondary fault, ruptured the surface at the western end of and above the main rupture and showing

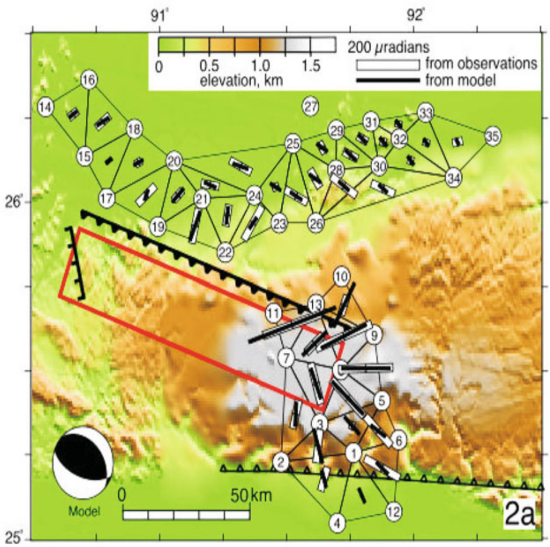

Fig. 4 Trigonometrical stations remeasured on and north of the Shillong Plateau following the 1897 earthquake. White rectangles are calculated from the triangulation observations, and black bars show the strains calculated for the best-fitting planar dislocation. Red rectangle indicates subsurface location of this SW dipping dislocation; thick black line with teeth shows the surface intersection of the continuation of this plane to the land surface (slip terminated 9 km below the surface). Short black line at western edge of fault plane indicates location of Chedrang fault. Line with open teeth to south of the Plateau shows location of the Dauki fault (Bilham and England, 2001).

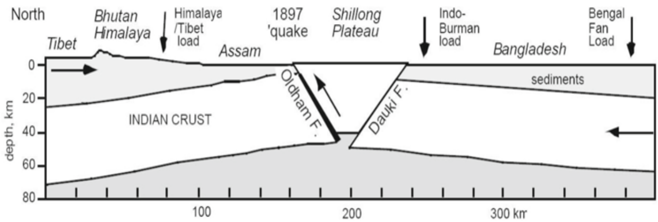

Fig. 5 N-S section from Tibet to the Bay of Bengal showing schematic geometry of Plateau pop-up (Bilham and England, 2001).

a vertical uplift of about 9.5 m with the east side up, on an approximately vertical exposed fault plane. Other fractures were also found at southwest of Chedrang fault and northern part of Plateau. In a recent study, Rajendran et al. (2004) opinioned that the earthquake rupture occurred near the northern limit of the Shillong Plateau. However, they could not precisely locate the rupture dimensions.

(2) 1905 Kangra Earthquake

The 4th April, 1905 Kangra earthquake occurred in the foothills of northwest Himalaya at 33°N and 76°E. The highest intensity, X on Rossi-Forel scale, was felt near the towns of Kangra and Dharamsala. Although this earthquake was assigned M = 8.4 by Richter (1958) and Ms = 8.0 by Kanamori (1977), Ambraseys and Bilham (2000) suggested a surface wave magnitude of Ms = 7.8 by reappraisal of the instrumental data with station corrections available for the event which is consistent with the intensity survey of this earthquake coordinated and compiled by Middlemiss (1910). Seven foreshocks were felt in just 24 hours prior to mainshock. In this earthquake more than 20,000 lives and 100,000 buildings were destroyed. The distribution of foreshocks suggests that 1905 large rupture is comparable to other great events of Himalaya except 1897 earthquake. Although extent of the rupture area is poorly constrained, several different possible rupture zones seem to be correlated with the observations. One is that the rupture occurred only beneath the area delimited by intensity VIII isoseismal, a zone of 100 km in length surrounding Kangra and Dharmsala. Second, its epicentral intensity distribution shows the maximum intensities ≥VIII around two regions Kangra and Dehradun which are separated by about 200 km, hence rupture was said to be the 280 km long fault zone along NW-SE trending boundary of Himalaya or third is that it is divided into two smaller segments that broke sequentially (Seeber and Armbruster, 1981).

The interpretation of levelling data of maximum seismic intensity reveals that 1905 rupture extends for about 250-300 km from the highest intensity area through the southeastern zone of high intensity where the coseismic elevation change was measured. Leveling data surveyed in 1904 and resurveyed in 1906 provide additional evidences that the rupture was not on the MBT but was on detachment that extends below the Himalayan front (Seeber et al., 1981; Chander, 1989; Gahalaut et al., 1992). The observed elevation changes were mostly coseismic, indicate less uplift on the northeast side than on the southwest side of MBT which would suggest normal movement during 1905 shock if slip occurred predominantly on the MBT. Ambraseys and Bilham (2000) calculated rupture area appropriate for a 7.8 magnitude earthquake in the range of 100×120 km^2 to 80×50 km^2 with 3-8 m of average slip. Assuming rupture between the zones of Himalayan Frontal thrust and moderate earthquakes bordering the southern edge of the Tibetan Plateau, the longest dimension of slip normal to the Himalayan arc is 80-100 km. Hence the greatest along-strike dimension of 120 km is significantly less than the proposed 280 km by Seeber and Armbruster (1981) but similar to the interpretation by Molnar (1990). This suggests that the main rupture was not extended continuously from Kangra through Dehradun. A reevaluation of the raw

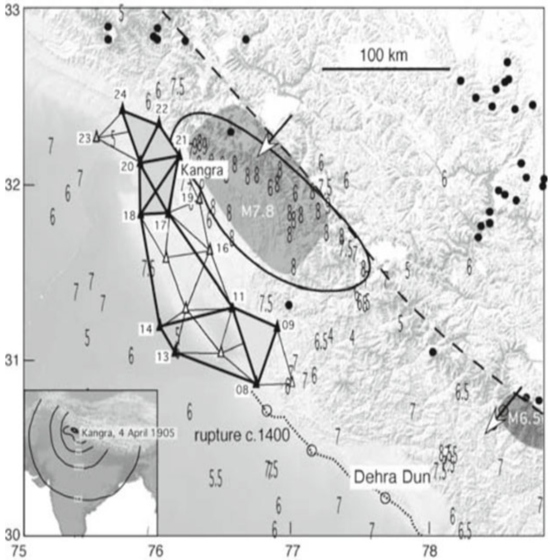

Fig. 6 Triangulation near the Kangra earthquake. Filled triangles indicate recovered GTS points: shaded triangles were used in shear strain analysis, and bold lines were used in linear strain analysis. The preferred rupture area is shaded. The MSK VIII contour (solid line) is interpolated from Ambraseys and Douglas (2004), with observations indicated by MSK number. Closed circles indicate M > 5.5 earthquakes since 1960; open circles indicate trench locations that define the c. 1400 rupture (dotted line). Dashed line approximates the 3.5 km elevation contour (Wallace et al., 2005).

leveling data reveals some systematic error in Middlemiss intensity distribution (Bilham, 2001) and shows that there was probably no or little uplift in that region. The absence of significant uplift or horizontal deformation restrict the rupture length less than 180 km (Fig. 6) which is consistent with the revised magnitude of M_s=7.8 with the probable rupture width of 50-70 km (Wallace et al., 2005).

(3) 1934 Bihar-Nepal Earthquake

The 1934 Bihar-Nepal earthquake is the most recent large historical event in the densely populated area of the Himalayan Front with an assigned Ms = 8.3 (Guttenberg and Richter, 1954) and moment Mo = 1.6×10^{28} dyne-cm (Chen and Molnar, 1977). Dunn et al. (1939) suggested that Bihar-Nepal earthquake did not result from movement along the MBT since no coseismic surface rupture was observed on this fault. He also observed that the largest region of intensity X is closely associated with a "slump belt" and a zone of soil liquefaction. The meizoseismal zone lies primarily on south of MBT and the region of intensity greater or equal to VIII extends about 300 km along the strike of the Himalaya and 250 km perpendicular to the strike (Seeber et al., 1981). In transverse direction it covers entire lesser Himalaya, the sub-Himalaya and the foredeep. The northern and southern boundaries of intensities fall in the transition zone of lesser and higher Himalaya and implies that seismic source extends under most of the area of about 75×10^3 km^2 of VIII intensity (Seeber et al., 1981). According to Chen and Molnar (1977), the epicenter was probably located in the Lesser Himalaya east of Kathmandu at 27.6°N and 87.1°E.

Macroseismic intensities and subsidence of the foreland revealed from leveling data suggest that the earthquake ruptured a 250–300 km along-strike segment of the arc (Bilham et al., 1998). The rupture area may have extended up to the MFT but probably not farther to the south (Chander, 1989). The northward extent of the rupture is not constrained at all. Three distinct areas of high intensities (≥VIII) have been discovered viz the large alluvial plains associated with ground failure, liquefaction, and slumping, the narrow belt near northern limit of outcropping belt suffered by high acceleration and Kathmandu Basin (Dunn, 1939). The 1833 event might have ruptured about the same arc segment as the 1934 earthquake (Bilham, 1995).

(4) 1950 Assam-Tibet Earthquake

The August 15, 1950 eastern Assam earthquake is the most recent great Himalayan Earthquake located in the extreme eastern and most remote portion of Himalayan front although epicenter of the earthquake probably lie in China. Numerous aftershocks beneath Himalaya in eastern Assam (Chen and Molnar, 1977) indicate part of rupture zone underlies Himalaya. The earthquake occurred at 28.38° N and 96.76° E having surface wave magnitude Ms = 8.4 (Guttenberg and Richter, 1954), moment magnitude Mw=8.6, and Moment Mo=10^{29} dyne-cm (Kanamori, 1977). It had the best instrumental coverage but not the best set of data on surface effect. On the basis of instrumental data, epicenter was located beyond the surface termination of Himalayan arc, in the Mishmi Mountains that bound the Assam basin towards the east-northeast and trend northwest (Seeber and Armbruster, 1981).

This event was extensively studied by Ben-Mehanem et al. (1974) who revised and added data to determine a fault plane solution with fault strike N26°W and dip of 60°E with nearly pure strike slip motion. Chen and Molnar (1977) found the P-wave first motion used by Ben-Mehanem et al. (1974) consistent with the thrust faulting on either a gently north-northwest or a steeply south-southeast dipping plane. They calculated seismic moment by assuming both low-angle thrust and Ben-Menahem et al.'s (1974) strike-slip fault plane solution and obtained a seismic moment of 7.8×10^{27} dyne-cm which is much smaller than the seismic moment of 2.5×10^{29} dyne-cm given by Ben-Menahem et al. (1974). A relocation of aftershocks of 1950 earthquake by Molnar and Pandey (1989) confirms that all the aftershocks lie beneath the Himalaya in a zone extending about 250±50 km west of the epicenter of the mainshock in east-west direction with 100 km width in north-south direction and thus the rupture occurred on a gently NNE dipping thrust fault.

3.1.2 Pre-Historical Earthquakes of Himalaya

Early earthquakes described in mythical terms include extracts in the Mahabharata (~1500 BC) during Kurukshetra battle (Iyengar and Sharma, 1999) and several semi-religious texts. Due to unavailability of adequate literature for Pre-historical earthquakes, little is known about Himalayan earthquakes in the 18th century and before. The significant large earthquakes which occurred in the period of 1500 to 1900 along Himalayan Seismic Belt (HSB) are 1505 Lo Mustang Earthquake, 1555 Srinagar earthquake, 1720 Uttar Pradesh earthquake, 1803 Uttar Pradesh earthquake, and 1833 Nepal earthquake.

(1) 1505 Lo Mustang Earthquake

The event of June 6, 1505 which occurred at 29.5°N and 83°E in southwestern Tibet was reported to be a great earthquake that was strongly felt in northern part of the Great Himalaya, along a distance of about 700 km from Guge in the northwest to Lo Mustang and Kyirong in the southeast (Ambraseys and Jackson, 2003; Bilham and Ambraseys, 2004). Bilham and Ambrasyes (2005) explicate that if slow earthquake occur, or if a substantial component of an historic great earthquake is caused by slip that does not radiate seismic energy, would result in the underestimation of seismic moment of that earthquake. Slow earthquakes imply the reduced frictional sliding as gently-dipping ruptures may be associated by modes of failure that do not permit seismic radiation to escape into the body of the earth. Considering the 1505 earthquake as one of such type, they assigned the magnitude 8.6<Mw<8.8 to this earthquake. Rajendran and Rajendran (2005) examined the available documents and suggested three possibilities for occurrence of this earthquake. In the first possibility they found that the 1505 earthquake is smaller in size than 1803 event of magnitude 8.1 and occurred in Garhwal Kumaun Himalaya, the second possibility states that the magnitude of 1505 earthquake is comparable to the 1803 event and occurred in the Tibet-Nepal border and third possibility is that it was indeed a great earthquake but occurred in Tibetan Plateau, and not associated with the frontal thrust. The first possibility has been ruled out since most of the reports show the extensive destruction in northern Nepal and southern Tibet due to this earthquake. However, shaking from long ruptures is likely to increase the duration of shaking, causing much more damage to the structure than estimated one and increasing the severity of liquifaction. Hence, the other two possibilities are also ambiguous and research is still going on for better understanding of this earthquake. On the basis of reported destruction and intensities in area of radius 250 km Ambraseys and Jackson (2003) suggested a magnitude of 8.2 for this earthquake having a rupture length of about 400-700 km with a downdip width of 70-90 km associated with 7-15 m of slip (Bilham and Ambraseys, 2005).

(2) 1555 Srinagar Earthquake

The September 2, 1555 Kashmir earthquake occurred at 33.5°N and 75.5°E and is the western-most significant and large earthquake of Himalaya. Many authors suggest that it was a shallow, large magnitude earthquake of Ms=7.6 on the basis of the very long duration of aftershocks, intensity distribution and damaging reports which extended for more than 100 km southeast from Srinagar (Ambraseys and Jackson, 2003). Bilham and Ambraseys (2004) assigned the moment of the order of $2.69'10^{27}$ dyne-cm to this earthquake which may produce the earthquake of rupture area of length 100 km and width 80 km with a reverse slip of about 2 m.

(3) 1720 Uttar Pradesh Earthquake

The July 15, 1720 Uttar Pradesh earthquake occurred at 30°N and 80°E. This earthquake occurred near Delhi causing damage and apparent liquefaction but little else is known of this event (Kahn, 1874; Oldham, 1883). This event, from its location, could have been a normal faulting event, but because of the absence of damage accounts from the Himalaya it may have been a Himalayan earthquake (Bilham, 2004). Bilham and Ambraseys (2005) calculated the seismic moment 1.91×10^{27} dyne-cm for this earthquake which gives an idea of rupture dimension of about 100 km long and 80 km wide assuming a reverse slip of about 1.8 m.

(4) 1803 Uttar Pradesh Earthquake

The September 1, 1803 Uttar Pradesh earthquake occurred at 31.5°N and 79°E which caused massive damage and loss of life in Central Himalaya and Gangetic plains. Seeber and Armbruster (1981) suggested this to be decollement earthquake, which implies the earthquake having magnitude greater than 8.0. Khattri (1992) estimated its magnitude between 6.0 and 7.6. Ambrasyes and Jackson (2003) studied the earthquake and assigned the magnitude Ms = 7.5 estimating the size of the area over which the shock was clearly felt. A later study based on more complete data re-assessed its magnitude as Mw = 8.1 (Ambraseys and Douglass, 2004). Bilham and Ambraseys (2005) assigned the moment magnitude of the order of 1.51×10^{28} dyne-cm to this earthquake. Rajendran and Rajendran (2005) calculated the size of this event using Frankel's equation and obtained the moment magnitude Mw=7.7 for this earthquake. They concluded that this earthquake occurred on a subsidiary thrust of the MCT within Garhwal-Kumaun Himalaya and it cannot be characterized as great plate boundary earthquake.

(5) 1833 Nepal Earthquake

The August 26, 1833 earthquake occurred at 27.7°N and 85.7°E near Kathmandu within or close to the rupture of 1934 Bihar-Nepal earthquake (Bilham, 1995). It was felt over a large part of northern India and was located at 25.1°N and 85.3°E near Patna south of river Ganga (Bilham, 1995). Seeber and Armbruster (1981) proposed its location west of Kathmandu and suggested that it may have occurred in Central Himalayan Gap. Khattri and Tyagi (1983) placed the earthquake approximately 130 km west of the epicenter of 1934 Bihar-Nepal earthquake on the edges of Central Himalayan Gap and assign the event M = 7.6. Bilham (1995) explained that the earthquake consisted of three shocks, the first caused alarm, the second, five hours later brought most of people out of their home and the third, 15 min later was the main shock which caused widespread structural damage in India and Nepal. Based on the reported intensities, he estimated its moment magnitude Mw = 7.7 and locate it at 50 km north or northeast of Kathmandu. The slip associated with the event may have been 1-2 m on a thrust fault, which may have ruptured a region adjoining or overlapping the rupture zone of the great 1934 earthquake (Bilham, 1995).

3.1.3 Earthquakes Reported from Paleoseismological Investigations in the Himalaya

A few earthquakes have been reported on the basis of paleoseismological investigations in the Himalaya and Shillong Plateau. Sukhija et al. (1999) reported their results from the meizoseismal area of the 1897 earthquake which revealed well-preserved liquefaction and deformed syndepositional features at 10 selected sites in the alluvial deposits along two north flowing tributaries of the Brahmaputra river. In addition to the 1897 event, they provided evidence for at least three large seismic events. Two of them occurred during 1450–1650 and 700–1050 AD, the third predates 600 AD. Their analysis suggests a return period of about 400-600 years for the large earthquakes in the Shillong Plateau. Sukhija et al. (2002) reported paleoseismological evidence of occurrence of 1934 Nepal Bihar and 1833 Nepal earthquakes as well as evidence of occurrence of two prehistoric seismic events dated during 1700 to 5300 years BP and earlier than 25,000 years BP. Kumar et al. (2006) reported results of their paleoseismological investigations at sites along the Himalayan frontal Thrust between Chandigarh and Ramnagar (Nainital). Radiocarbon ages of samples obtained from the displaced sediments indicate that surface rupture at each site took place after ~A.D. 1200 and before ~A.D. 1700. Trench exposures and vertical separations measured across scarps in the eastern part of their region, are interpreted to indicate single-event displacements of ~11–38 m. Lave et al. (2005) presented paleoseismological evidence of occurrence of a great earthquake in the east central Nepal. They estimated that the earthquake occurred at ~1100 AD with a surface displacement of ~17 m and lateral extent and size that could have exceeded 240 km and Mw 8.8. Another major conclusion of this work was the absence of evidence of surface rupture during the 1934 Nepal-Bihar earthquake.

3.2 Indian Shield Region Earthquakes

Even today, earthquake occurrence in stable continental regions is not fully understandable. In most of the cases, the relationship between intraplate earthquakes and the subsurface seismogenic structure is not known. In order to improve our understanding of intraplate earthquakes, a considerable amount of work has been done in the past two decades. Several characteristics of intraplate earthquakes are now well known and more features appear to be emerging. For instance, intraplate earthquakes, especially those in stable continental interiors, usually have relatively long or very long recurrence intervals. Intraplate events are commonly characterized by very large areas of perceptibility compared with most shocks of similar magnitudes along plate boundaries. The interiors of any Lithospheric plates have also been found to be characterized by large horizontal compressive stress.

The Indian Peninsula is known as stable continental region dominated by Precambrian rocks. The seismicity of peninsular India was appeared to be very slow (Gutenberg and Richter, 1954; Chandra, 1977) prior to occurring of three damaging earthquakes in last 12 years. These earthquakes occurred in peninsular India, which is characterized by slow deformation and low seismic productivity (Johnston, 1989). Occurrence of three earthquakes during a brief interval of ten years naturally triggered a lot of discussion on the mechanism and pattern of recurrence of earthquakes in SCR-India. Other significant earthquakes in Indian Shield regions are 1819 Rann of Kachchh earthquake, 1969 Bhadrachalam earthquake and 1967 Koyna earthquake.

3.2.1 1819 Rann of Kachchh Earthquake

The June 16, 1819 Allah Bund (or Great Rann of Kachchh) earthquake is among one of the largest global intraplate earthquakes (Johnston and Kanter, 1990). The 1819 earthquake produced an about 80-90-km-long, 6-km-wide and 3-to-6m-high uplift known as the Allah Bund (Oldham, 1926; Bilham, 1999; Rajendran and Rajendran, 2001) across the Kori branch of Indus river (Fig. 7). A geometric moment magnitude of M=7.7±0.2 is obtained from the surface deformation and the inferred slip parameters, consistent with a magnitude estimated empirically from the intensity distribution (Bilham, 1999). Bilham (1999) suggested a shallow (from 10 km to near the surface) reverse-slip rupture on a 90-km-long 50–70° N-dipping fault plane to match the measured elevation changes from the event. Bilham et al. (2003) take the great depth and short lateral fault length of the 2001 Bhuj earthquake rupture into consideration and incorporate new topographic and remote sensing observations of the morphology of the Allah Bund fault scarp to obtain updated fault parameters. The 1819 event is estimated to have a

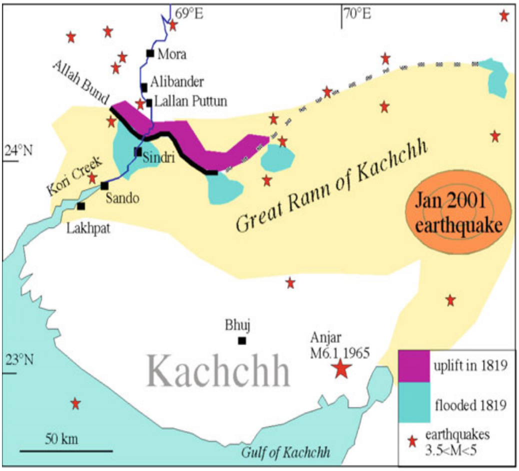

Fig. 7 Uplift during the 1819 Kachchh earthquake dammed the Kori River north of a zone of uplift termed the Allah Bund, and submerged the region to its south surrounding the fort at Sindri. On the basis of morphological changes recorded by Survey of India maps Oldham (1926) suggests that faulting may have extended a further 100 km to the east (dashed). (Bilham, 1999)

50-km-long rupture dipping 45° to the north with 3–8 m slip. The slip is set to 5.5 m in this study, consistent with a Mw = 7.7 earthquake for a rupture extending to 30-km depth.

3.2.2 1969 Bhadrachalam Earthquake

The April 13, 1969 Bhadrachalam earthquake is one of the major intraplate earthquake associated with paleorift zones in the stable continent region of Indian peninsula. It occurred on an 800 km long narrow NW trending Mesozoic rift of Godavari valley or Garben. Hence it is also known as Godavari valley earthquake. In northwest, it joins Narmada-Son lineament in the middle of the Indian peninsula and meets the east coast of India at southeastern end (Burke et al., 1978). It might be the first and only significant earthquake occurred in Godavari valley as only minor earthquakes have been reported in this region during past 200 years (Gupta et al., 1970). Indian seismological centre located the mainshock epicenter at 17.9°N and 80.6°E with body wave magnitude of m_b = 5.7 and moment magnitude Mw = 5.3 at a depth of 25 km. On the basis of body waveform analysis, Chung (1993) found strike slip dominant focal mechanism for this earthquake. The strike-slip motion represents a reactivated fault motion under the present-day stress field. The 1970 Broach earthquake of India is also an example of paleorift zone earthquake. It accompanied thrust motion with a small strike-slip component (Chung, 1993). These cases indicate that both thrust faulting or strike-slip faulting can occur on paleorift grabens reactivated by the present-day tectonic stresses depending on the orientation of the fault with respect to the applied stress field.

3.2.3 1967 Koyna Earthquake

The Koyna-Warna region of relatively stable peninsular India is a unique site in the world where the seismicity that reportedly began soon after the impoundment of the Koyna reservoir in 1961 has continued for over 40 years (Gupta, 1992, 2002; Talwani, 1997). The main Koyna earthquake of December 10, 1967 (M 6.3) is the largest earthquake near a reservoir, ever recorded globally, and the ongoing earthquake occurrences in the Koyna-Warna region have been considered as the reservoir triggered earthquakes (Chander and Kalpna, 1997; Rastogi et al., 1997; Talwani, 1997; Mandal et al., 1998; Gupta, 2002). The Koyna-Warna region in southwestern part of the Deccan volcanic province lies to the east of the west facing N–S escarpment parallel to the west coast from the gulf of Cambay to the peninsular tip. Our knowledge about the seismicity of the region prior to 1962 (i.e., prior to the reservoir impoundment) is very limited due to the absence of seismic stations in the area. Since 1963, more than 100,000 earthquakes, including about 170 of $M \geq 4$, about 17 of $M \geq 5$, have been reported from the Koyna-Warna region (Gupta, 2002) and frequency of the earthquakes of past 30 years is almost steady. Such frequency of earthquakes, especially those exceeding M 5.0, in a short span of time, is a rarity in the stable shield regions. Hence seismicity associated with Koyna earthquake is unique and of interest for many researchers since decades.

3.2.4 1993 Killari Earthquake

The 1993 Killari earthquake, also known as Latur earthquake (m_b 6.3, Ms 6.4, Mw 6.2), of September 29, 1993 occurred on the previously unmapped fault with no surface expression in the Deccan traps of peninsular India is considered to be a stable continental region, and caused destruction in an about 15 km wide area (MM intensity VIII). USGS estimated the epicenter of the mainshock at about 12 km west of Killari at a focal depth of 6.8 km. Several estimates of the fault plane solutions for this earthquake are available and all of them indicate predominantly reverse slip on the ESE trending nodal planes. The SSW dipping plane has been considered as the fault plane (Seeber et al., 1996; Baumbach et al., 1996; Gupta et al., 1998) on the basis of aftershock distribution, damage pattern and surface faulting. Despite its low magnitude, the damage due to the earthquake was extensive, because of extremely poor quality of buildings.

3.2.5 1997 Jabalpur Earthquake

The Jabalpur earthquake of May 21, 1997 is considered as the best-monitored Indian earthquake as it occurred in the central part of Indian shield with a very good azimuthal coverage of Indian seismic stations. The earthquake occurred in the lower crust of an ENE-WSW trending failed rift zone, known as Narmada-Son-Tapti failed rift zone which transects the Indian peninsular shield area into the northern and southern blocks. It is the most active paleorift zone, which evolved during the Archean and Proterozoic periods with magmatism of Cretaceous and Tertiary ages, which is similar to the New Madrid seismic zone (Liu and Zoback, 1997). Episodic reactivation of the failed rift is evident by the presence of varied rock formations ranging in ages from the late Archean to early Proterozoic. Two prominent deep faults termed as the Narmada South and Narmada North faults (NSF and NNF) with ENE-WSW strike have been mapped extensively in the region (Fermor, 1936; Nair et al., 1985; Roy and Bandyopadhyay, 1990). In the past, earthquakes with magnitude more than six have occurred in the failed rift zone and most of them are considered to be associated with the NSF.

The maximum intensity of shaking during the Jabalpur earthquake (m_b 6.0, Ms 5.6, Mw 5.8) was VIII on the MSK scale. The earthquake had a focal depth of about 36 km and is assumed to have occurred on the downdip extension of the NSF (Kayal, 2000). Fault plane solution of the earthquake suggest reverse slip on the SSE dipping steep plane. Field investigations related to damage survey indicate that the damage was maximum in a zone of 15×35 km^2 (Acharya et al., 1998) which lies to the north of reported earthquake epicenter by the India Meteorological Department (IMD) and USGS.

3.2.6 2001 Bhuj Earthquake

The Bhuj earthquake of January 26, 2001 was the largest intra-continental earthquake of the modern era of seismology, which occurred in the failed rift region on a steeply south-dipping reverse fault in the Rann of Kachchh region. The geologic structures in the epicentral region evolved during a long history of tectonic activity that began in the Proterozoic and involved several major tectonic episodes that fragmented Gondwanaland during Mesozoic and Paleogene periods (Biswas, 1987). In the late Triassic or early Jurassic, a number of smaller rift systems developed deep sedimentary basins, including the Kachchh basin. These structures were reactivated as a result of regional compression arising due to Indian plate movement in the Cenozoic which is evident from the fold and thrust belt along the Kachchh mainland fault system and the Allah Bund fault and also by the occurrence of major reverse earthquakes in the past 200 years, namely, the 1819 Allah Bund (Bilham, 1998), the 1956 Anjar and the 2001 Bhuj earthquakes. The main shock (m_b 6.9, Ms 7.9, Mw 7.6) occurred at an estimated depth of 25 km (IMD). Focal mechanism solutions suggest predominantly reverse motion on a steeply south dipping (51°-66°) fault. Thus the earthquake occurred in the lower crust on a steeply dipping reverse fault and the rupture did not extend up to the surface, or project towards a mapped surface fault. The earthquake caused large damage in the nearby cities. The main reason for this is the poor engineering, and poor quality of construction with poor building material.

3.3 December 2004 Sumatra-Andaman Earthquake

The December 26, 2004 Sumatra-Andaman earthquake (Mw 9.2) nucleated off the western coast of northern Sumatra and propagated north-northwest (Stein and Okal, 2005). The earthquake occurred along the eastern margin of the Indian plate where Indian plate obliquely subducts under the Sunda plate. The extent of aftershocks suggests that the rupture length of the earthquake was about 1400 km (Fig. 8). It is considered as the overall fourth largest earthquake since 1900 and is the largest since the 1964 Prince William Sound, Alaska earthquake. The tsunami generated by this earthquake caused more casualties than any other in the recorded history. In total, more than 200,000 people were killed in the countries surrounding Indian Ocean. With the rupture length of about 1400 km, it is the earthquake with a maximum rupture length. Another important aspect of this earthquake is that fast slip occurred in the southern part with a magnitude of slip reaching 15 m, which extended to the north-northwest direction at a velocity of 2.5 km/s, rupturing the 1300 km long plate boundary in about 8-10 minutes (Ammon et al., 2005; Ishii et al., 2005). The seismological data do not constrain either the coseismic surface displacements or coseismic slip on the rupture under Andaman-Nicobar islands, as the slip in this part occurred at a time scale beyond the seismic band (Ammon et al., 2005; Lay et al., 2005). In the subsequent one hour period, additional slow slip occurred in the Andaman-Nicobar region (Bilham, 2005; Banerjee et al., 2005). However, Vigny et al. (2005) argued against slow slip and suggested that the entire displacement at GPS sites in the northern Thailand occurred in less than 10 minutes after the earthquakes. Using far-field GPS sites located at about 400-3000 km from the rupture, they derived a slip model for this earthquake. However, even these data do not provide a reliable estimate of coseismic surface displacements. In addition to the far-field GPS data (Vigny et al., 2005; Banerjee et al., 2005; Catherine et al., 2005), estimates of surface displacements have been reported from near-field GPS sites in Andaman-Nicobar Islands (Gahalaut et al., 2006). These data suggest that due to this earthquake the Andaman-Nicobar moved by 3-6 m horizontally in the SW direction and experienced a general subsidence of about 1-2 m.

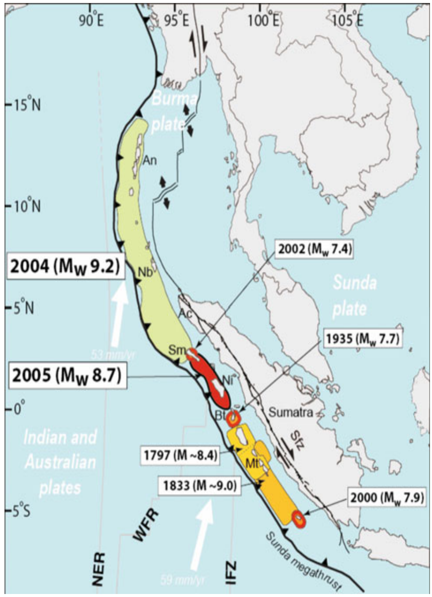

Fig. 8 The India Sunda subduction zone and rupture of the 2004 Sumatra Andaman earthquake (Briggs et al., 2006).

4. GEODETIC CONSTRAINTS ON INTERSEISMIC DEFORMATION IN THE HIMALAYA AND RATE OF CONVERGENCE

In India, mainly the Survey of India undertakes the precise leveling work. However, data along a very few leveling lines are available in the public domain. Leveling observations along the Saharanpur-Mussoorie line have extensively been used to understand the effect of the 1905 Kangra earthquake (Chander, 1989; Gahalaut and Chander, 1992; Bilham, 2001) to assess the status of strain accumulation in the region (Gahalaut and Chander, 1994) and to understand the crustal deformation mechanism during earthquake cycle (Gahalaut and Chander, 1997a). The elevation changes along a leveling line from Pathankot to Dalhousie in Punjab Himalaya reveal uplift rate of 4-6 mm/year in the Lesser Himalaya and are consistent with strain accumulation on the detachment at the rate of 10-12 mm/year (Gahalaut and Chander, 1999). In central Nepal, the leveling data along a line from Birganj to Kodari via Kathmandu during the interseismic period reveal low uplift rate (<2 mm/year) in the Outer Himalaya while high uplift rate (6-8 mm/year) in the Lesser and southern Higher Himalaya (Jackson and Bilham, 1994). These data are consistent with the model of strain accumulation on the detachment at the rate corresponding to the plate convergence rate of 18-20 mm/year during the interseismic phase (Gahalaut and Chander, 1997b; Bilham et al., 1997).

In past two decades, the conventional land based geodetic techniques have been replaced by more accurate and fast space based GPS measurements. Extensive measurements have been undertaken in the Nepal Himalaya. The leveling, GPS, DORIS data have been analysed (Jackson and Bilham, 1994; Bilham et al., 1997; Gahalaut and Chander, 1997b, 1999; Jouanne et al., 1999; Avouac, 2003; Bettinelli et al., 2006) using an elastic dislocation model of interseismic strain and taking into account the uncertainty on India plate motion. The mean convergence rate across Central and Eastern Nepal is estimated to be 19±2.5 mm/year (Fig. 9). The detachment was found to be locked from the surface to a depth of about 20 km over a width of about 115 km. The slight discrepancy between the geologically estimated deformation rate of 21±1.5 mm/year (Lave and Avouac, 2000) and the 19±2.5 mm/year geodetic rate in Central and Eastern Nepal can be explained by possible temporal variations of the pattern and rate of strain in the period between large earthquakes in this region. GPS measurements in the Garhwal and Punjab Himalaya show strain accumulation at the detachment at the rate of 18 and 14 mm/year (Banerjee and Burgmann, 2002; Jade et al., 2004). If the detachment is assumed to be fully locked then this estimate corresponds to the convergence accommodated in the Himalaya. It may be noted here that the estimates derived from the leveling and GPS measurements are very consistent.

5. GEODETIC CONSTRAINTS ON INTERSEISMIC DEFORMATION IN THE INDIAN SHIELD REGION AND RATE OF PLATE MOTION

GPS measurements have given a big boost in estimating the plate motion, to verify the models on plate motion and to estimate the crustal deformation through earthquake cycle in the plate boundary as well as plate interior regions. At present, in India, there are two permanent International GNSS (formerly GPS) System (IGS) stations located at Bangalore and Hyderabad. GPS measurements at these two sites along with several other permanent sites across the country have provided a robust estimate of Indian plate motion which is 5.1 cm/year towards N51ºE in the central Indian region. This estimate is consistent with the models of plate motion. These measurements have also provided the evidence of extremely slow rate of strain accumulation within the India, which is consistent with the low frequency of earthquake occurrence, as compared to the plate boundary regions, e.g., Himalayan and Andaman region. It is estimated that about 2 mm/year of strain accumulation occurs across the N-S length of Indian peninsular region (Fig. 10). Large part of it is presumably accommodated across the Narmada-Son failed rift region (Banerjee et al., 2008).

6. HIMALAYAN SEISMIC GAP AND ASSOCIATED SEISMIC HAZARD

Within the framework of the seismotectonic models, the seismic gap hypothesis has been applied on the great earthquakes, which are caused by the rupturing of the convergent plate boundaries (Fedotov, 1965; Sykes, 1971). This hypothesis states that major earthquake are likely to occur along the sections of the detachment of convergent plate margins which have ruptured in past but have not experienced any great earthquake at least in past few decades. The possibilities of experiencing a great earthquake in such regions are directly proportional with time elapsed since the occurrence of last great earthquake because strain accumulates over decades or centuries due to consequence of slow plate motions.

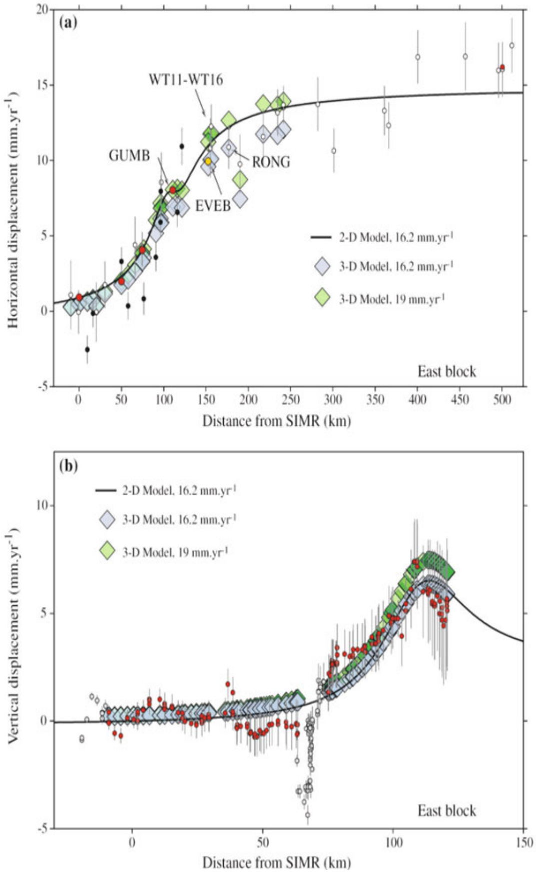

Fig. 9 **(a)** Horizontal velocities derived from GPS and DORIS stations across the Himalaya of Central and Eastern Nepal projected on a north-northeast cross-section (Bettinelli et al., 2006). The continuous black line shows prediction from a model of interseismic strain computed from a creeping dislocation embedded in an elastic half-space. Blue and green diamonds show, respectively, prediction of a 3D point-source dislocation model for a slip rate of 16.2 and 19 mm/year; (**b**) Observed (red dots) and modelled vertical displacements along the leveling profile across Central Nepal projected along the Kathmandu section (Jackson and Bilham, 1994). Grey dots show data not included in our determination of the best model. These data include some leveling data clearly affected by subsidence in Kathmandu valley and some points in the lowlands.

Seeber and Armbruster (1981) interpreted that the last four Himalayan great earthquakes have ruptured off about 1400 km of the Himalayan detachment. They estimated the rupture length 300 km for 1905 Kangra, 1934 Bihar Nepal and 1950 Assam earthquakes whereas for the 1897 earthquake, they suggested a rupture length of about 500 km. They identified two seismic gaps unruptured since 1800: first, the

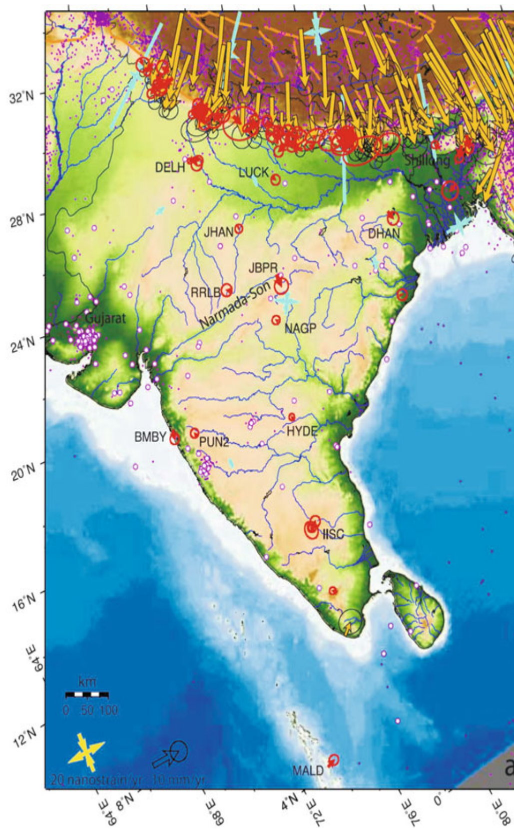

Fig. 10 GPS velocities in India plate reference frame and derived principal strain axes and magnitudes. Red arrows are GPS velocities of <4 mm/year magnitude, orange arrows have larger rates with respect to India. Magenta dots and circles indicate earthquakes. Note that stations lying south of the Narmada-Son region show almost zero velocity while those north of it but south of Himalayan region, show southward velocity of about 2 mm/year (Banerjee et al., 2008).

segment to the west of 1905 Kangra earthquake rupture located in Kashmir region and lies between 1885 and 1905 earthquakes and second, the segment in Uttaranchal between 1803 and 1833 ruptures. However, the tectonics of Kashmir Himalaya is poorly understood. They were not sure whether the detachment under this region is able to produce great earthquake. Hence according to Seeber and Armbruster (1981), a gap in Uttaranchal would be the most possible location of future great earthquake. They also suggested that 100 km gap between the ruptures of 1897 and 1950 earthquakes probably have been ruptured by 1943 and 1947 earthquakes and thus leaving no seismic gaps between these ruptures. They have suggested the repeat time of a great Himalayan earthquake to be about 200-270 years.

Khattri and Tyagi (1983) and Khattri (1987) analyze the space-time patterns of seismicity in the Himalaya plate boundary and recognize the existence of three seismic gaps: (1) the Kashmir Gap, an unruptured area to the west of the rupture of 1905 Kangra earthquake, (2) the Central Gap lying between the ruptures of 1905 Kangra earthquake and the 1934 Bihar-Nepal earthquake and (3) the Assam Gap between the ruptures of 1897 Shillong Plateau earthquake and the 1950 Assam earthquake. They found the reduced level of seismic activity in Central Gap from 1960 onwards and a similar seismic drop was noted in the Assam Gap from 1967 onwards; hence they characterized these two gaps as the region of relatively high level of seismicity from the point of view of future great earthquakes contrary to the view of Seeber and Armbruster (1981). Further they proposed the recurrence interval for these earthquakes between 200-500 years with a likely value of 300 years.

Molnar (1987), Molnar and Pandey (1989) and Molnar (1990) identified rupture lengths of great Himalayan earthquakes of 1905, 1934, 1897 and 1950 to be about 280 km, 200±40 km, 200±100 km and 250 km respectively. Thus, according to them only 30-35% of the plate margin has ruptured since 1897. Chander (1988) observed ground level changes due to 1905 Kangra earthquake and 1934 Bihar-Nepal earthquake and identified the susceptible seismic gap of nearly 700 km between the rupture zones of these earthquakes.

Bilham and Wallace (2005) and Bilham et al. (2001) analysed the seismic gap (Fig. 11) and estimated slip potential in each Himalayan segments (Fig. 12). They suggested that most of the Himalaya segments, except the 1934 and 1950 earthquake regions, can produce great earthquakes.

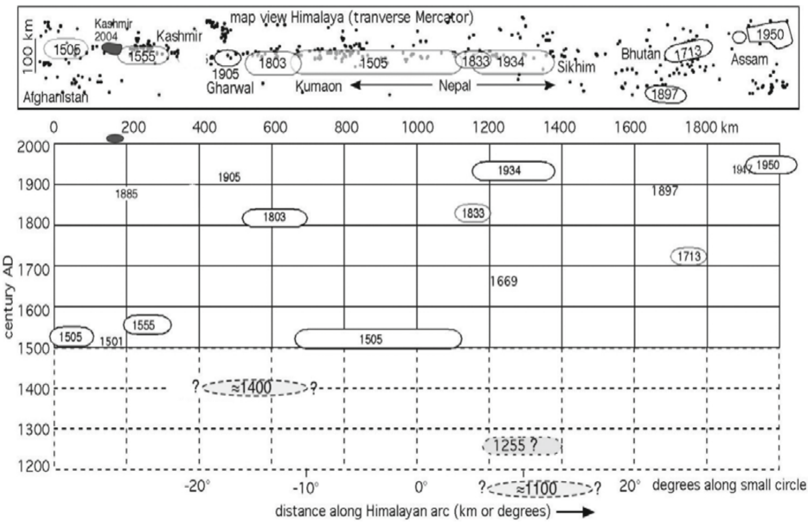

Fig. 11 The Himalayan arc plotted as angular distance from the Thakola graben in Nepal with the time-space history of the inferred ruptured zones of known major earthquakes. The rupture zones of none of these earthquakes are known precisely. Inferred rupture length and identified seismic gap in the Himalayan arc (Bilham and Wallace, 2005).

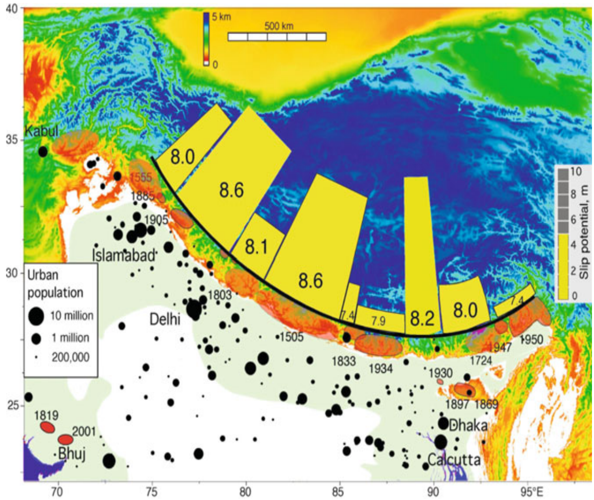

Fig. 12 Seismic potential of Himalayan arc (Bilham and Wallace, 2005). Urban population is shown by filled black circles. The height of each trapezoid is proportional to the current slip potential in meters, and the numbers refer to the potential size of Mw should the same segment length slip as is currently believed to have occurred in the last earthquake. The slip potential in the eastern Himalaya is tentative since the effects of the 1897 Shillong earthquake are uncertain and we know of no great historical earthquakes in Bhutan with the exception of a possible event in 1713 (Ambraseys and Jackson, 2003).

7. SEISMIC HAZARD AND ITS MITIGATION

The scientific challenge is to learn more about these giant earthquakes. From GPS geodesy we know how much closer India approaches Tibet each year (2 cm/year). From geological excavations of the faulted frontal range of the Himalaya we know how much slip occurs in a few giant earthquakes (8-10 m). From seismological studies we know how much slip occurred in recent great earthquakes (2-6 m). Simple arithmetic yields the astounding possibility that almost 3/4 of the Himalaya could have a magnitude 8 earthquake today, and that in parts of the west-central Himalaya we could have an earthquake as big as M = 8.2. After the 1993 Latur earthquake in peninsular India, seismological network for earthquake monitoring has been expanded and modernized. The India Meteorological Department (IMD), the primary agency for monitoring, maintains a network of more than 50 seismological observatories.

The biggest problem with future Himalayan earthquakes is not the determination of their timing; it is the problem that they will inevitably occur. The longer we wait, the larger they will be. Since population densities have increased tenfold or more since the last of the great Medieval earthquakes, and since building styles have in many cases become more vulnerable to seismic shaking, the next great Himalayan event will be much more disastrous than those in recorded history (Bilham, 2004). Various attempts have been made to quantify the seismic hazard in the Himalaya and plate interiors (Khattri et al., 1984; Kumar and Bhatia, 1999), and all of them reflect high seismic hazard in the Himalayan and NE India region.

Seismic hazard assessment of SCRs is complicated also because of the incompleteness in data (Jaiswal and Sinha, 2007). In the absence of high quality earthquake data from each of the SCRs, lack of attenuation relations of acceleration, and poor historical records of earthquake occurrence, assessment of the seismogenic processes may have to rely also on data from analogous settings elsewhere. As more data are generated from various source regions, it may be possible to identify analogies in their characteristic sizes, patterns of recurrence and deformation mechanisms, taking us closer to realistic hazard assessment. Nevertheless, the comparison of the probabilistic seismic-hazard map developed with the hazard map specified in the Indian Standards shows that the design parameters in the Indian Standards may significantly underestimate the seismic hazard in some regions of peninsular India.

Since earthquake prediction is not possible as yet, it is important to learn to live with earthquakes. Earth Scientists will continue to learn more about the earthquakes, their occurrence processes, potential regions of future earthquakes and the expected damage scenarios in a region in case such an earthquake occurs. It is important to follow the long-term and short-term mitigation schemes. Under the long-term scheme, it is necessary that a strict region-based building code is implemented in the country. This will definitely reduce the damage and loss of lives during the next great earthquake. Worldwide, significant development has taken place in this direction (Allen, 2007), which includes, for example, quantification in terms of probability of earthquake occurrence of the next big earthquake in a region on a given fault, attenuation laws using strong ground motion arrays etc. Under the short-term mitigation scheme, seismic microzonation, shake map, mapping and quantification of geological structures influencing the ground shaking, deployment of earthquake early warning systems etc. may be taken up.

In India, micro-zonation studies for major cities have been taken up by various agencies which are sponsored by the Ministry of Earth Sciences and the Department of Science and Technology (DST), Government of India, New Delhi. However, a unified and holistic approach in taking up such studies is required. The National Disaster Mitigation Authority (NDMA), under the Ministry of Home Affairs, has realised that in order to move towards safer and sustainable national development, development projects should be sensitive towards disaster mitigation. A few but significant steps towards vulnerability reduction, putting in place prevention and mitigation measures and preparedness for a rapid and professional response have been taken. NDMA has launched a massive awareness generation campaign and building up of capabilities as well as institutionalization of the entire mechanism through a techno legal and techno financial framework to gradually move in the direction of sustainable development. The various prevention and mitigation measures are aimed at building up the capabilities of the communities, voluntary organizations and government functionaries at all levels. Particular stress is being laid on ensuring that these measures are institutionalized considering the vast population and the geographical area of the country.

8. EARTHQUAKE EARLY WARNING SYSTEM

The idea of earthquake early warning is simple and is based on the principle that (i) electromagnetic waves travel faster than the elastic waves, and (ii) P waves travel faster than the more damaging elastic S waves in an elastic medium (Nakamura, 1984; Wu and Kanamori, 2005). P and S waves are generated simultaneously during the earthquake, but with distance they get segregated. Presently, two types of early warning systems (EWS) are in operation around the world. One is a front-detection EWS: seismometers installed in the earthquake source area give early warnings to more distant urban areas. The other is an on-site EWS, which determines the earthquake parameters from the initial portion of the P wave and predicts the more severe ground shakings of the following S-wave trains. Some crucial facilities, like nuclear power plant, high speed trains, gas pipelines, etc. may be shut down and people may get a few seconds to come out of the buildings. Such warning systems, also referred as Earthquake Alarms Systems (ElarmS) have been implemented in a few countries such as Japan, Taiwan, Mexico, Turkey and Romania, and have been tested offline in California, Italy, Alaska (http://www.elarms.org/). Mexico is the classic example where EWS can help tremendously. Though Mexico city is not very prone to earthquakes, but a distant earthquake along the western Mexican coast can cause extensive damage due to its soil condition. Thus, a warning of few seconds at Mexico city about the earthquake along the coast can help in reducing the damage. A similar case exists in India. Though major cities in the north, like New Delhi, Lucknow, Kanpur, etc. are not in the earthquake-prone region, they are located close to the central seismic gap in the Himalayan region where great earthquake is expected. Hence, a warning of few seconds can reduce the damage. However, such systems are yet to be implemented in India.

One of the problems in implementing and installing earthquake early warning systems is the accurate estimation of the size of earthquake in real time and the assessment of extent of damage at the target site due to that earthquake (Allen, 2007). A starting and crucial point in this regard could be nuclear power plant facilities which are located in the Indo-Gangetic plains, e.g., Narora power plant in Uttar Pradesh. To implement EWS for safeguarding other facilities, we need to increase automation and public awareness about it. Also, there should be proper evacuation plans for the public in the residence, school and office complexes so that an early warning of few seconds may be utilized to save lives rather than increase in loss of lives due to chaos and stampede.

9. CONCLUDING REMARKS

Earthquake occurrence in the Himalaya and plate interiors is attributed to the ongoing plate motion and convergence with the neighbouring plates. Great earthquakes in the Himalaya occur through episodic slip on the detachment under the Outer and Lesser Himalaya, while small and moderate size earthquakes of the Himalayan seismic belt continue to occur near the downdip part of the seismogenically active detachment. Occurrence of great and major earthquakes along the Himalayan arc, e.g., 1934 Nepal-Bihar, 1950 Assam, 1905 Kangra in the twentieth century, 1803 and 1833 in nineteenth century and earlier earthquakes like 1505 and other events inferred from paleoseismological investigations attest that majority of the length of the Himalayan arc has potential to generate great or major earthquakes. Evidence that no great or even major earthquake has occurred in the Himalayan arc since 1950 and strain accumulation is underway in the central seismic gap region where great earthquakes have occurred in the past, suggest that a great earthquake may occur in this region. In other seismic gap regions (i.e., Kashmir and Assam), lack of evidence of strain accumulation coupled with poor historical earthquake records do not guarantee that great earthquakes did not and cannot occur in these regions. In-depth investigations are required to rule that out.

In the peninsular India, a few earthquakes that occurred in past 200 years have been reviewed in this chapter. All these earthquakes, except for the 1997 Jabalpur and 2001 Bhuj earthquakes, had very shallow focal depth (less than 10 km) and their focal mechanism is consistent with the approximately N-S maximum stress direction and on-going plate motion. Both 1997 Jabalpur and 2001 Bhuj earthquakes, along with a few other moderate magnitude earthquakes, occurred along the failed rift regions. Thus, these regions pose a serious hazard due to future major or moderate magnitude earthquakes in the peninsular India.

It is necessary to take up additional scientific studies, involving GPS measurements of crustal strains, crustal structure identification using various seismological and seismic methods, earthquake source parameters, ground motion attenuation relations, etc. At the same time, it is important to learn more about the previous earthquakes, their occurrence processes and to identify potential regions of future earthquakes. Based on the findings of such studies, it is desirable to develop damage scenarios and micro-zonation maps of some selected cities. Depending upon the feasibility, earthquake early warning systems may also be installed at some selected cities. The rapid growth of IT and communication technologies can help in disseminating the earthquake related information quickly and implementing it appropriately. Implementation of building codes and public awareness is the key to reduce the loss of lives and damage to civil structures, as it is said "*Earthquakes don't kill people, but buildings do*".

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