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Seismotectonics and large earthquake generation in the Himalayan region

Harsh Gupta [a,b,*], V.K. Gahalaut [b]

[a] National Disaster Management Authority, New Delhi 110029, India
[b] CSIR-National Geophysical Research Institute (Council of Scientific and Industrial Research), Uppal Road, Hyderabad, India

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ABSTRACT

Bounded by the western and eastern syntaxes, the Himalayan region has experienced at least five M~8 earthquakes during a seismically very active phase from 1897 through 1952. However, there has been a paucity of M~8 earthquakes since 1952. Examining of various catalogues and seismograms from the Gottingen Observatory, it is established that this quiescence of M~8 earthquakes is real. While it has not been possible to forecast earthquakes, there has been a success in making a medium term forecast of an M 7.3 earthquake in the adjoining Indo-Burmese arc. Similarly we find that in the central Himalayan region, earthquakes of M > 6.5 have been preceded by seismic swarms and quiescences. In the recent past, based on GPS data, estimates have been made of the accumulated strains and it is postulated that a number of M~8 earthquakes are imminent in the Himalayan region. We examine these estimates and find that while earthquakes of M~8 may occur in the region, however, the available GPS data and their interpretation do not necessarily suggest their size and time of occurrence and whether an earthquake in a particular segment will occur sooner in comparison to that in the neighboring segment. We also comment on the inference of occurrence of M~8 earthquakes based on M8 algorithm for the region. We conclude that while an M~8 earthquake could occur any time anywhere in the Himalayan region, there is no indication as of now as to where and when it would occur. We impress on the need for preparedness to mitigate the pending earthquake disaster in the region.

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* Corresponding author at: CSIR-National Geophysical Research Institute (Council of Scientific and Industrial Research), Uppal Road, Hyderabad, India. Tel.: +91 4023434669; fax: +91 4023434651.
E-mail address: harshg123@gmail.com (H. Gupta).

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1. Introduction

The continuing interaction of the India Eurasia continental plates has given rise to the mighty Himalaya and the Tibetan Plateau. It is a classical example of collision tectonics, and attracts scientists to understand the orogenic processes, global climate change and its relation with the erosion and tectonic processes. Geographically, the Himalayan mountain range lies between the eastern and western Himalayan syntaxes. The northern boundary of the Himalayan range is considered at the east-flowing Yarlung Tsangpo and west-flowing Indus River whereas the southern boundary is the Main Frontal Thrust (MFT) that marks the topographic break and also the northern limit of the Indo-Gangetic plains (Yin, 2006). Geologically, the Himalayan region is divided into (1) Outer or Sub-Himalaya (Tertiary strata); (2) Lesser or Lower Himalaya (non-fossiliferous low-grade metamorphic rocks); (3) Greater or Higher Himalaya (crystalline complex consisting of gneisses and aplitic granites); and (4) Tethyan Himalaya (marine, fossiliferous strata). There are four major structural units in the Himalaya, (1) the Main Frontal Thrust (MFT), that lies between the sediments of the Indo-Gangetic plains and Outer Himalaya; (2) the Main Boundary Thrust (MBT), that lies between the Outer and Lesser Himalaya; (3) the Main Central Thrust (MCT), that lies between the Lesser and Higher Himalaya and (4) the South Tibet Detachment (STD) that lies between the Higher and Tethys Himalaya (Fig. 1). The Indus Tsangpo Suture Zone (ITSZ) marks the northern boundary of the Tethys Himalaya (Chatterjee et al., 2013; Hebert et al., 2012). From west to east, the Himalayan region has been divided into the western (Kashmir, Zanskar, Spiti, Himachal, Garhwal Kumaun), central (Nepal, Sikkim and south-central Tibet), and eastern (Bhutan, Arunachal and southeastern Tibet) segments (Thakur, 1992; Yin, 2006).

The Indian plate moves towards northeast at a rate of about 5 cm/year and about 2 cm/year of the convergence between the India and Eurasia is accommodated in the Himalayan region. According to the most acceptable and widely applicable model of underthrusting and earthquake occurrence, the convergence in the Himalaya is accommodated on the detachment (Seeber and Armbruster, 1981). The detachment (also referred as the decollement or the Main Himalayan Thrust, MHT) is the surface between the underthrusting Indian shield rocks and the overlying Himalayan rocks (Fig. 1). The part of the detachment that lies under the Outer and Lesser Himalaya is seismogenic and slips episodically in a stick–slip manner. It accumulates strain during the interseismic period when it is locked, which is released during the infrequent earthquakes through a sudden slip on the detachment. The detachment that lies under the Higher and Tethys Himalaya slips aseismically and does not contribute to strain accumulation. The gently dipping seismic and aseismic parts of the detachment are connected through a mid crustal ramp. In this model, the major thrusts, namely, the MFT, MBT, MCT and 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, 1984; Molnar, 1990; Pandey et al., 1995, 1999; Gahalaut and Kalpna, 2001). A majority of the earthquakes of the Himalayan seismic belt are of the thrust type, with slip vectors perpendicular to the Himalayan arc (Fig. 2). Further north of the Higher

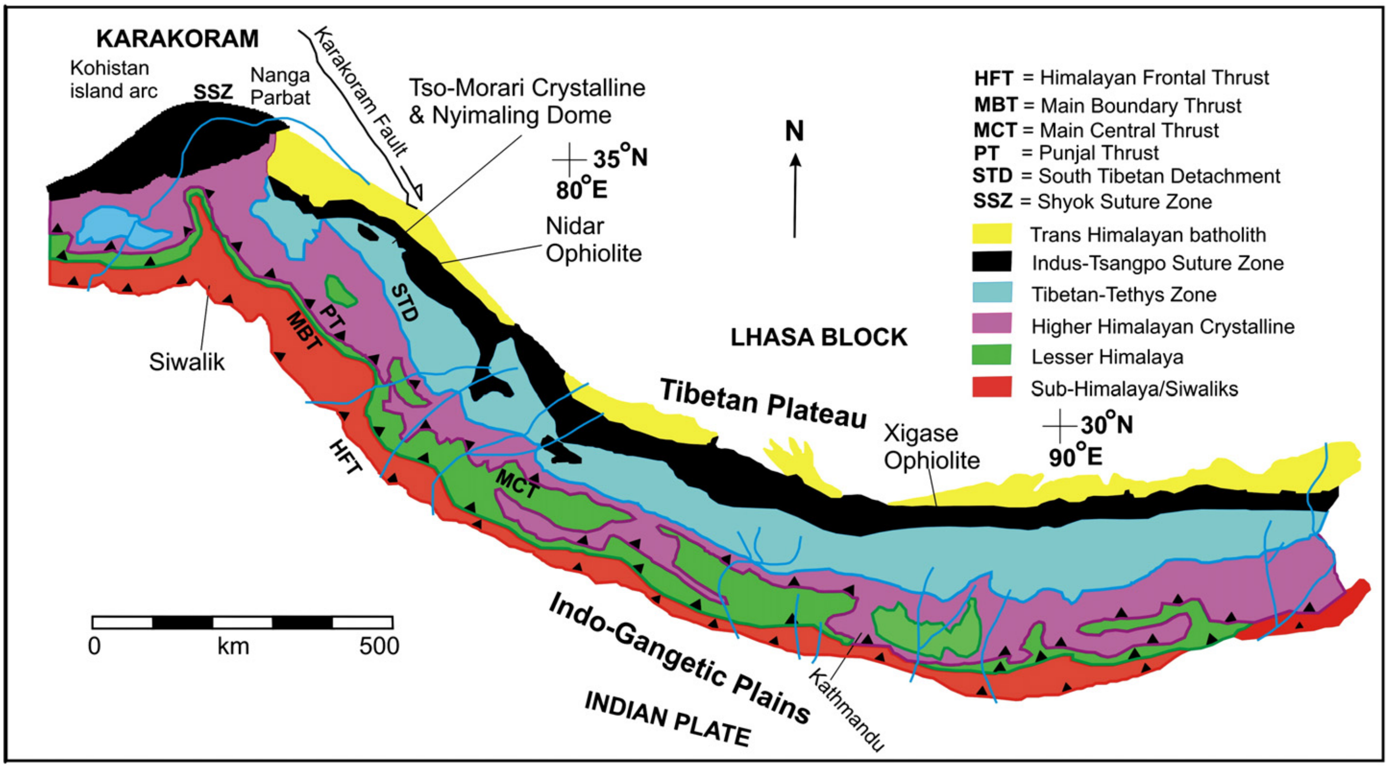

Fig. 1. General geology and tectonics of the Himalayan arc. HFT — Himalayan Frontal Thrust, MBT — Main Boundary Thrust; MCT — Main Central Thrust, STD — Southern Tibet Detachment.

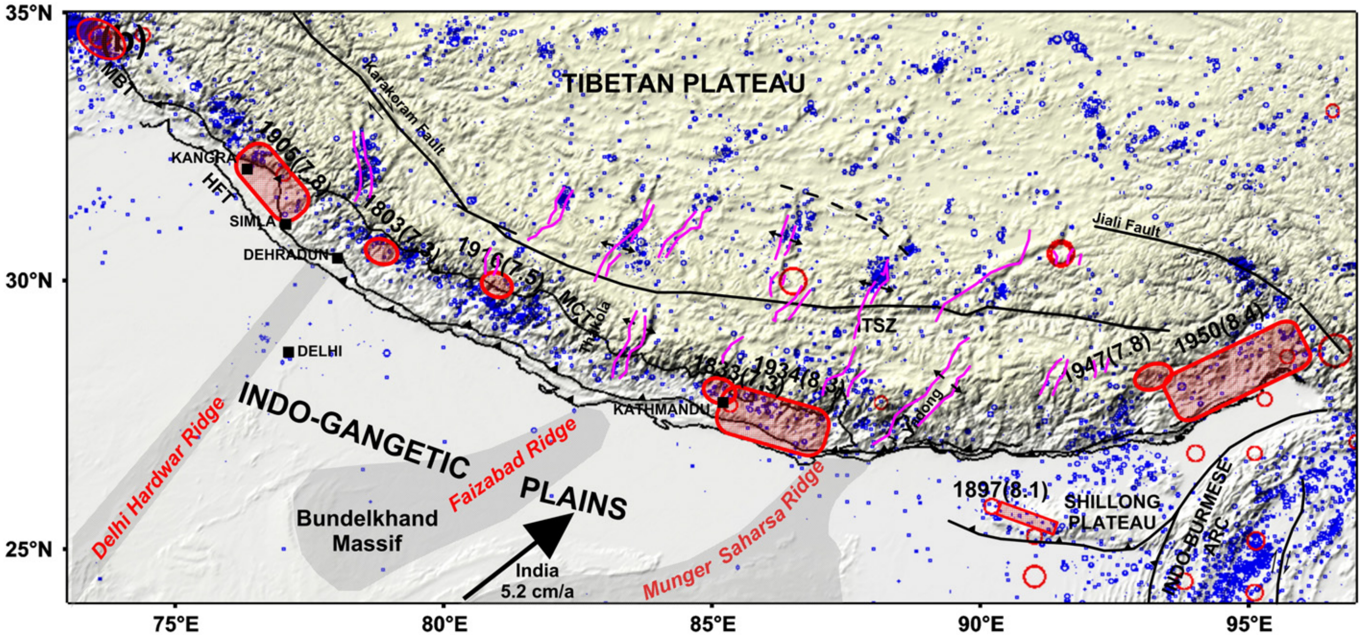

Fig. 2. Major tectonic features and seismicity of the Himalayan arc. Earthquakes are from the ISC catalogue. The ruptures of earthquakes of M > 7.2 of past 200 years in the Himalayan arc are shown by red rounded rectangles and ellipses. Earthquakes of M > 7 > 7.2 are also shown by red circles.

Himalaya, most 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. Focal mechanisms of these earthquakes indicate eastward extrusion of the Tibetan Plateau. In this article we will review the historical thrust earthquakes of the frontal Himalayan arc, earthquakes from the paleoseismological data, results of geodetic measurements in the Himalaya, seismic gaps in the Himalayan arc region and the possibility of occurrence of great earthquakes in the Himalayan region.

2. Significant earthquakes in the Himalayan region

2.1. Confirmation of earthquake magnitudes

Credible instrumental data are available for the Himalayan earthquakes from 1897 onwards. As no M ~ 8 earthquake had occurred in the Himalayan region since 1950, whereas 4 such events had occurred in a short span from 1897 through 1950, and there were several M > 7 earthquakes as well, there was a concern that probably the magnitudes of earlier earthquakes were overestimated. If continuous observations are available from a single seismic station, and the instruments are properly calibrated, it is possible to have an internally consistent magnitude and a homogeneous catalogue for a particular geographical region. This opportunity is available from the recordings at the Gottingen University seismic station in Germany, where well calibrated Wiechert Seismograph had been operating uninterruptedly. To address this issue, Gupta et al. (1993) verified the magnitudes of the Himalayan region earthquakes of M > 7 for the period 1903 through 1985. There were a total of 37 earthquakes of magnitude ≥7 which were considered. No records were available for three of these earthquakes. The magnitudes were determined by using the P-, S- and surface waves from long and medium period instruments. After this re-examination Gupta et al. (1993) did not propose any substantial revision in the magnitudes with the exception of the Tibetan earthquake of December 15, 1934, for which the surface wave (Ms) magnitude is revised from 7.1 to 7.5. Most other magnitudes were verified to be within ±0.2 units. These analyses led to the conclusion that there is no significant error in the estimates of the magnitude of the M ~ 7 magnitude Himalayan earthquake during the period 1903b through 1985, and indeed an M ~ 8 magnitude earthquake has been missing for the region since 1950.

2.2. Earthquakes of M ~ 8 in the Himalayan region

A number of catalogues of major earthquakes are available. Richter (1958) dedicated a chapter to great earthquakes in the Indian region. Ambraseys and Douglas (2004) examined the isoseismals of north Indian earthquakes for the past 200 years and developed a relation to estimate the surface wave magnitude from the radii of isoseismals and converting them to Mw magnitudes.

We examine a number of catalogues and report the earthquakes of M ~ 8 in the Himalayan region in Table 1.

The November 18, 1951 earthquake was an aftershock of the August 15, 1950 great earthquake. From the above we would like to infer that there were at least 5 M ~ 8 earthquakes since the instrumental recording started in 1897. The other event belonging to this class is the 1505 earthquake.

We briefly discuss four significant earthquakes, namely, the 1897 Shillong Plateau; 1905 Kangra; 1934 Nepal Bihar and 1950 Assam

Table 1
Earthquakes of M ~ 8 in the Himalayan region.

Earthquake	Ambraseys and Douglas (2004)	NOAA	Abe (1994)	Pacheco and Sykes (1992)	Gutenberg and Richter (1954)	Richter (1958)
1505, June 6	8.16					
1897, June 12	8.03	8.7	8.0	8.7	8.7	
1905, April 04	7.79	8.6	8.1	7.4	8.0	8.6
1934, January 15	8.11	7.6	7.7	7.5	8.3	8.4
1950, August 15	8.44	8.7	8.6	8.6	8.7	8.7
1951, November 18		8.0	8.0	8.0	7.9	7.9

earthquakes, that occurred in a span of about 50 years in the Himalaya and adjoining region (Fig. 2). Although the great 1897 Shillong Plateau earthquake was a great earthquake, it is not considered as the great Himalayan earthquake. However, we discuss it here briefly. Similarly, the 1905 Kangra earthquake is also discussed, though some investigators have suggested a revision of its magnitude from 8.0 to 7.8. We also discuss some other significant Himalayan earthquakes, which are inferred from the limited historical records and paleoseismological investigations.

2.2.1. 12 June 1897 Shillong Plateau earthquake

Richter (1958) assigned a magnitude of 8.7 for this earthquake, whereas Gutenberg (1956) Kanamori and Abe (1979), and Abe (1994) assigned it as 8.0–8.2. The estimate derived from the geodetic data is 8.1 (Ambraseys, 2000; Bilham and England, 2001). This earthquake is the largest well documented historical earthquake in India (Oldham, 1899). The earthquake occurred beneath the Shillong Plateau, which was one of the districts of Assam. This is one of the earliest earthquakes to demonstrate that acceleration exceeded 1 g, as boulders were uplifted from the ground. There is also a reporting of visible observations from this earthquake (Oldham, 1899). Buildings were damaged up to a distance of 300 km, and ground shaking was experienced by human observers up to a distance of 1500 km from the epicenter as reported by Gutenberg and Richter (1954). Bilham and England (2001) analyzed the historical triangulation data in the region to suggest that, contrary to the popular assumption that this earthquake occurred on the gently north dipping fault under the Shillong Plateau (Seeber and Armbruster, 1981; Molnar, 1990; Gahalaut and Chander, 1992), the earthquake occurred on the south and steep dipping rupture near the northern edge of the Shillong Plateau. Ambraseys and Bilham (2003) reevaluated the intensity data for this earthquake and found them consistent with the above model. They suggested a revision of its magnitude to 8.1.

2.2.2. 4 April 1905 Kangra earthquake

This earthquake was assigned a magnitude of 8.4 by Richter (1958) and Ms 8 by Kanamori (1977) on the basis of the instrumental data. Middlemiss (1910) provided an extensive report about the damage and intensity due to this earthquake. Ambraseys and Bilham (2000) suggested that the large magnitude of the earthquake was probably due to Charles Richter rounding up Beno Gutenberg's handwritten magnitude-calculation ($M = 7.8$) to the nearest integer, and partly due to the area of high-intensity shaking (Middlemiss, 1910) that extended almost 300 km along the arc, which suggested an earthquake with a magnitude 8.0. A re-evaluation of the felt intensities by Ambraseys and Douglas (2004) using the MSK intensity scale confirmed that although Middlemiss' Rossi–Forel contours were 1 to 1.5 intensity units too large near the epicenter, a region of high intensities remained near Dehradun with intensities falling as low as MSK V in the region between Dehradun and Kangra. Though, the reason for the high intensity at Dehradun has been ascribed to be caused by a triggered $M > 7$ earthquake, probably at 30–40 km depth in the Indian plate (Hough et al., 2005a,b), it is still an issue to be resolved, probably a local site condition enhanced the damage in the region. Recently, Wallace et al. (2005) remeasured the part of the Great Triangulation Survey network in the Kangra region by using the GPS. They estimated the coseismic slip during the earthquake as 7 m and the rupture length of no more than 150 km. The constraints are not strong, but they confirmed that the rupture did not extend to the frontal thrusts of the Himalaya, a conclusion consistent with the findings of geologists in 1905, who found no evidence for a surface rupture.

2.2.3. 15 January 1934 Nepal–Bihar earthquake

Several estimates of the focal parameters of this earthquake are available. Gutenberg and Richter (1954) assigned a magnitude of 8.3 for this earthquake. Roy (1939), Richter (1958), Singh and Gupta (1980) estimated the epicenter in the Gangetic plains, south of the Main Frontal Thrust (MFT), whereas, Seeber and Armbruster (1981) and Chen and Molnar (1977) estimated it in the Outer and Lesser/Higher Himalaya respectively. The macroseismic effects of the earthquake were recorded by Dunn et al. (1939a,b). The highest intensity was documented in two regions, namely, near Kathmandu and in the Indo-Gangetic plains. In the latter region, known as the slump belt for this earthquake, soil liquefaction was widespread. Ambraseys and Douglas (2004) reevaluated the intensity of the 1934 Nepal–Bihar earthquake and found that most of the damage was actually concentrated in the Nepal region with high MSK intensity reaching VIII. Thus, the damage in the Indo-Gangetic plains was mainly due to local site condition. The earthquake rupture was confined in the Himalaya (Chander, 1988; Molnar, 1990) with a length of about 200–300 km and a slip of 6 m (Pandey and Molnar, 1988). Molnar and Deng (1984) estimated a seismic moment of 4.1×10^{21} Nm.

2.2.4. 15 August 1950 Assam earthquake

Though this is the most recent great earthquake with Ms as 8.4 and Mw as 8.6 (Gutenberg and Richter, 1954) in the Himalaya (Fig. 1), and it had the best instrumental coverage of that time, our knowledge about this earthquake is the poorest. This is mainly because of the inaccessibility of the region of its occurrence. The remoteness of the region prohibited a comprehensive investigation of the damage associated with it. The earthquake occurred at the northeast end of the Himalaya. Occurrence of numerous aftershocks beneath the Himalaya in eastern Assam implies that at least part of the rupture zone underlies the Himalaya (Molnar, 1990). This earthquake caused a strong aftershock of $M \sim 8$ on the same day, about 7.5 h after the mainshock. Chen and Molnar (1977) found that the data used by Ben-Menahem et al. (1974) indicating the strike slip mechanism, are also consistent with the thrust faulting on a gently north–northwest dipping plane, which is similar to the focal mechanism solutions of other earthquakes in this region. The most dramatic feature of this earthquake was the landslides. Mathur (1953) found by air reconnaissance that landslide covered 15,000 km^2, or about 1/3 of the surface in an area of 46,000 km^2 (Bilham, 2004). Molnar and Pandey (1989) reexamined and relocated the aftershock data and suggested that relocated aftershocks lie beneath the Himalaya. They inferred dimensions of the rupture zone to be about 250 km in its east–west dimension and 100 km in the north south direction.

2.2.5. 8 October 2005 Kashmir earthquake

Although the magnitude of this earthquake was only 7.6, it was probably the most damaging earthquake, ever occurred in the Himalaya in the past two centuries. It claimed lives of more than 80,000 people. The earthquake occurred through a thrust motion on a 75 km long fault in the Indo-Kohistan Seismic Zone with a maximum surface offset of about 7 m. One important feature of this earthquake which distinguishes it from other Himalayan earthquake is that its rupture extended up to the surface. It was marked with extensive landslides. The rupture was rather steep (with a dip of about 20°) in comparison to other moderate and major Himalayan earthquakes (Gahalaut, 2008).

2.3. Other significant Himalayan earthquakes

Iyengar and Sharma (1999), Ambraseys and Jackson (2003), Ambraseys and Sharma (1999) and Bilham and Ambrasey (2005) examined the historical literature in Sanskrit and Persian and reported several earthquakes from the Himalayan and adjoining regions that occurred in a historical period prior to 1800 AD. Amongst the earliest known major earthquake in the Kashmir region, Iyengar and Sharma (1999) reported a major earthquake circa 1250 BC, known as Wular Lake earthquake. Amongst several other reported earthquakes, the September 1555 Kashmir earthquake was a major earthquake (Iyengar and Sharma, 1999).

The earthquake of 6 June 1505 in southwestern Tibet is considered as a major event (Ambraseys and Jackson, 2003). It was strongly felt, with damage to local houses along the northern part of the Great Himalaya. Ambraseys and Jackson (2003) estimated a magnitude of about 8.2. However, Rajendran and Rajendran (2005) analyzed the historical accounts of this earthquake and suggested that either it was not a great earthquake but it occurred in the Himalayan region or it was a non-plate boundary great earthquake that occurred in the Tibetan region. Lack of severe damage in the Indo-Gangetic plains guided them to suggest the second possibility.

For the earthquake of 1 September 1803 (Mw 7.1) that probably occurred in northern Kumaun–Tibet, data are insufficient to assign intensities in locations that can define without ambiguity the extent of the epicentral area (Ambraseys and Jackson, 2003). Ambraseys and Jackson (2003) assigned an approximate magnitude of Ms = 7.5 for this earthquake. This was later revised to Mw = 8.09 by Ambraseys and Douglas (2004). However, a recent analysis of the macro-seismic data from the Himalaya and Indo-Gangetic plains by Rajendran and Rajendran (2005) puts the magnitude of this earthquake as not more than 7.7. They suggested that this earthquake occurred somewhere close to Devprayag and Srinagar in the Garhwal Himalaya and is probably not a plate boundary earthquake.

The 26 August 1833 an M 7.7 earthquake that occurred near Kathmandu consisted of three shocks. The first caused alarm and the second, 5 h later, brought most people out of their homes. The main-shock (Mw = 7.69, Ambraseys and Douglas, 2004) occurred 15 min later causing widespread structural damage in India and Nepal, but the combined loss of life in India and Nepal was only 500 because most people were already in the open, alarmed by the two foreshocks. Bilham (1995) opined that probably it was not a detachment earthquake.

Ambraseys and Jackson (2003) also mentioned some other historical earthquakes, e.g., the earthquake of 1713, somewhere in Bhutan or in Arunachal Pradesh with Ms = 7, the earthquake of 1751 that occurred in the upper reaches of the Sutlej river in Tibet Ms 7.0, The earthquake of 11 June 1806 that occurred in the region between Samye and Cona in Tibet, near its border with eastern Bhutan with a magnitude of about 7.5. Another significant earthquake worth mentioning is the 29 July 1947 earthquake that occurred slight west of the 1950 earthquake. Molnar (1990) suggested a magnitude of about 7.9 for this earthquake based on the estimated seismic moment of 2×10^{20} Nm (Molnar and Deng, 1984).

2.4. Earthquakes reported from paleoseismological investigations in the Himalaya

Paleoseismological investigations in India started with the work in the Shillong Plateau region. Sukhija et al. (1999) were amongst the first to report the results of any paleoseismic investigations in the Himalaya and adjoining region. They 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 yr for the large earthquakes in the Shillong Plateau. Sukhija et al. (2002) reported paleoseismological evidence of occurrence of the 1934 Nepal–Bihar and the 1833 Nepal earthquakes as well as evidence of occurrence of two prehistoric seismic events dated 1700 to 5300 years BP and earlier than 25,000 years BP. Kumar et al. (2001, 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 surface rupture at each site that 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. Lavé et al. (2005) presented paleoseismological evidence of occurrence of a great earthquake in the east central Nepal. They estimated that the earthquake occurred around ~1100 AD with a surface displacement of ~17 m and lateral extent and size that could have exceeded 240 km with a magnitude of Mw 8.8. Another major conclusion of this work was the absence of evidence of the surface rupture during the 1934 Nepal–Bihar earthquake.

3. Quiescence of major earthquakes (M ≥ 7.5) since 1952

The Muzaffarabad earthquake of October 8, 2005 is the only earthquake of magnitude ≥7.5 to have occurred in the Himalayan region since the 17th August 1952 M 7.5 earthquake. The last M ~ 8 earthquake was the aftershock of the great 1950 earthquake that occurred on the 18th November 1951. Satyabala and Gupta (1996) examined the earthquakes in the Himalaya and the north east India regions (latitude 20 to 38° north and longitude 75 to 100° east), comprising the portions of the Himalaya and Arakan Yoma fold belts for the period from 1897 through May 1995. They made use of the catalogues prepared by Abe (1994), NOAA, Pacheco and Sykes (1992), Gutenberg and Richter (1954) and Gupta et al. (1986, for the north-east India region earthquakes; and 1995). They reported that there had been 14 major earthquakes of M ≥ 7.5 during the period 1897 to 1952, including 5 earthquakes of M 8 and larger. No such event occurred during the period 1952 through 1992. For earthquakes of 7.5 ≥ M ≥ 7.0 the numbers were 11 and 6 for the two periods, while for 7.0 ≥ M ≥ 6.5 these numbers were 19 and 15 for the two periods. Satyabala and Gupta (1996) concluded that there is a real paucity of M > 7.5 earthquakes in the study area. We provide an updated table of the earthquakes in the region up to 2011. It can be seen from this table that the paucity for M ≥ 7.5 earthquakes continues. The following is the updated table from Satyabala and Gupta (1996) (Table 2).

4. Geodetic constraints on interseismic deformation in the Himalaya and rate of convergence

Prior to the GPS based deformation measurements in the Himalaya, a few reports of crustal movement based on the leveling data are available. 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 et al., 1994) and to understand the crustal deformation mechanism during an earthquake cycle (Gahalaut and Chander, 1997a; Chander and Gahalaut, 1999). The elevation changes along a leveling line from Pathankot to Dalhousie in Punjab Himalaya reveal an uplift rate of 4–6 mm/year in the Lesser Himalaya and are consistent with strain accumulation on the detachment at the rate of about 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 a low uplift rate (<2 mm/year) in the Outer Himalaya while a 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 (Bilham et al., 1997; Gahalaut and Chander, 1997b).

In the past two decades, the conventional land based geodetic techniques have been replaced by more accurate and fast space based GPS

Table 2
Magnitude distribution of earthquakes in the Himalayan region.
Updated from Satyabala and Gupta (1996).

Magnitude	1897–1952	1953–2011
M ≥ 7.5	14	2
7.5 > M ≥ 7	11	9
7 > M ≥ 6.5	19	27

measurements. Extensive measurements have been undertaken in the Nepal Himalaya. The leveling, GPS, DORIS data have been analyzed (Jackson and Bilham, 1994; Bilham et al., 1997; Gahalaut and Chander, 1997b, 1999; Jouanne et al., 1999; Avouac, 2003; Bettinelli et al., 2006; Ader et al., 2012) by using an elastic dislocation model of the interseismic strain. The mean convergence rate across Central and Eastern Nepal is estimated at 18–20 mm/yr. The detachment is assumed to be locked from the surface to a depth of about 20 km over a width of about 115 km. The moment deficit rate in the region is about 6.6×10^{1} Nm/yr on the detachment whereas, the moment released by the seismicity over the past 500 years, amounts to only 0.9×10^{19} Nm/yr. Thus the large slip deficit should be released in the next great earthquake in the region. The GPS network in the Nepal region has reported no large slow slip event in the past 20 years (Ader et al., 2012). The GPS measurements in the Garhwal and Punjab Himalaya show a strain accumulation at the detachment at the rate of 18 and 14 mm/year (Banerjee and Burgmann, 2002; Jade et al., 2004).

There are a few issues with the GPS measurements and their analyses. In all cases, the surface displacement rates have been interpreted by using the strain accumulation model and have been extended up to the detachment to simulate the slip deficit. It is essential to try out alternate models with or without strain accumulation. The other coupled problem is with the estimation of the strain budget in the Himalaya. It is assumed that the convergence rate estimated from the geological investigations applies to the Himalaya and the entire moment rate deficit (estimated from the earthquakes) should occur through strain accumulation and will be released through slip during great earthquakes. It is now known that slow slip and aseismic slip on the faults may affect the strain budget tremendously. Unfortunately, there are not enough continuous GPS in the Himalayan region to settle this issue. Although in the Nepal region, no slow slip event has been detected in the past 20 years, and it is not necessary that they are absent from the entire Himalaya. There may be some spatial and temporal dependencies of such events and hence they have not been detected so far, as the GPS network coverage in the Himalaya is sparse both in time and space.

5. Seismic gap and estimates of return period of great earthquakes of the Himalaya

The seismic gap hypothesis is based on the concepts of plate tectonics and elastic rebound theory. It was developed after seismologists worked out a concept about how great earthquakes occur along the boundaries of plates (Fedotov, 1965; Sykes, 1971). The concept of the existence of an earthquake cycle, in which it takes hundreds of years to build up the elastic strain that is eventually released within seconds to minutes during the occurrence of great earthquakes, originated with the H.F. Reid's observations following the 1906 San Francisco earthquake. The third element important to the current concept of how great earthquakes occur is the recognition that the shear stress along the plate boundaries is low. Based on these facts, the basic seismic gap hypothesis can be defined as follows: "*The energy for large and great earthquakes along plate boundaries is accumulated by plate motions, from low to maximum levels. This process takes decades to centuries to load a plate boundary segment. Great earthquakes are more likely in "loaded" segments, called "seismic gaps," than in segments recently unloaded by great ruptures. Seismic gaps are likely to rupture in one or a small number of large, gap-filling earthquakes*" (Wyss and Wiemer, 1999).

However, it has been realized that because of the unknown creep and coseismic slip history, it is not certain that a seismic gap will ever be filled, or that the rupture stops at its edge. In fact in view of recent earthquakes (e.g., the 2010 Chile, M 8.8) in which the significant slip occurred over the region which ruptured a few decades back (Lay, 2012), the theory appears to be too simplified. Nevertheless, the above concepts have been applied to the Himalayan convergent plate margin to identify seismic gaps. The way it has been stated above, it appears an easy task to identify the seismic gaps in the Himalayan arc. However, all the great earthquakes in the Himalaya, occurred before the modern instrumental era. Thus, lack of information and instrumental data about the rupture extent, slip and mechanism prohibits us to exactly define the regions which have fully or partially released the accumulated strain. Further, the historical records of earthquakes in the Indian subcontinent are really poor, we are not even sure of great earthquakes that may have taken place just a couple of hundred years back. Based on the historical earthquake data and inferred rupture extent of great earthquakes, it has been suggested that some segments of the detachment under the Himalayan arc have not experienced major and great earthquakes in the past 100 years or so (Seeber and Armbruster, 1981; Khattri, 1987; Molnar, 1990; Bilham et al., 2001). One of the assumptions in proposing seismic gaps is that all the segments along the entire Himalayan arc have the potential to generate large earthquakes. Three main seismic gaps have been identified in the Himalaya:

(i) Khattri and Wyss (1978) proposed that the Assam gap extends in the region between the 1950 Assam and 1897 Shillong Plateau earthquake ruptures. However, it has now been found that the 1897 Shillong Plateau earthquake did not release the strain along the Himalayan detachment, as the rupture of the earthquake was not located on the Himalayan detachment and hence it is not considered as the Himalayan earthquake (Gahalaut and Chander, 1992; Bilham and England, 2001). Thus the actual Assam seismic gap is now redefined as between the 1950 Assam and 1934 Bihar–Nepal earthquake ruptures (Fig. 1) Unfortunately, our historical records of earthquakes in this gap region are too scanty and short to suggest whether great earthquakes have actually occurred in this region. GPS measurements in the region have just been initiated to document the evidence of strain accumulation in the region. So, as such we are not sure whether this region has the potential to generate a great earthquake.

(ii) The gap between the 1905 Kangra and 1934 Bihar–Nepal earthquakes (Fig. 1) is known as the Central gap (Seeber and Armbruster, 1981). However, in recent years it has been argued that the 1905 Kangra earthquake with an Mw 7.8 was not a great earthquake and its rupture did not extend up to Dehradun, and the length of this gap has increased. The historical data and paleoseismological investigations suggest that this region has experienced great earthquakes in the past (Kumar et al., 2001, 2006; Ambraseys and Jackson, 2003; Lavé et al., 2005) and geodetic observations suggest that strain accumulation is underway (Chander and Gahalaut, 1994; Gahalaut and Chander, 1997b; Jouanne et al., 1999; Bilham et al., 2001; Banerjee and Burgmann, 2002; Jade et al., 2004). Thus this region probably has the potential to generate a great earthquake and hence may be declared as a seismic gap.

(iii) The Kashmir gap lies west of the 1905 Kangra earthquake rupture (Seeber and Armbruster, 1981; Khattri, 1987) (Fig. 1). This region has experienced a strong earthquake in September 1555. But it is not certain whether it was a great earthquake. Moreover, the smaller width of the seismogenic detachment and low rate of strain accumulation (Gahalaut and Chander, 1999; Banerjee and Burgmann, 2002), possible presence of salts/anhydrites in the region, suggest that probably only major earthquakes may occur in this region.

Recently, Bilham et al. (2001) applied the concept of the Seismic gap in the Himalayan arc. They assumed that the arc and the process are uniform throughout and every segment of the Himalaya has the potential to generate great earthquakes. They postulated that most of the regions of the Himalayan arc have accumulated sufficient strain since the last earthquake. Specifically, the regions lying in the above seismic gaps have accumulated slips of more than 8 m to be released in future great earthquakes. The Kashmir, Central and Assam gap regions have the potential to generate at least one, three and two great earthquakes respectively (Bilham et al., 2001).

6. Efforts made in earthquake prediction and forecasting

On the basis of occurrence of historical great earthquakes in the Himalaya, the estimates of the rate of convergence accommodated it, and limited paleoseismological investigation and earthquake recurrence intervals have been estimated which vary from 200 years to 1000 years (Seeber and Armbruster, 1981; Sukhija et al., 1999). Other than these long term predictions, no medium term or short term prediction has been attempted for the Himalayan earthquakes. However, a few attempts towards earthquake forecasting in medium term using the statistical analysis of the earthquake catalogues have been attempted. We discuss two such prominent forecasts in the Himalaya and nearby Indo-Burmese arc region. We also analyze the seismicity in the central Himalaya to see if there existed any precursory seismicity activity before the earthquakes of $M > 6.5$.

6.1. Algorithm M8 forecast

In the past few decades, some emphasis has been given on the statistical analysis of the earthquake data and efforts have been made to forecast the earthquakes. The prominent methods/algorithms in this category include the M8–MSC algorithm. These algorithms essentially look for the flux intensity of earthquakes, the deviations from long term trends, and the earthquake clustering through spatio-temporal variations in the seven mathematical functions (Kossobokov, 2011). In case in a region, six of them show anomalous values, then a TIP (Time of Increased Probability) for an impending earthquake is issued. These calculations are done routinely and TIPs are updated. Presently in the Himalayan region, a TIP has been diagnosed in the NW Himalaya, in the region of the 1905 Kangra earthquake. Elsewhere, in the Indian plate region, TIPs diagnosed in the beginning of this year in the Indian Ocean, off Sumatra Island, proved to be right, as two great earthquakes (Mw 8.6 and 8.2) actually occurred on 11 April 2012. Fortunately these earthquakes occurred within the Indian plate through a strike slip motion and hence no major tsunami could be generated. However, there have been several failure stories as well, e.g., (i) the TIP for 2004 Sumatra earthquake was not diagnosed, as the right set of parameters were not chosen to normalize the functions in the algorithm; (ii) the TIP for the 2010 Chile earthquake could be diagnosed in the M8 algorithm but not in the CN; (iii) the TIP for the 2011 Japan earthquake expired 70 days before the occurrence of this earthquake. Thus there has been some success in forecasting earthquakes by using these methods.

6.2. Medium term earthquake forecast

Precursors to large earthquakes have been investigated for a long time. This has been recently reviewed by Uyeda et al. (2011). An effort in this direction was made by Gupta and Singh (1986, 1989) in the north east India region by using the generalized precursory swarm hypothesis approach (Evison, 1982). Encouraged by the discovery of a precursory swarm and quiescence preceding the M 5.4 Cachar earthquake of December 30, 1984, they investigated $M \geq 7.5$ in the region bound by 20 and 32° north latitudes and 88 and 98° east longitudes adjacent to the Himalayan frontal arc (Fig. 3). They found that the main shock magnitude (Mm) has a correspondence with the magnitude of the largest event (Mp) in the swarm, and the time interval (Tp) between the onset of the swarm and the occurrence of the main shock in days. These relations are:

$$\begin{aligned} Mm &= 1.37\ \ Mp - 1.41, \ \ \text{and} \\ Mm &= 3\ \ \log\ \ Tp - 3.27. \end{aligned}$$

They observed that it is important to recognize an area where an earthquake swarm has already occurred and the region is experiencing the precursory quiescence. They (Gupta and Singh, 1986) observed one such region in the vicinity of the India–Burma border and concluded that: "1) *Moderate magnitude to great earthquakes in the North-East India region are found to be preceded, generally, by well defined earthquake swarm and quiescence periods,* 2) *on the basis of an earthquake swarm and quiescence period, an area bound by 21°N and 25 1/2°N latitude and 93°E and 96°E longitude is identified to be the site of a possible future earthquake of M 8 ± 1/2, with a focal depth of 100 ± 40 km. This earthquake should occur any time from now onwards. Should it not occur till the end of 1990, this forecast could be considered as a false alarm*". This is a typical medium term forecast. The occurrence of the August 6, 1988 earthquake with the following focal parameters has proved this forecast to be true (Table 3):

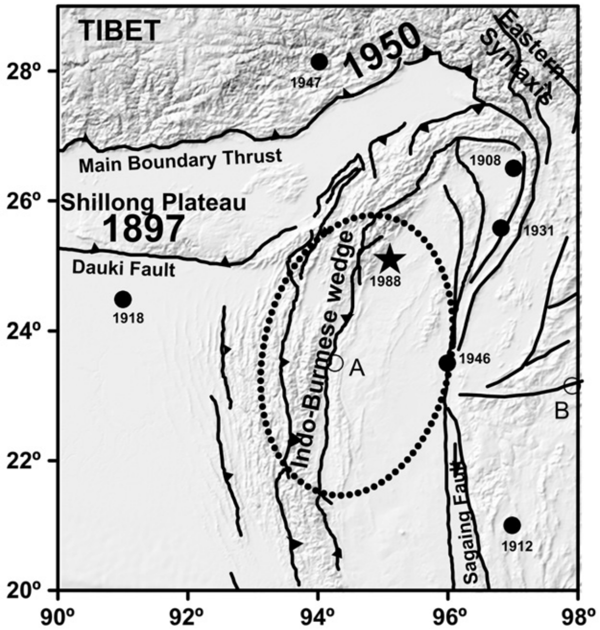

Fig. 3. Earthquakes of $M \geq 7.5$ in the north-east India region since 1897 (filled circles). Elliptical area shows the preparation zone for an $M = 8 \pm 0.5$ earthquake identified by Gupta and Singh (1986). After the last M 7.5 earthquake of August 17, 1952 the first largest earthquake of M 7.3 in the entire region occurred on August 6, 1988, shown by the star. This was followed by two more earthquakes of M 7.3 on November 6, 1988 (A) and January 5, 1991 (B) (after Gupta and Singh).

All the focal parameters of this earthquake are within the stipulated parameters of the Gupta and Singh's (1986) medium term forecast other than the magnitude which is slightly less than 7.5. The probability of occurrence of such an earthquake in the area under consideration and the time window is 0.048, which is very small (Gupta, 2001). Hence, it may be concluded that it was a significant achievement (Gupta, 1988).

6.3. Precursory seismicity changes in Central Himalaya

We analyze the seismicity in the central Himalayan region to see whether any precursory swarm and quiescence precede earthquakes in the region. From the discussion in the preceding sections, it appears that this region has a relatively larger potential to generate a great earthquake. The population density in this region and in the adjoining Indo-

Table 3
Forecast of August 6, 1988 earthquake.

Earthquake parameters	Prediction Gupta and Singh, 1986)	Occurrence NEIS
Epicenter	21°N–25 1/2°N 93°E–96°E	25.116°N 95.171°E
Magnitude (M)	8 ± 1/2	7.3
Depth	100 ± 40 km	115 km
Time	February 1986–December 1990	August 6, 1988 (00:36:26.9 G.C.T.)

Gangetic plains is the maximum and hence a large population is exposed to the seismic hazard. Fig. 4a gives the location and magnitudes of 9 earthquakes of M ≥ 6.0 that occurred during a short span of 33 years from 1966 through 1999. The Ms 6.8 Kinnaur earthquake of January 19, 1975 was preceded by a reasonably well defined swarm during 1963 through 1968 when 5 earthquakes of M ≥ 5.5 occurred followed by a remarkable quiescence of such events during 1968 to January 19, 1975 when the M 6.8 Kinnaur earthquake occurred (Fig. 4b). This phenomenon of swarm and quiescence is not so pronounced before the occurrence of the M 6.8 Uttarkashi earthquake of October 19, 1991 and the M 6.6 Chamoli earthquake of March 28, 1999. After the March 28, 1999 Chamoli earthquake of Ms 6.6, there has been no M ≥ 5.5 (Fig. 4b) in the region. This quiescence is noticeable and may be a precursor to an M ~ 6.5 earthquake.

7. Concluding discussion

The proposed seismic gaps in the Himalaya and the reported evidence of the strain accumulation rate in various Himalayan segments do suggest that a great earthquake can occur in the Himalaya. However, due to a lack of reliable data pertaining to the previous great earthquakes in the region and insufficient data to understand the earthquake occurrence and strain accumulation process, it is not possible to say whether a great earthquake in a particular segment will occur before a great earthquake in a neighboring segment. In the past ten years, there have been a few cases in which the occurrences of great and major earthquakes defied, in some way or other, our conventional understanding of their genesis (Lay, 2012). Their occurrences surprised all of us, particularly, the great 2010 Maule, Chile earthquake (M 8.8). The rupture of the earthquake partly overlapped with the rupture of previous major earthquakes which occurred just eight decades ago, defying the concept of the seismic gap theory. It has been proposed that the famous four great and major earthquakes in the Himalaya (discussed earlier) exhibited some kind of time clustering and hence occurred within about 50 years. However, no such earthquakes occurred in the preceding and following fifty years' time. Thus it is prudent to assume that a great earthquake can occur anywhere in the Himalaya and its time cannot be forecasted.

The other question here is whether an upper threshold on the earthquake magnitude can be estimated in the Himalaya. In the past few years, the occurrences of great earthquakes, namely, the 2004 Sumatra Andaman (M 9.2) and 2011 Tohoku (M 9.0) earthquakes, have really

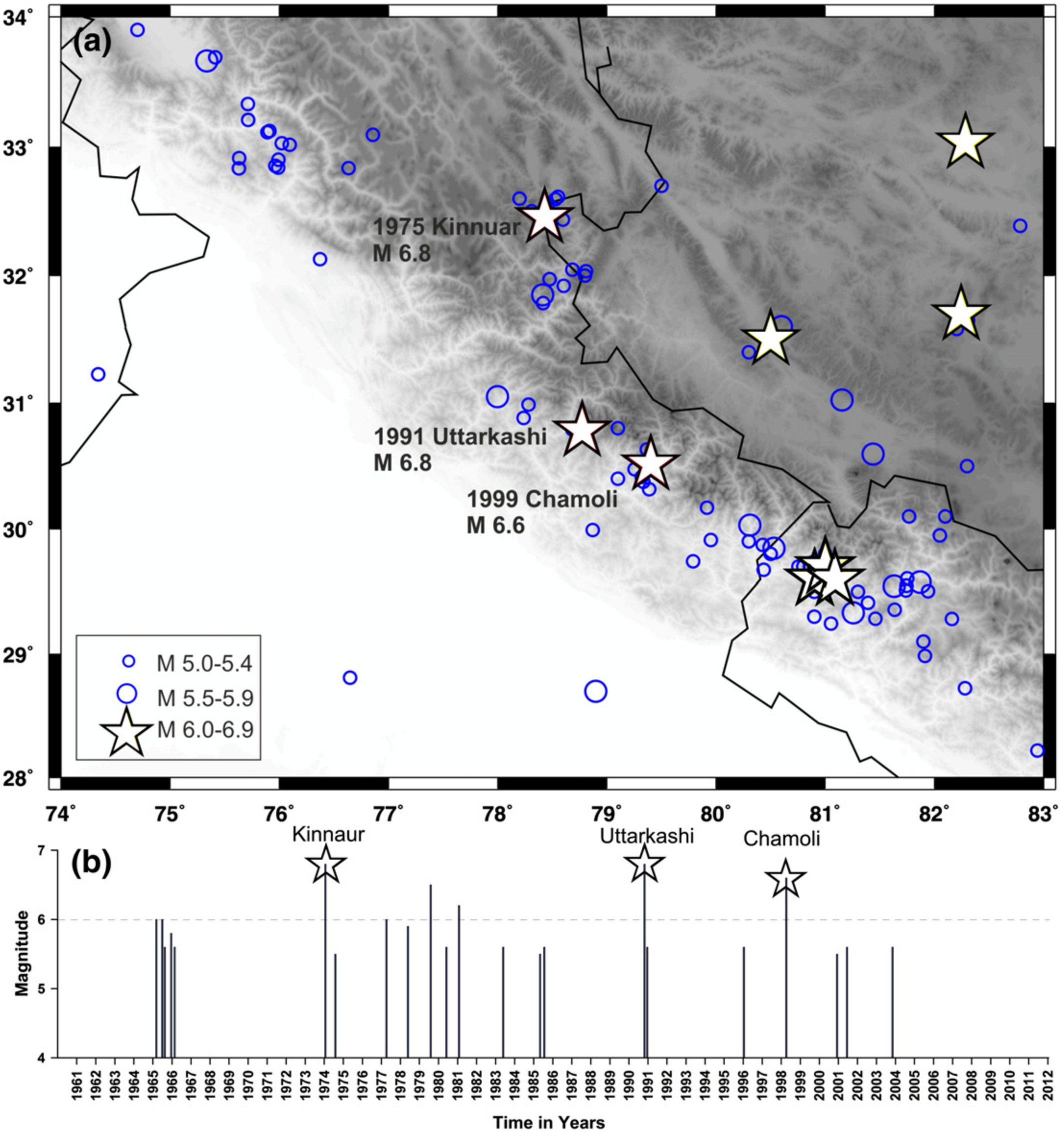

Fig. 4. (a) Earthquakes in the central Himalaya since 1960. (b) Temporal plot of M ≥ 5.5 earthquakes.

challenged our conventional understanding as these earthquakes occurred where such large magnitude earthquakes were not expected to occur (Lay, 2012). In view of this, now it is difficult to decide an upper magnitude threshold in a region. However, in almost all worldwide cases it has been seen that in a subduction zone, the extents of the earthquake ruptures have been contained by the subducted ridges (Robinson et al., 2006; Sparkes et al., 2010; Zhao et al., 2011). In the Himalaya too, such a possibility has been examined and it has been found that the subduction of three prominent ridges, namely, the Delhi Hardwar, Faizabad and Munger Saharsa ridges, under the Himalayan arc have actually affected the seismicity of the region (Gahalaut and Kundu, 2011). In no case, the ruptures of great and major earthquakes of the past two hundred years could breach these ridges. Thus it is possible that in the Himalaya, earthquakes with longer ruptures (say more than 600 km) cannot occur as the arc is segmented by these ridges. However, considering the case of the 2011 Tohuku earthquake, it may still be possible that a giant earthquake may occur with a rupture no longer than 600 km (Fig. 5). We note in passing that giant earthquakes with longer ruptures have occurred in the subduction zone however, their occurrences on the collisional zones have not been reported so far.

Considering the high population density and unprecedented growth in poor construction in the Himalayan foothills and Indo-Gangetic plains, we are of the view that even the occurrence of a major earthquake will be disastrous for the region. The 2005 Kashmir earthquake with a magnitude of only 7.7, is an example which claimed about 80,000 human lives. Occurrence of a great magnitude earthquake anywhere along the Himalayan arc can claim lives of up to 1 million people. Hence it is important to stress on the need of earthquake preparedness and enforcement of good construction practices. Other than the continuing efforts to understand the earthquake occurrence processes through seismological and GPS networks in the Himalaya, it is important that early earthquake warning systems be installed which may mitigate the risk in high population density regions in the Indo-Gangetic plains, adjoining the Himalayan arc.

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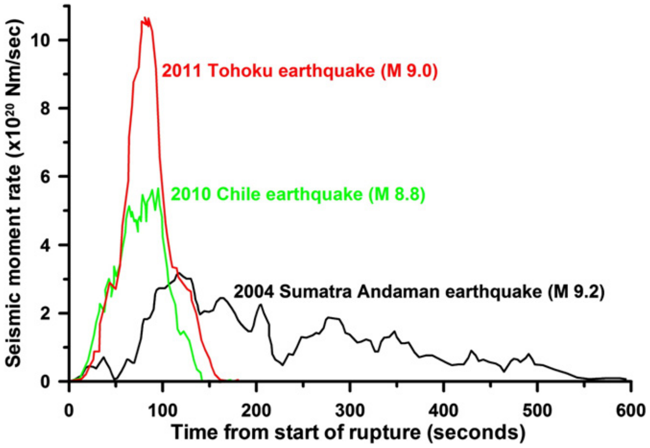

Fig. 5. Comparison of the seismic moment rate release of 2004 Sumatra Andaman earthquake with the 2010 Chile and 2010 Tohoku earthquakes (Lay and Kanamori, 2011). Note the quick and high seismic moment release during the 2011 Tohoku earthquake in which a high slip (~50 m) occurred on a rupture of ~500 km long.

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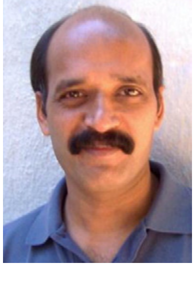
Harsh K. Gupta is currently a Member of the National Disaster Management Authority of India. He is globally known for providing the first geophysical evidence of an enormously thick crust below the Himalaya and Tibet Plateau regions, identifying the common characteristics of artificial water reservoir triggered earthquakes and discriminating them from normal earthquakes, setting up India's first permanent station at Antarctica in a record time, and in recent years, spearheading the designing and commissioning of the Tsunami Warning System for India. He has published over 200 papers and written 4 pioneering books, published by Elsevier. Recently he edited the Encyclopedia of Solid Earth Geophysics published by Springer.



V.K. Gahalaut is a scientist at the CSIR-National Geophysical Research Institute, Hyderabad. He received his master's and doctorate degrees from University of Roorkee (now Indian Institute of Technology), India. He started working on Himalayan earthquakes, crustal deformation and geodynamics in 1989 and then expanded his research on understanding earthquakes and crustal deformation in the Indo-Burmese arc, Indian shield region, failed rift regions, and Andaman Sumatra subduction zone. He has contributed immensely in establishing the Indian GPS network.