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GR Focus

The devastating Muzaffarabad earthquake of 8 October 2005: New insights into Himalayan seismicity and tectonics

N. Purnachandra Rao [a,*], P. Kumar [a], Kalpna [a], T. Tsukuda [b], D.S. Ramesh [a,b]

[a] *National Geophysical Research Institute, Uppal Road, Hyderabad 500007, India*
[b] *Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan*

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Abstract

The recent earthquake of 8 October 2005 in the Muzaffarabad region in western Himalaya destroyed several parts of Pakistan and the north Indian state of Jammu and Kashmir. The earthquake of magnitude 7.6 claimed more than 80,000 lives, clearly exposing the poor standards of building construction — a major challenge facing the highly populated, earthquake prone, third world nations today. In this paper, we examine variations in the stress field, seismicity patterns, seismic source character, tectonic setting, plate motion velocities, GPS results, and the geodynamic factors relating to the geometry of the underlying subsurface structure and its role in generation of very large earthquakes. Focal mechanism solutions of the Muzaffarabad earthquake and its aftershocks are found to have steep dip angles comparable to the Indian intra-plate shield earthquakes rather than the typical Himalayan earthquakes that are characterized by shallow angle northward dips. A low p-value of 0.9 is obtained for this earthquake from the decay pattern of 110 aftershocks, which is comparable to that of the 1993 Latur earthquake in the Indian shield — the deadliest Stable Continental Region (SCR) earthquake till date. Inversion of focal mechanisms of the Harvard CMT catalogue indicates distinct stress patterns in the Muzaffarabad region, seemingly governed by an overturned Himalayan thrust belt configuration that envelops this region, adjoined by the Pamir and Hindukush regions. Recent developments in application of seismological tools like the receiver function technique have enabled accurate mapping of the dipping trends of the Moho and Lithosphere–Asthenosphere Boundary (LAB) of Indian lithosphere beneath southern Tibet. These have significantly improved our understanding of the collision process, the mechanism of Himalayan orogeny and uplift of the Tibetan plateau, besides providing vital constraints on the seismic hazard threat posed by the Himalaya. New ideas have also emerged through GPS, macroseismic investigations, paleoseismology and numerical modeling approaches. While many researchers suggest that the Himalayan front is already overdue for several 8.0 magnitude earthquakes, some opine that most of the front may not really be capable of sustaining the stress accumulation required for generation of great earthquakes. We propose that the occurrence of great earthquakes like those of 1897 in Shillong and 1950 in Assam have a strong correlation with their proximity to multiple plate junctions conducive for enormous stress build up, like the eastern Himalayan syntaxis comprising the junction of the India, Eurasia plates, and the Burma, Sunda micro-plates.

Keywords: Great earthquakes; Himalaya; Indian plate; Muzaffarabad earthquake; Seismic hazard; Stress inversion

Contents

* Corresponding author. Tel.: +91 40 23434700; fax: +91 40 27171564.
E-mail address: raonpc@ngri.res.in (N.P. Rao).

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1. Introduction

On 8 October 2005 at 03:50:40 UTC, an earthquake of magnitude 7.6 occurred close to the Muzaffarabad region, and destroyed several parts of Pakistan, Jammu and Kashmir. The quake was located at latitude of 34.493° N, longitude 73.629° E and a focal depth of about 26 km (United States Geological Survey). The event proved to be a major disaster claiming more than 80,000 lives in Pakistan and India. It was followed by several aftershocks of magnitude greater than 5.0 in the vicinity of the main shock, about 110 in 27 days. Interestingly, the clustering of the aftershocks is roughly 50 km to the NW of the main shock (Fig. 1). The largest aftershock had a magnitude of about 6.3. More aftershocks are expected to occur in the months to come. The earthquake source mechanism of the 8 October 2005 earthquake is a thrust fault mechanism with a NNE oriented principal compressive stress axis direction (Harvard University) typical of the Himalayan region (Fig. 1). However, the fault plane dips at an angle of 29° northeastward, steeper than those along the Himalayan arc. Even the aftershocks of this event, with magnitudes varying from 5.0 to 6.3 (Table 1) have similar focal mechanism, with dips as high as 45°. Stress inversion of these focal mechanisms indicates their distinction from the mechanisms of the neighbouring Himalayan front, Pamir and Hindukush regions.

The occurrence of the 8 October earthquake in the western segment of the Himalaya provides an opportunity to re-evaluate the hazard potential of the Himalayan belt that witnessed several great earthquakes in the past. Inversion of focal mechanisms of the Harvard CMT catalogue indicates distinct stress patterns in the Muzaffarabad region, corresponding to the overturned configuration of the MBT and MCT thrusts, compared to the neighbouring Himalaya, Pamir and Hindukush regions. Recent developments in application of seismological tools like the receiver function technique have provided in unprecedented detail, the fine-scale structure of the collision front in the form of layering in the crust, delamination of upper and lower crust, mapping of the decollement surface and determination of its anisotropic character. Further, identification of lower crustal eclogitisation and delineation of dipping trends of the Moho and LAB of the Indian lithosphere underthrusting beneath southern Tibet has become a reality. These have significantly improved our understanding of the collision process by providing fresh insights into the mechanism of Himalayan orogeny and uplift of the Tibetan plateau besides providing vital constraints on the seismic hazard that the Himalaya presents.

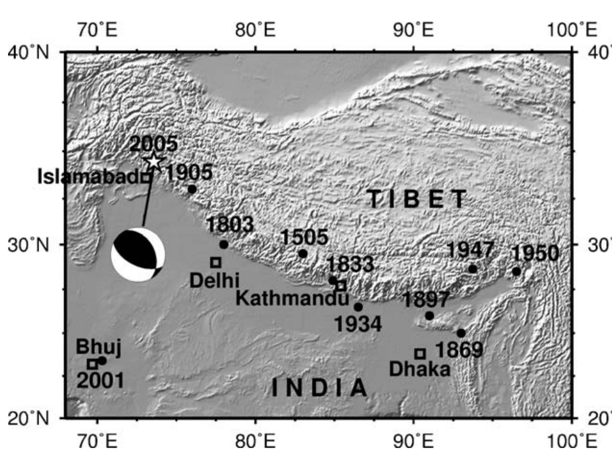

Fig. 1. Topography map of the Himalayan region indicating the significant earthquakes since historical times, including the recent Muzaffarabad earthquake of 8 October 2005 along with its focal mechanism.

In the present study we examine variations in the stress field, seismicity patterns, seismic source character, tectonic setting, geodynamic parameters like plate motion velocities, geometry of the underlying subsurface structure and its role, if any, in generation of very large earthquakes and draw constraints from available geodetic data to evaluate the seismic hazard of these spatially separated segments of the great Himalayan mountain system.

2. Geology and tectonics

The Himalayan orogen stretches over a 2500 km range, from Kashmir in the West to Arunachal in the East. Broadly it may be classified into four lithotectonic units — the Outer Himalaya, the Lesser Himalaya, the Greater Himalaya and the Tethyan Himalaya (Gansser, 1964; Valdiya, 1980, 1992; Hodges, 2000) (Fig. 2). The Outer Himalaya is the southernmost unit bordering the Indo-Gangetic plains, and comprises folded and faulted Siwalik molasse sediments of Miocene age. The Lesser Himalaya is the higher mountain belt further north reaching an elevation of about 2000 m on an average. It comprises fossiliferous Riphean sediments covering a lateral sequence of thrust sheets that jumped from north to south in course of the great continent–continent collision. The Greater Himalaya comprises the highest mountain range reaching up to 6000 m, and primarily consists of crystalline rocks. Further north lies the Tethyan Himalaya comprising fossiliferous sediments of Precambrian to Cretaceous age, bordering a suite of ophiolite and mélange that represent the India Eurasia suture. The region

Table 1
A list of the mainshock and aftershocks of the 8 October 2005 Muzaffarabad earthquake with magnitude greater than 5.0 (source: United States Geological Survey)

Date and Time	Lat	Lon	Depth	Mag
2005/10/08 03:50:40.6000	34.476	73.577	26	7.7
2005/10/08 04:02:24.2000	34.483	73.245	10	5.7
2005/10/08 04:26:11.2000	34.643	73.152	10	5.8
2005/10/08 05:08:41.4000	34.681	73.28	10	5.5
2005/10/08 05:19:48.1000	34.699	73.137	10	5.6
2005/10/08 05:26:05.0000	34.726	73.149	10	5.5
2005/10/08 05:34:52.6000	34.222	73.586	10	5
2005/10/08 06:15:24.3000	34.508	73.399	10	5.5
2005/10/08 06:42:30.5000	34.621	73.523	10	5.4
2005/10/08 08:21:51.9000	34.748	73.187	10	5.2
2005/10/08 09:01:55.1000	34.601	73.234	10	5.2
2005/10/08 09:36:50.8000	34.228	73.946	10	5
2005/10/08 10:16:58.1000	34.706	73.069	10	5.1
2005/10/08 10:46:29.3000	34.735	73.149	10	6.3
2005/10/08 11:28:42.2000	34.641	73.272	10	5.3
2005/10/08 11:33:33.7000	34.702	73.173	10	5.5
2005/10/08 12:08:28.1000	34.568	73.177	10	5.5
2005/10/08 12:25:22.1000	34.785	73.141	20	5.9
2005/10/08 12:44:51.6000	34.733	73.209	10	5.3
2005/10/08 13:46:01.0000	34.611	73.161	10	5.1
2005/10/08 19:08:00.6000	34.754	73.266	10	5
2005/10/08 21:45:09.6000	34.59	73.149	10	5.5
2005/10/08 22:04:27.0000	34.563	73.266	10	5.1
2005/10/09 04:58:54.5000	34.655	73.062	10	5.1
2005/10/09 07:09:18.5000	34.538	73.153	10	5.5
2005/10/09 08:30:00.6000	34.559	73.135	7	5.8
2005/10/09 12:38:14.0000	34.784	73.155	10	5.1
2005/10/09 14:56:47.5000	34.75	73.402	10	5
2005/10/09 19:20:37.4000	34.336	73.743	10	5.4
2005/10/09 19:47:01.4000	34.697	73.005	10	5.1
2005/10/10 12:38:11.9000	34.735	73.072	10	5
2005/10/12 20:23:38.4000	34.871	73.095	10	5.6
2005/10/13 20:49:21.9000	34.681	73.112	10	5.3
2005/10/14 19:37:41.8000	34.788	73.079	10	5.1
2005/10/17 10:43:11.8000	34.824	73.143	35	5.1
2005/10/19 02:33:29.4000	34.789	72.993	10	5.7
2005/10/19 03:16:21.4000	34.768	73.038	10	5.6
2005/10/19 12:47:27.8000	34.712	73.137	10	5.1
2005/10/23 15:04:20.7000	34.834	73.01	10	5.6
2005/10/24 13:14:20.0000	34.931	73.188	35	5
2005/10/26 01:42:41.0000	34.122	73.945	10	5
2005/10/28 21:34:14.5000	34.671	73.141	10	5.5
2005/11/06 02:11:52.6000	34.443	73.381	10	5.3

Depths indicated as ‘10’ are fixed values.

further north is referred as the Trans-Himalaya. The significant east–west tectonic features separating these litho-units are the Main Central Thrust (MCT) separating the Greater and Lesser Himalaya, the Main Boundary Thrust (MBT) bordering the Lesser and Outer Himalaya, and the Main Frontal Thrust (MFT) confining the entire orogen from the south.

The general understanding is that initially active subduction occurred along the Indo-Tsangpo Suture Zone (ISZ) during the Mesozoic to Early Tertiary period, where in the oceanic Indian lithosphere subducted beneath the Tibetan landmass. Subsequently, with the collision of India and Asia during Eocene, active subduction ceased, paving way for underthrusting of the Indian subcontinent along intracontinental thrusts during Middle Tertiary. Seeber and Armbruster (1981) postulated a gently dipping thrust plane going underneath the Indo-Gangetic plains, the Outer and the Lesser Himalaya, referred as the detachment plane that coincides with the upper surface of the subducting Indian lithosphere. The MBT and MCT that dip steeply near the surface are believed to flatten out at depth, merging with this detachment plane, contemporarily hosting most of the earthquakes (Ni and Barazangi, 1984). The total convergence between India and Asia is estimated to be about 2000–3000 km of which about 300–500 km seems to have occurred along the Himalaya (Molnar et al., 1977).

The Himalayan arc is bound by complex syntaxial bends both in the west and east. The western syntaxis is characterized by a complete overturn of the MBT and MCT, further bound by a complex system of thrusts, mainly the Pamir and the Hindukush to the north and west, respectively. Unlike in the Himalaya, these are zones of intense seismicity in the shallow to intermediate depth range. The seismicity trend delineates two separate segments dipping in opposite directions, leading to controversial interpretations of whether it results from a single contorted slab or two separate slab segments. Further down south-west lies the India–Arabia plate boundary comprising a slow left lateral strike-slip faulting. The eastern Himalayan syntaxis formed by the EW trending India–Eurasia plate and NS trending India–Burma plate margins is one of the most complex and seismically active regions. The syntaxis region has witnessed the largest ever Himalayan earthquakes, each of magnitude about 8.7 in 1897 and 1950.

3. Great earthquakes and hazard in the Himalaya

The Himalayan front has been the site of some of the world’s most disastrous earthquakes. Notable among them during the last century or so, are the 1897 Shillong (M~8.7), 1905 Kangra (M~7.8), 1934 Bihar–Nepal (M~8.3), 1950 Assam (M~8.7) and the recent 2005 Muzaffarabad (M 7.6) earthquakes. Significant historical earthquakes include those in 1255 and 1411, and two in the central Himalaya, in 1505 and 1803. Several destructive earthquakes also took place in the intra-plate or the stable continental part of the Indian shield region. They are the 1967 Koyna (M 6.3), 1969 Bhadrachalam (M 5.7), 1993 Latur (M 6.3), 1997 Jabalpur (M 5.8) and 2001 Bhuj (M 7.6) earthquakes. Fig. 3 shows the spatio-temporal distribution of historical earthquakes of magnitude ≥ 7.0) in the Himalaya since 1200 A.D.

The quiescence in the Himalayan region since 1950 (Satyabala and Gupta, 1996), in terms of earthquakes of magnitude greater than 8.0 has been a matter of great concern, with expectation of large earthquakes in the immediate future, especially in the central part of the Himalaya (Bilham et al., 2001). While it is well understood that the main causative mechanism of earthquake generation is the ongoing collision between the India and Eurasia plates, the mode of underthrusting and the sequence of convergence of various segments of the arc is not well understood. With a number of highly populated megacities coming up in the fertile Indo-Gangetic plains, the fear of the next large earthquake in the Himalayan front has always been a matter of grave concern. Studies related to

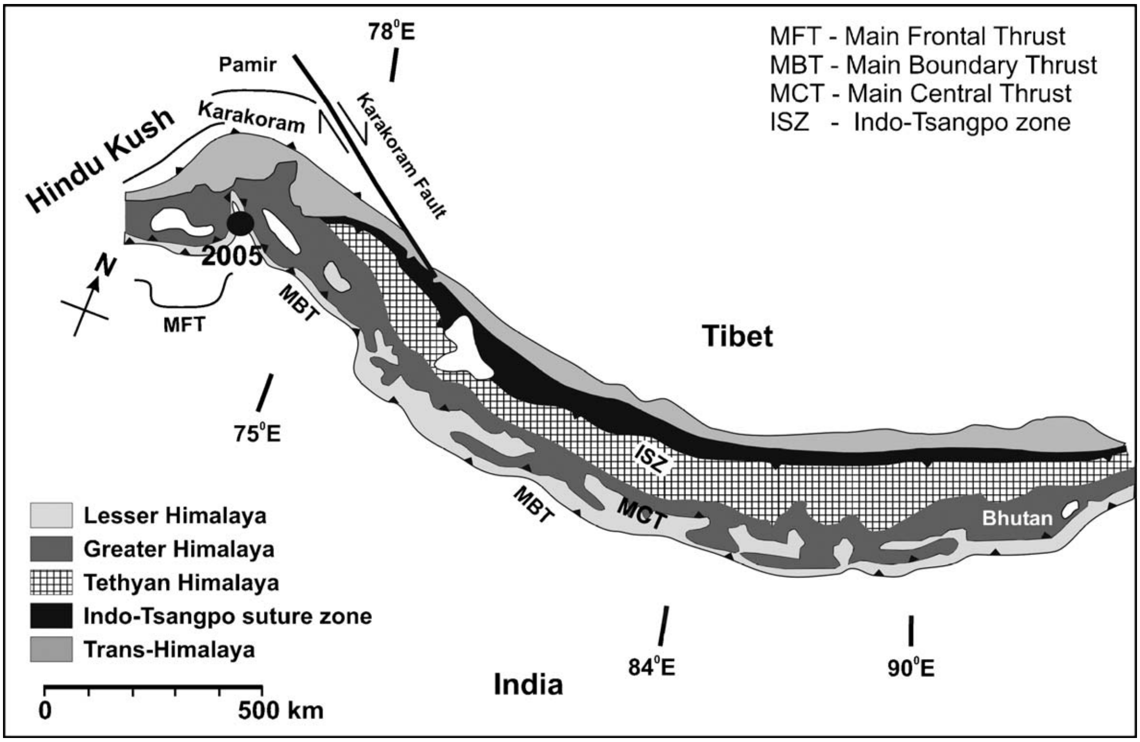

Fig. 2. Geological and tectonic map of the Himalayan region (modified after Hodges, 2000).

earthquake focal mechanisms reveal the ambient stress patterns and modes of failure besides enabling us to identify favourable environments for earthquake occurrence governed by the stress–strain interplay.

4. Focal mechanisms in the Himalaya

The most characteristic feature of the earthquake focal mechanisms in Himalaya is their shallow (5–10°) north dipping thrust fault planes with a shallow distribution of focal depths. Clearly these are distinct from the focal mechanisms in the adjoining regions (Fig. 4). The Tibetan plateau in the north is dominated by shallow to intermediate depth seismicity with normal faulting along NS trending fault planes and strike-slip motion along EW planes. These mechanisms clearly accommodate the eastward extension of Tibetan crust in response to the underthrusting of India beneath Eurasia (Tapponier and Molnar, 1977). The focal mechanisms in the Pamir–Hindukush

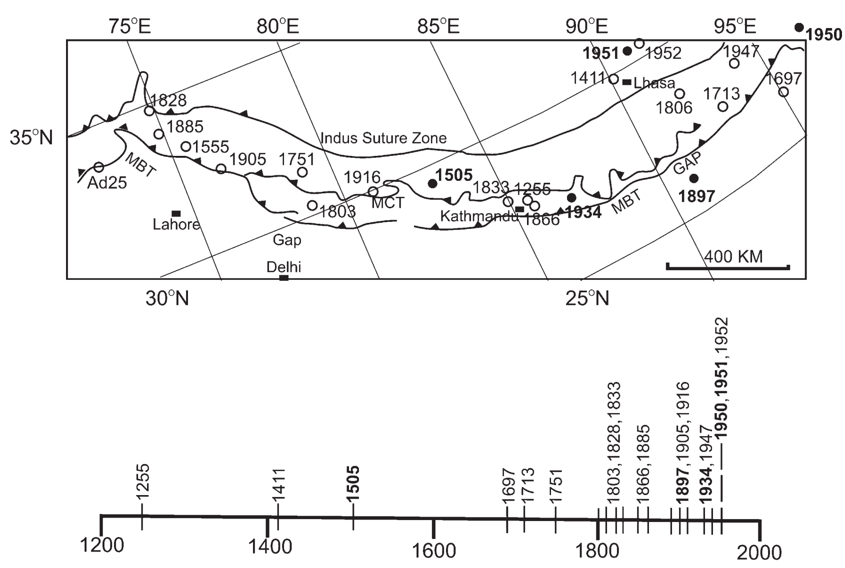

Fig. 3. Space–Time distribution of very large and great earthquakes in Himalaya since historical times along with the year. Bold text/filled circles represent earthquakes with $M \geq 8.0$ while normal text/unfilled circles represent earthquakes with M 7.0–8.0. (modified after Rajendran and Rajendran, 2005).

stretch are mostly thrust and strike-slip type with the principal compressive stress axis oriented NNW, unlike in the Himalaya. Further east, the focal mechanisms in the Burmese arc display a unique segregation of strike-slip type mechanisms in the upper 90 km and thrust type mechanisms below 90 km, along the eastward dipping Indian lithospheric slab (Kumar and Rao, 1995). Interestingly, the P axis remains oriented predominantly in the NNE direction, rather than the eastward direction of slab dip. Based on a comparison with subduction zones worldwide, Rao and Kumar (1999) demonstrated that subduction in the Burmese arc has come to an end in the recent times and has been replaced by a strike-slip environment, where the Indian plate along with its eastward dipping lithospheric slab is being dragged northward.

The focal mechanism of the 8 October 2005 Muzaffarabad earthquake indicates thrust faulting along a NNW oriented fault plane (Fig. 4, inset) and a NNE oriented principal compressive axis trend, quite common to the Himalayan earthquakes. However, the dip angle of 29° estimated by the Harvard University is much higher than the observed shallow dip of 5–15°, typical of Himalayan earthquakes. Kumar et al. (1998) demonstrated that in the Himalaya the dip of the north dipping fault plane of the thrust earthquakes increases from about 5° in the west to about 40–50° in the east. However, it can be seen

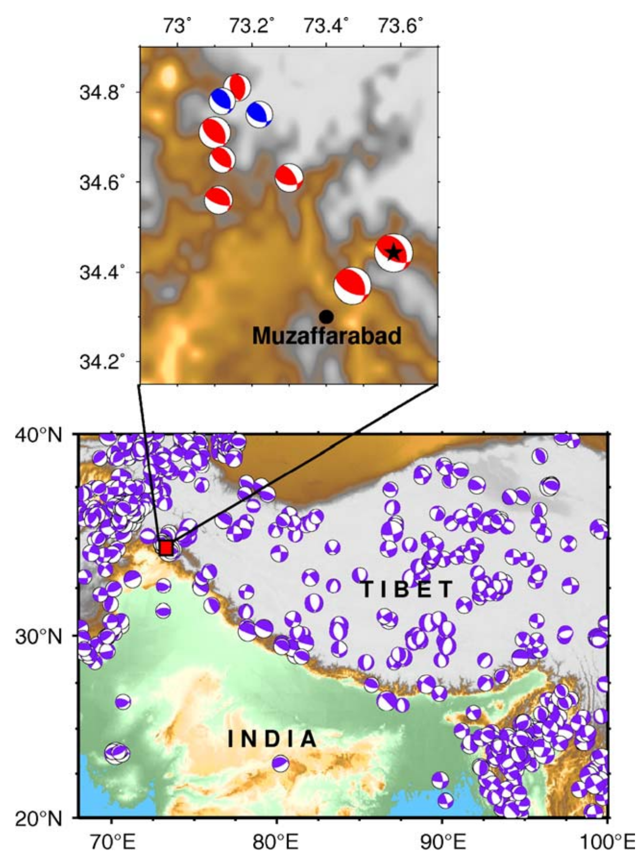

Fig. 4. Focal mechanism solutions of earthquakes in the Himalya, Tibet, Pamir and Hindukush regions, from the Harvard CMT catalogue. Inset: a close up of the Muzaffarabad region indicating the focal mechanisms of the 8 October 2005 Himalayan earthquake and its aftershocks. The blue coloured mechanisms correspond to earthquakes prior to the 8 October 2005 event.

that although the recent earthquake of 8 October 2005 and its aftershocks occurred in the westernmost part of the Himalayan arc, they seem to be quite distinct with fault planes dipping as much as 45° (Fig. 5). In the past, hardly two earthquakes are known to have occurred with this mechanism prior to the 8 October 2005 event. A few earthquakes with such steep dipping fault planes were reported earlier in the Garhwal–Kumaon Himalaya (Branowski et al., 1984; Ni and Barazangi, 1984) that were believed to be associated with duplexes under the Lesser Himalaya (Srivastava and Mitra, 1994). In view of the distinct, steep dipping fault planes associated with the recent Muzaffarabad earthquake, a characteristic rare to earthquakes of the Himalayan front, we embark upon a detailed study of stress field in each of the significant segments of the Himalaya using the source mechanism data.

5. Stress inversion and *p*-value

In the present study we invert focal mechanisms of the Himalayan region obtained from the Harvard CMT catalog, using the linear least squares inversion approach of Michael (1984, 1987) to obtain the best fitting compressive ($\boldsymbol{\sigma}_1$), intermediate ($\boldsymbol{\sigma}_2$) and tensile ($\boldsymbol{\sigma}_3$) stress field vectors. The inversion method provides the option of using a set of single planes in case of a priori knowledge of the true plane or both the planes of each focal mechanism in case of ambiguity. The accuracy of the results are tested by using the standard Bootstrap technique, where inversion is carried out with 2000 resamples to get a 95% confidence region for each of the 3 vectors.

The stress inversion is carried out for the Hindukush, Pamir, Himalaya and the Muzaffarabad regions separately to understand the changes in the stress field. Fig. 6 indicates the results of stress inversion and the confidence regions of the $\boldsymbol{\sigma}_1$, $\boldsymbol{\sigma}_2$ and $\boldsymbol{\sigma}_3$ axes in each case. The Hindukush and Pamir regions indicate a similar NNW oriented $\boldsymbol{\sigma}_1$ direction. However, while the former is dominated by a near vertical $\boldsymbol{\sigma}_3$ axis corresponding to slab pull in a highly inclined Hindukush subduction zone, the latter indicates sub-horizontal $\boldsymbol{\sigma}_1$ and $\boldsymbol{\sigma}_3$ axis orientations (Fig. 6a, b). The Himalayan arc displays a NNE oriented $\boldsymbol{\sigma}_1$ axis in conjunction with the direction of the ongoing India–Eurasia collision (Fig. 6c). Interestingly, the stress field governing the recent Muzaffarabad earthquake and its aftershocks (Fig. 6d) appears distinct from those occurring along the Himalayan front like the 1991 Uttarkashi or the 1999 Chamoli earthquakes, and are in fact, more in conjunction with the intraplate earthquakes of the Indian shield region, like the 1993 Latur, 1997 Jabalpur or the 2001 Bhuj earthquakes. In view of the above, it would be interesting to study the aftershock decay pattern given by the *p*-value of this earthquake in comparison to other significant events in the past. The *p*-value is an important parameter that characterizes a seismogenic region and is based on the modified Omori's law (Utsu, 1961)

$$n(t) = K/(t+c)^p \tag{1}$$

where K and c are constants. The *p*-value signifies information about the local stress conditions and heterogeneity of the rocks.

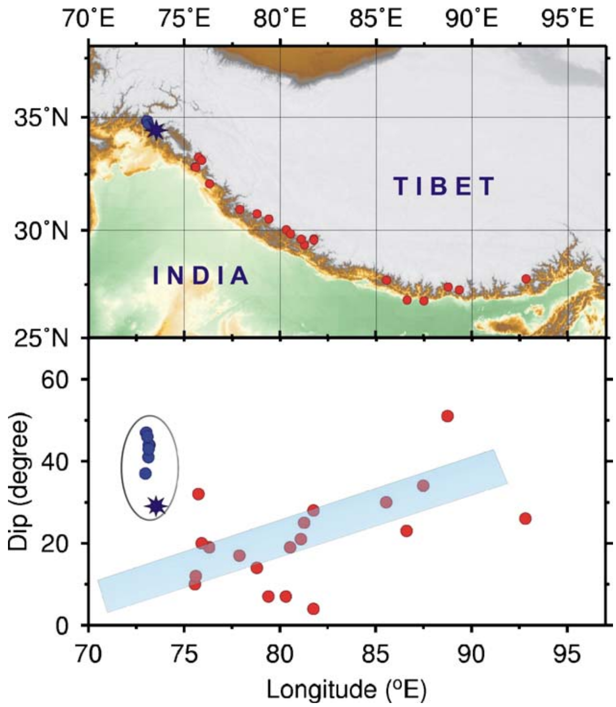

Fig. 5. Variation of the dip angles of the shallow northward dipping fault planes of Himalayan earthquakes, from west to east. Note that the recent Muzaffarabad earthquake of 8 October 2005 and its aftershocks, all have steeply dipping fault planes and fall in a cluster separate from the observed average trend for typical Himalayan earthquakes.

The rate of decay of aftershocks is considered to be normal if the p-value is equal to 1. A slow decay is indicated for $p<1$ while a fast decay of aftershocks is given by $p>1$. In general the p-values are found to be low for the Indian peninsular (~0.5) and high for the Himalayan earthquakes (~1.7), with some exceptions like the 1991 Uttarkashi and the 1999 Chamoli earthquakes (Jain, 2005). The p-value for the 8 October 2005 earthquake is computed using 110 aftershocks with a magnitude threshold of 3.0. A low value of 0.9 is obtained (Fig. 7) much closer to that of the Indian shield earthquakes. Incidentally the p-value of the 1993 Latur earthquake was also 0.9 (Baumbach et al., 1994) similar to that of the Muzaffarabad earthquake. However, in view of the continuing aftershock activity the estimated p-value is not final, but considering stationarity of the physical process involved, the governing distribution is unlikely to change drastically.

It is interesting to note that the 8 October 2005 Muzaffarabad earthquake occurred in a distinct tectonic setup, enveloped by overturned thrust belts in the western Himalaya (Fig. 2) surrounded by the Himalayan arc in the east, the Pamir and the Hindukush regions to the north and west, respectively. The stress pattern in this region, therefore, appears to be a resultant of the complex interplay of these three tectonic zones with respect to the Indian shield in the south. This is quite evident from the distinct focal mechanism types, results of stress inversion and also the intermediate p-value obtained from analysis of the aftershock data. This raises an important question whether the recurrence pattern of large earthquakes in the western Himalayan syntaxis is governed by the stress accumulation and strain release pattern depending on the Indian plate motion along the Himalayan arc, or is it controlled mainly by the complex variation of crustal structure in the vicinity.

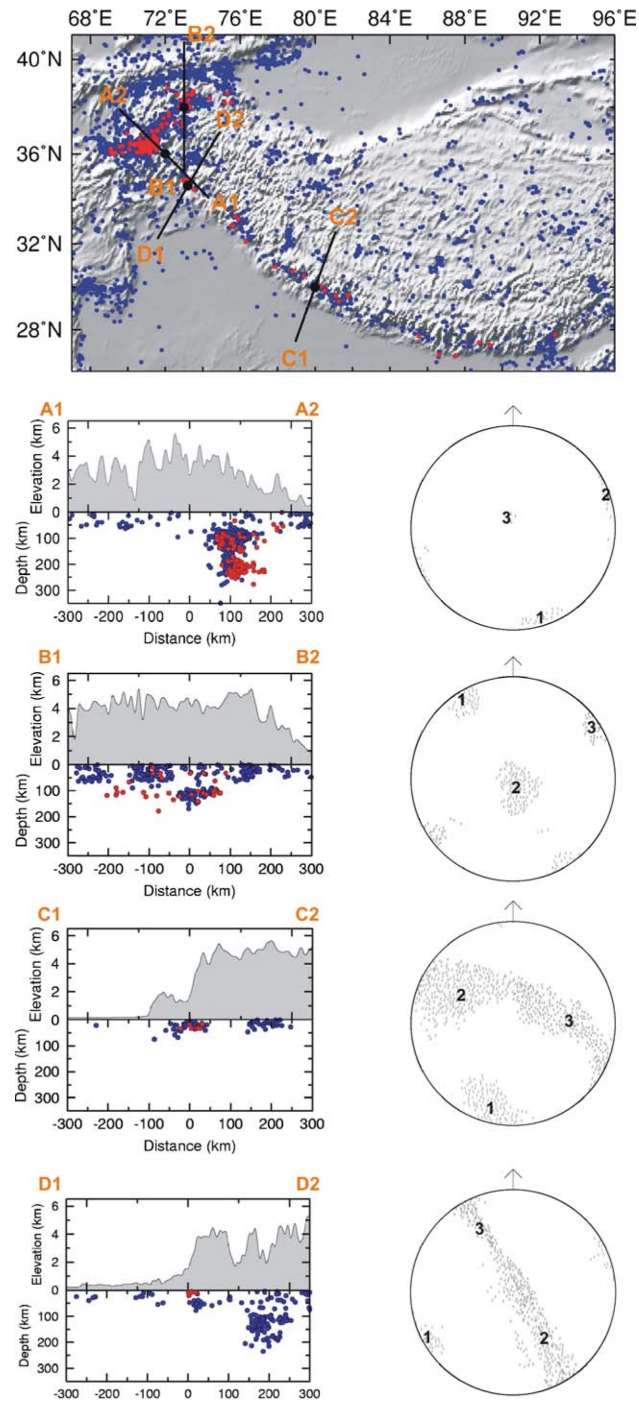

Fig. 6. Results of stress inversion of focal mechanism data in the (a) Hindukush, (b) Pamir, (c) Himalayan front and (d) Muzaffarabad regions using the method of Michael (1984, 1987). Also shown on the left are the depth sections corresponding to profiles cutting across each of these regions. Red and blue circles indicate the earthquake locations. Red circles are the data used for inversion in this study in view of focal mechanism data available from the Harvard CMT catalog.

6. Crustal structure

Knowledge of the crustal structure along various segments of the Himalaya and its impact in understanding the genesis, recurrence of large devastating Himalayan earthquakes remained largely obscure till recently due to absence of detailed images of the crust, and poor information of the underlying lithospheric disposition. As large Himalayan earthquakes typically occur in the shallow regimes of the crust with a possible causal linkage to their deeper domains, knowledge of the finer crustal structure, its disposition and nature assumes both importance and significance. Fortunately, the last few years have witnessed a quantum jump in our understanding of the crust–mantle structure beneath the Himalaya and Tibetan plateau regions due to major international collaborative initiatives like International Deep Profiling of Tibet and Himalaya (INDEPTH) etc involving the USA, Germany, Canada, China and France (Nelson et al., 1996). Through innovative experimental design using powerful probing techniques like the 'receiver function' based on P-to-S and S-to-P converted phases, the crust and stratified nature of the lithosphere/mantle beneath various segments of the Himalaya have been imaged with unprecedented detail (Yuan et al., 1997; Kind et al., 2002; Kumar et al., 2005; Ramesh et al., 2005; Kumar et al., submitted for publication).

Most studies of crustal structure in the Himalayan region have been confined to the Tibetan plateau. The first study to estimate crustal thickness using surface wave dispersion in the Tibetan Plateau and Himalaya was by Gupta and Narain (1967) who estimated a double thickness of up to 70 km. With the advent of broadband data, important findings followed with the identification of a low velocity zone in southern Tibet and several discontinuities in the crustal layering (Yuan et al., 1997; Kind et al., 2002). Further south, not many studies have been reported for the Himalayan front, due to inaccessibility of the region and non-availability of seismological networks. But more recently, using a network of broadband stations in northeast India, Ramesh et al. (2005) imaged the crust and mantle beneath the eastern Himalaya using P receiver functions. Clearly, a northward dipping Moho in the Himalayan foredeep is observed at a depth of about 30 km, which deepens to about 50 km further north beneath the Himalayan convergence zone (Fig. 8A). An important outcome of their studies is the detection of an additional upper mantle discontinuity at depths of 280–300-km, whose impact and role in the dynamics of the eastern Himalaya remain to be investigated. In general, the Indian lithosphere in the eastern Himalaya seems to be undergoing a shallow angle subduction.

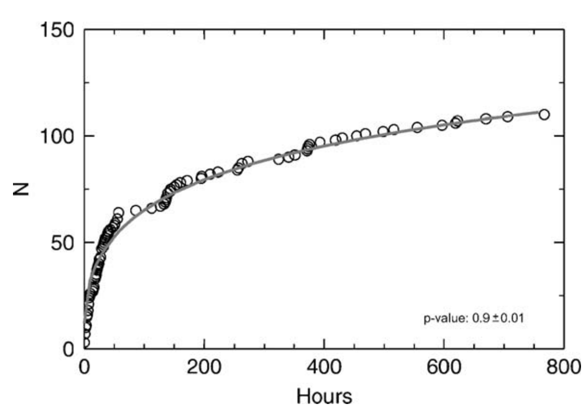

Fig. 7. p-value for the aftershock sequence of the 8 October 2005 Muzaffarabad earthquake using 110 aftershocks in magnitude range of 5 to 6.3.

Using a dense network of broadband stations in Nepal, Central Himalaya, Schulte-Pelkum et al. (2005) studied the crustal structure in detail and suggested the presence of a strong anisotropic zone (20%) above the brittle–ductile region in the Indian crust that coincides with the decollement just south of the Greater Himalaya (Fig. 8B). The large magnitude (20%) of such strong anisotropy whose origin lies in ductile deformation at depths of about 20–30 km clearly indicates localization of very large strain accompanied by significant pure shear that spawn the giant slips required to generate great earthquakes at shallow depths, acting as stress-accentuators. The presence of such asperities capable of retaining large strain energy are characteristic of megathrusts, in this case the imaged decollement surface, such as the MBT and MCT that may or may not coincide with the decollement surfaces.

In the western Himalaya, most of the studies are confined to the Pamir–Hindukush region (Pandey et al., 1991; Sandvol et al., 1994) while there is scanty data from the recent earthquake region. Available sparse data do not indicate any spectacular structural heterogeneities in the crust or upper mantle of the order discussed for the eastern Himalaya above. More recently the S-to-P receiver function technique has emerged as a powerful tool (Farra and Vinnik, 2000) especially to image the Lithosphere–Asthenosphere Boundary (LAB) in addition to the Moho. For instance, in the Tien-Shan–Karakoram region in western Himalaya, Kumar et al. (2005) mapped the crust, upper mantle and LAB structure that provides direct seismic evidence of continental subduction in the Karakoram region with the crustal thickness of ~80 km and the LAB at a depth of ~120 km (Fig. 8C). The clear dipping of the Asian lithosphere beneath the cold and strong Indian lithosphere is interpreted as evidence for continental subduction of the Asian lithosphere, an inference that is also supported by tomography studies (Friederich, 2003). This strongly suggests that the Indian lithosphere retains its identity till at least just north of Karakoram where it meets the subducting Asian lithosphere, testifying its mechanically strong character unlike in the eastern Himalaya where its traceability and northward limit has always remained dubious. Conceding similarities in tectonic and geodynamic ambience of the western and the eastern Himalaya, presence of a less deformed crust overlying a mechanically strong lithosphere, and with the absence of large-scale heterogeneity/asperity in the crust with a genetic link to the deeper domains, the essential ingredients to generate great earthquakes in the western region seem to be missing. It is therefore important to map the nature and configuration of the decollement to understand their role in Himalayan earthquake genesis.

It seems from the above that megathrusts hold the key to spatial disposition of occurrence of the great earthquakes in the Himalaya. Several recent studies (Shipley et al., 1994; Bilek

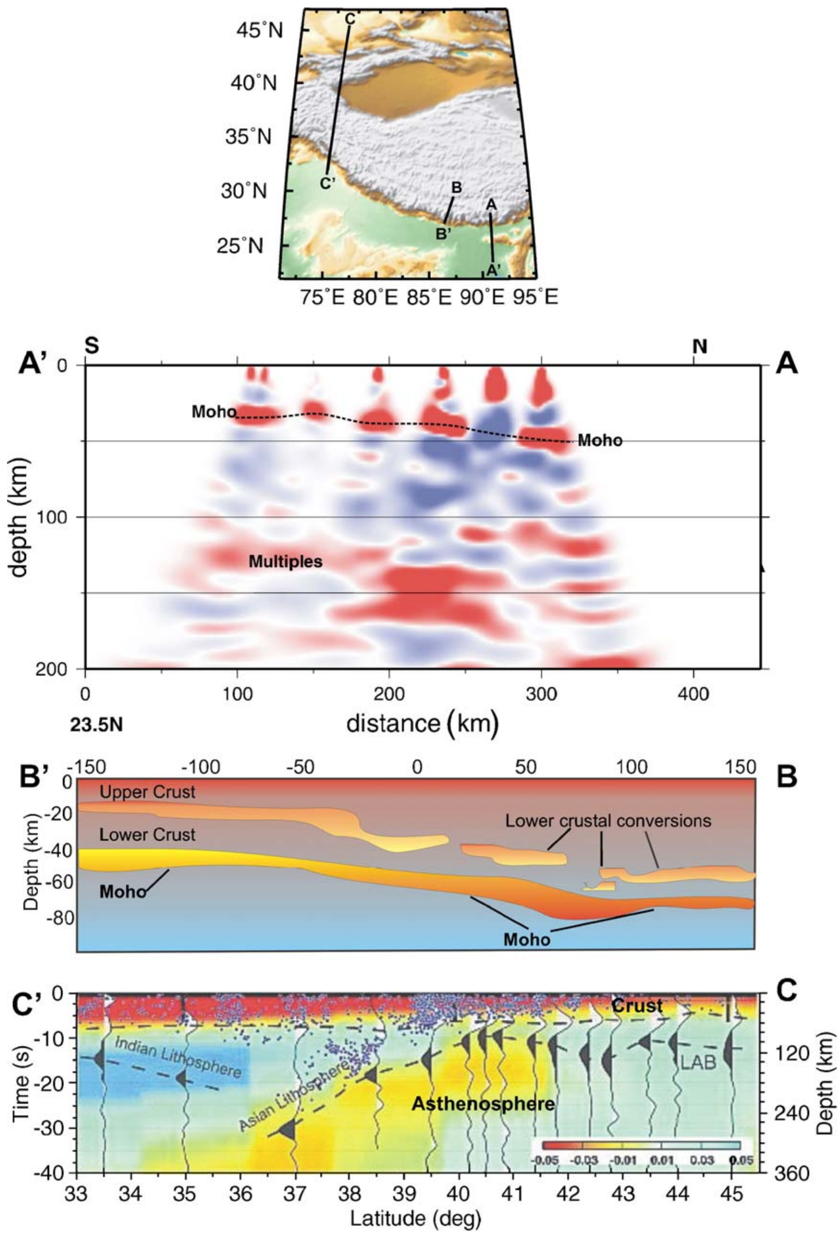

Fig. 8. Depth sections of crustal models in the Himalaya obtained from recent studies of receiver function along 3 profiles in (A) Eastern Himalaya using P-to-S converted phase (modified after Ramesh et al., 2005), (B) Central Himalaya using P-to-S converted phase (modified after Schulte-Pelkum et al., 2005), (C) Western Himalaya using S-to-P converted phase (modified after Kumar et al., 2005).

and Lay, 1998; Nedimovic et al., 2003; Nakanishi et al., 2004) have neatly summed the character of megathrusts and identified them to be made up of three distinct asperity–nonasperity zones: an up dip aseismic zone, a locked seismogenic zone where large slips associated with mega-magnitude rupture would occur followed by an active earthquake release zone at the down dip section. These zones interestingly possess different physical states and properties and hence can remain elusive from getting mapped by various geophysical tools. Imaging this intriguing nature of the sub-elements of the megathrusts is a real challenge to be overcome by earth scientists. Potentially, the geodetic measurements have the promise to at least provide a glimpse of the transition from locked to stable sliding regions on the megathrusts. However, there are other problems that plague these measurements. In any case, it should be interesting to distil similar information about the crust from the western Himalaya to make a meaningful comparison with the eastern counterpart, especially in the context of the much-awaited great earthquake in the postulated seismic gaps.

7. Plate motion modeling and GPS studies

Numerical modeling of relative plate motions (e.g., DeMets et al., 1990, 1994) is based on spreading rates derived from magnetic reversal patterns encrypted on the sea floor across spreading ridges, as well as spreading directions obtained from transform faults and earthquake slip vector data along plate boundaries. The relative motion of the Indian plate with respect to the Eurasian plate, obtained through this kind of modeling is best described by an Euler pole at latitude 28.4° and longitude 93.4°, with an anticlockwise rotation. Consequently, the India–Eurasia plate velocity varies from about 4.5 cm/year in the western Himalaya to about 5.5 cm/year in the eastern Himalaya (Guptasarma et al., 1991). However, only a small portion of this convergence is actually consumed between India and southern Tibet, with the remainder accommodated in Tibet further north. Global positioning System (GPS) measurements carried out extensively in the Nepal region (Larson et al., 1999) constrain the convergence rates across the Nepal Himalaya to about 18±2 mm/year indicating that about 2 cm/year of strain is accumulating across the locked portion south of Greater Himalaya. These results indeed show reasonable correspondence with the inferences derived from images obtained by receiver function analysis that reveal the special structure capable of storing large amounts of strain at shallow depths that can be taken up as slip in great earthquakes at later times. Three-dimensional modeling indicates that the detachment fault is locked over about 140 km width, along a 500 km stretch of Nepal Himalaya. Further, an eastward extension across southern Tibet, at a rate of about 11±3 mm/year between northwestern Nepal and Lhasa is reported. Broadly, portions of southern Tibet are getting displaced eastward along the right lateral Karakorum–Jiali fault zone and the left-lateral Kunlun and Xianshuihe–Xiaojiang faults (Larson et al., 1999).

8. Strain rates and velocity field

Seismic strain rates were previously computed using the scalar seismic moment along with slip vector estimates from historical data. A slip rate of 2–3 cm/year in the dip direction of the inferred decollement in the Himalaya was reported by Seno and Eguchi (1983). Using the summation of seismic moment tensors (Kostrov, 1974) with modern digital data, a convergence of 1.8–2 cm/year in the Himalayan arc region was inferred (Molnar and Deng, 1984; Ekstrom and England, 1989). In the Tibetan plateau region, the strain rates were computed by Holt et al. (1991) through summation of moment tensor elements for a period of 25 years using modern data, and for 85 years including historical data. Broadly, a NS contraction of 4 mm/year and an EW extension of 11 mm/year are indicated. Extension during continental convergence is not an inevitable consequence of crustal thickening. In the case of Tibet, England and Houseman (1989) suggest potential energy changes associated with convective thinning mechanism at the base. Three-dimensional finite element method (FEM) modeling of the deformation and stress field in the Himalaya–Tibetan plateau region was performed by Sato et al. (1996). The study indicates that the Tibetan plateau in the North is experiencing an EW extension of about 6 mm/year and a maximum uplift of 4 mm/year at the Greater Himalaya, in the southern fringe of the plateau. In the Tibetan plateau, the computed stress field agrees well with the strike slip faulting within the plateau, but not with the normal faults observed in the southern part. Strain rate computation by Rao et al. (2003) indicates predominant crustal thickening in the Himalaya with a clear transition to crustal thinning in the Tibetan plateau region, just across the Indo-Tsangpo suture zone where EW extension is the predominant mechanism. The computed strain rates are in the ratios of $-4:1.6:2.4$ and $-4:14:-10$ for Himalaya and Tibet, respectively, indicating a model of thinning seismic upper crust in the EW direction decoupled from a thickening aseismic lower crust, both in equilibrium, in the Tibetan plateau. Incidentally, results discussed from the receiver function analysis in the central Himalaya indeed succinctly bring out decoupling/detachment of the upper part of the Indian crust along the decollement (base of the delineated anisotropic zone) from the deeper portion and its incorporation into building of the Himalaya, while the decoupled lower part continues its descent beneath Tibet.

9. Discussion

The 8 October 2005 Muzaffarabad earthquake had a magnitude M_w of 7.6 at an estimated focal depth of about 26 km according to the United States Geological Survey. Modeling of broadband waveform data (Yamanaka, 2000) indicates an almost simple triangular source time function, with a duration of about 30 s, and rupture on a fault plane about 50 km long. The focal mechanisms of the 8 October 2005 Muzaffarabad earthquake and its aftershocks are found to be distinct from those of the Himalayan arc. In fact they appear comparable to the typical intra-plate earthquakes of the Indian shield, like the 1993 Latur, 1997 Jabalpur and the 2001 Bhuj earthquakes which have thrust type focal mechanisms with steeper fault planes than those seen for the Himalayan thrust earthquakes like the 1991 Uttarkasi or the 1999 Chamoli earthquakes. Even the stress fields inferred for these two regions are found to be different, possibly indicating that the Muzaffarabad region entangled in the western syntaxial fold belt enveloped by the MBT and MCT is not a simple continuation of the standard seismogenic decollement surface of the Indian plate beneath the Himalaya. For an earthquake of magnitude 7.6, the terrible loss of more than 80,000 lives is unbelievable, and can certainly be attributed to the poor standards of building construction — a major challenge facing the highly populated earthquake prone regions in developing countries, in general.

9.1. Seismic hazard of the Himalayan region

The Seismic zonation map of India brought out by the Bureau of Indian Standards, Government of India (IS 1893, 2002) clearly indicates that the Himalayan region, including the northeastern states of India, as well as the Kutch region in western India that experienced the world's deadliest intra-plate earthquake in 2001 (Gupta et al., 2001), fall in zone V, the zone of highest seismic hazard in India. The probabilistic seismic hazard map of India and adjoining regions prepared under the Global Seismic Hazard Assessment Programme (GSHAP) of the United Nations (Bhatia et al., 1999) indicates a Peak Ground Acceleration (PGA) of 0.25–0.3 g in parts of Himalaya, up to 0.35–0.4 g in the Burmese arc and northeast India, and a maximum of 0.5 g in the Pamir–Hindukush regions.

Assessment of seismicity in the Himalaya during the last two centuries by several researchers indicates a very alarming hazard situation for the years to come. Seeber and Armbruster (1981) estimated the rupture extents of great earthquakes in western Himalaya and identified a seismic gap — an unruptured segment lying between the segments of the 1885 and 1905 earthquakes. Based on analysis of space–time seismicity patterns, Khattri (1987) identified three seismic gaps in the Himalaya. They are (1) the Kashmir gap to the west of the 1905 Kangra earthquake, (2) the central gap between the 1905 Kangra and the 1934 Bihar–Nepal earthquakes, and (3) the Assam gap between the 1897 Shillong and the 1950 Assam earthquakes. He also indicated that these great earthquakes were both followed and preceded by long periods of seismic quiescence of about 20 years. Bilham et al. (2001) classified the Himalayan arc into 10 segments of ~220 km length each and assumed a convergence rate of about 2 m per century between Himalaya and southern Tibet based on analyses of river terraces (Lavé and Avouac, 2000) and GPS observations in Nepal Himalaya (Larson et al., 1999), with almost entire potential slip being elastic. Assuming an average slip of about 4 m for an 8.0 magnitude earthquake to occur, they infer that at least 6 of these portions are already due for a great earthquake. Further, based on reevaluation of lower magnitudes and rupture lengths of the 1833 Nepal earthquake (Bilham, 1995) and the 1905 Kangra earthquake (Ambraseys and Bilham, 2000; Wallace et al., 2005) they argue that if these earthquakes have released lesser strains than earlier believed, then a much greater threat of seismic hazard awaits the Himalayan foothills than that believed so far.

A view point contrary to the hypothesis of Bilham et al. (2001) arguing for possibly lower magnitudes of Himalayan earthquakes comes from Rajendran and Rajendran (2005). Based on analysis of macroseismic data of the 1505 and 1803 earthquakes in central Himalaya which indicates magnitudes lesser than 8.0, they infer that great earthquakes are probably rare in the Himalayan front with recurrence interval running into thousands of years. Further they propose that the detachment plane in the Himalayan front is too weak to store energy capable of generating great earthquakes and that only the higher level thrusts of the Himalaya are tectonically active. For further understanding of this issue, as the historical earthquake data becomes inadequate, it would be necessary to look for paleoseismological evidence in future. A few studies have been reported for the Shillong plateau region south of the eastern Himalaya (Sukhija et al., 1999).

9.2. Limitations of geodetic data

The geodetic based studies using recent GPS and past geodetic data from triangulation surveys in the Himalaya have significantly improved our understanding of earthquake recurrence and enhanced our insight into the seismic hazard of the region. However, estimates of hazard and grim warnings about the lurking great earthquakes ready to strike at any time in the Himalaya have largely stemmed from data based on the Great Triangulation Surveys during the British times, with a few supplements from recent GPS surveys. It may be noted that while GPS gives instantaneous deformation pattern, geodetic results provide long-term pattern, and in case of occurrence of large earthquakes in the intervening periods, the strain rates may be significantly contaminated leading to inconsistencies in estimation of long term and short term deformations. Hence, comparison of past geodetic data (long-term deformation), past seismicity data and present GPS measurements (current deformation) may be fraught with several errors, as is evident from case histories in California and Japanese islands (Sagiya et al., 2000). For example, the GPS measurements in Chugoku region of the Japanese islands yielded strain rates considerably smaller than in surrounding regions in spite of occurrence of at least three well recorded $M > 7$ earthquakes in the same district between 1872–1943. Hence, extrapolation of the present deformation pattern from GPS to a longer time period is not as straightforward as it is often made to be.

9.3. Plate junctions and great earthquakes

A careful examination of the seismicity pattern in the Himalayan front clearly indicates that great earthquakes ($M > 8.0$) are clustered near the eastern syntaxis rather than distributed along the arc (Fig. 3). This raises serious doubts about the possibility of occurrence, leave alone recurrence, of great earthquakes in central and western Himalaya. The eastern Himalayan syntaxis is a complex tectonic zone of multiple-plate interaction, where the Himalayan and the Burmese thrust zones have converged, managing to squeeze out the Shillong plateau by a pop-up uplift mechanism (Rao and Kumar, 1997; Bilham and England, 2001), resulting in the 1897 Shillong earthquake (M 8.7), the greatest ever in the Indian subcontinent. Another great earthquake that shook the India–China border region is the 1950 Assam earthquake (M 8.7) that occurred on a multiple plate junction comprising the India, Burma, Eurasia and Sunda plates. Recently Rao and Chary (2005) demonstrated that most of the world's largest earthquakes in the last century (10 out of 12) with magnitudes ranging from 8.5 to 9.5 tend to occur close to multiple plate junctions, since these junctions provide geometries capable of large stress build-up requisite for generation of great earthquakes. While the eastern Himalayan syntaxis with two earthquakes of magnitude close to 8.7 forms a good example, the recent Sumatran earthquakes of 26 December 2004 (M_w 9.0) and 28 March 2005 (M_w 8.7) also occurred on a similar multiple plate junction comprising the India, Burma, Australia and Sunda plates (Fig. 9). The only exceptions seem to be the great Alaskan earthquakes of 1957 and 1965 along the western Aleutian trench, which need a closer investigation.

9.4. Change in tectonic scenario

Seismotectonic studies have indicated a major change in the Indian plate scenario during the last few million years. The Himalayan continent–continent collision reached a saturation point after about 40 million years of existence, leading to a southward jump of the stress accumulating due to incessant plate collision. A diffuse deformation zone separating the India and Australia plates developed in the northeastern Indian Ocean region about 7 million years ago, owing to a greater resistance of the Indian plate at the Himalayan front as compared to a smoother subduction of a faster Australian plate at the Sunda trench (Stein and Okal, 1978). The new plate boundary is defined by extension in the west, convergence in the east and strike-slip motion along the Ninetyeast ridge (Gordon et al., 1990) (Fig. 9). The other important development was the anticlockwise rotation of Sundaland (Karig et al., 1979) leading to a westward migration of the Burmese arc forming the current NS trending eastern margin of the Indian plate. Subsequently, in the Burmese arc, the eastward subduction of India–Burma seems to have come to a halt and replaced, instead by a right lateral strike-slip environment similar to that along the Sagaing fault further east as the Indian plate drags the eastward subducted slab north-northeastward (Kumar and Rao, 1995; Rao and Kumar, 1999) (Fig. 9). Finally, the resultant scenario comprises an overturned lithospheric slab locked up against eastern Himalaya (Rao and Kalpna, 2005), as evidenced also by results of seismic tomography (Bijwaard et al., 1998). The other complications affecting the eastern margin are the pop up uplift of the Shillong plateau wedged between the India–Eurasia and India–Burma thrust zones (Rao and Kumar, 1997; Bilham and England, 2001) and incursion of the Ninety east ridge into the Burmese arc as the Indian plate migrates northward, and opening of the Andaman Sea between the Burma and Andaman arcs about 11 million years ago (Curray et al., 1979). Additionally, it may be important to note that the Euler pole models of plate motion (DeMets et al., 1990, 1994) predict a higher velocity (~5.5 cm/year) near the eastern syntaxis as compared to that near the western syntaxis (~4.5 cm/year), probably leading to a greater stress build up in the east. All the above tectonic factors are contemporaneous in geological time and need a very careful examination to substantiate the idea that neotectonic changes in the Indian plate scenario might have transformed the eastern Himalayan syntaxis into a potential seismic zone capable of generating great earthquakes.

10. Future scope

The recent developments in broadband seismology, especially during the last decade or so, have greatly helped us to map in great detail, the crust–mantle structure beneath the Himalaya. This has enabled a much better understanding of the underlying causative geodynamic processes, especially connecting the evolution of Himalaya with the existing diverse models of uplift of the Tibetan plateau in the north. While detailed studies have been carried out so far in Tibet under various international programmes, it is only in the recent times that the receiver function technique has been extensively used to map the western, central and eastern Himalaya. The S-to-P Receiver function technique, an important modification of the standard P-to-S technique has proved most effective for deciphering the LAB, hitherto untraceable with seismological tools. This method also has the distinct advantage that the piercing points have a larger offset from the stations, and hence enable mapping of regions farther away from the stations, often in inaccessible areas like the Himalaya. Another such method that offers a great potential for mapping inaccessible regions is modeling of the long period Pnl waves, which are extremely sensitive to the crustal thickness, upper mantle velocity and the V_p/V_s ratio. The greatest advantage of this method is that it maps the region covered by the mesh of ray paths connecting the events and the stations. For instance, with seismic stations all along the Himalayan foothills and events occurring south of Tibet, it is possible to obtain the crust–mantle structure of the largely inaccessible parts of Himalaya, provided they are within a delta range of about 16°. In general, deployment of a high density

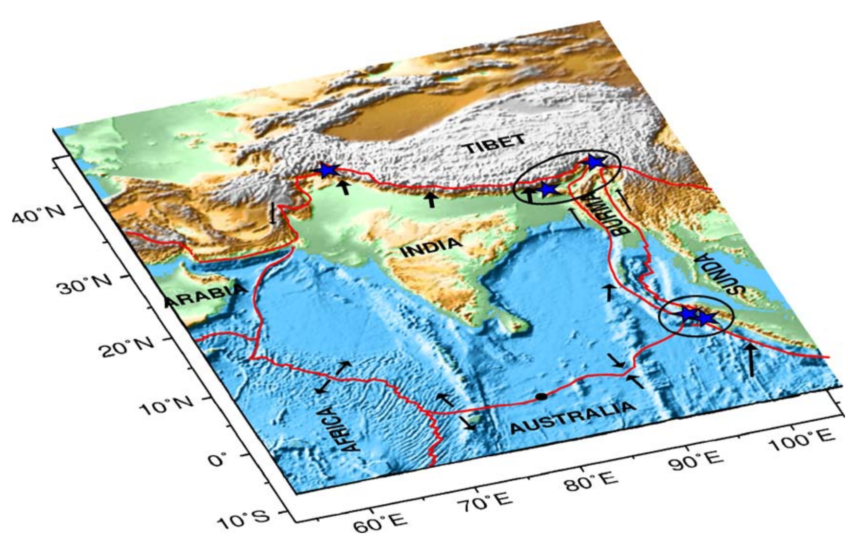

Fig. 9. A cartoon depicting the tectonic scenario of the Indian plate and the neighbouring plates. The vectors represent plate motion velocities along the Indian plate margins, computed using NUVEI-1A model (DeMets et al., 1994). Black circle represents the Euler pole of rotation of the India–Australia plate pair. Presence of great earthquakes close to the quadruple plate junctions is noteworthy.

network of broadband stations holds the key to a complete imaging of the detailed structure beneath the Himalaya.

The other important approach that needs to be adopted on a large scale is deployment of a dense network of GPS stations in the Himalaya. In spite of the limitations in uniquely interpreting the GPS results in conjunction with the geodetic, seismological and geological data, the method has a great scope of identifying and delineating the active zones in the Himalaya. At present, only small portions of Himalaya, mostly in Nepal have been studied using GPS.

Finally, it is important to have a detailed understanding of the ambient stress field of the Indian shield region in response to the ongoing continent–continent collision along the Himalaya. Numerical techniques like the Finite Element Modelling (FEM) should be deployed to infer the stress distribution and mode of deformation, especially in the complex syntaxial regions of both, the eastern and western Himalaya. The proposed hypothesis that multiple plate junctions can provide the requisite strength for stress accumulation capable of generating great earthquakes needs a detailed investigation, using three dimension modeling approach. Some of the outstanding questions that remain to be carefully investigated are:

- What is the spectrum of mechanisms causing brittle failure in the Himalayan crust, gleaned from earthquake studies carried out so far?
- What is the seismogenic characterization of various segments of the Himalayan crust based on a synthesis of available geological/geophysical signatures from field experiments?
- What can we understand from more intensive studies to infer neotectonic activity and palaeo-seismicity studies in this region?
- Can we evolve strategies towards discerning seismogenic faults (both surfacial and hidden) in the Himalaya based on the above and in the light of scale model laboratory experiments for understanding the reactivation of pre-existing weak zones and their interplay, even on a long-range basis in the present day stress regime?
- How do we synthesize geodetic, seismological and geological data to reliably infer the observed deformation patterns?

To answer the above questions it would be required to deploy a multi-parametric approach keeping in view the regional stress systems, possible locale specific excessive stress build-up factors, palaeo-seismic approaches and new conceptual frameworks in consonance with the non-stationarity of the earthquake phenomenon, rather than purely mathematical modeling or geological characterization of seismogenic faults in the present day scenario.

While uncertainties prevail in the seismic hazard assessment of the Himalayan region, the issue of preparedness becomes one of the most vital ones. Seismic microzonation studies of mega cities along the Himalayan foothills and in the Indo-Gangetic plains have already been initiated by the Government of India. Site response studies in the capital city of New Delhi have been carried out (Mukhopadhyay et al., 2002; Iyengar and Ghosh, 2004) that clearly delineate the zones that are likely to amplify the earthquake ground motion by virtue of thick layers of alluvial cover corresponding the Yamuna river. As the saying goes, "Earthquakes don't kill but buildings do", there cannot be a better example than the recent Muzaffarabad earthquake that claimed more than 80,000 lives for a magnitude of only 7.6. Future efforts should therefore focus upon design and construction of earthquake resistant buildings as per the requirement of the local micro-zones. It is high time that building codes pertaining to such designs are made mandatory by all governments of the affected nations.

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N. Purnachandra Rao (1963), with a Ph.D. in seismology is a senior scientist with the National Geophysical Research Institute (NGRI), Hyderabad, India, leading projects in Earthquake source studies and Seismic Microzonation. He has specialized in the seismotectonics of the Indian plate region with emphasis on the Himalaya–Tibet and Burma–Andaman regions. Dr. Rao is also a recipient of D.Sc. from the University of Tokyo, Japan, in 2000 and visited GFZ, Potsdam as an Alexander von Humboldt fellow during 2003–04.

P. Kumar (1972) obtained his Ph.D. in Crustal Seismics in 2002 and is a research scientist with NGRI, working in the field of solid earth Geophysics imaging the lithospheric structure beneath various geotectonic provinces applying the S–P and P–S receiver function technique. He has experience in imaging the lithosphere–asthenosphere boundary in tectonic scenarios as diverse as Oceanic plumes to Continent–Continent collision zones. He visited GFZ, Potsdam as DAAD fellow during 2003–05. His current research interest is in development of newer tools for imaging of the earth's deep interior.

Kalpna (1968) obtained a Ph.D. from IIT Roorkee in 1996, specializing in development and application of poro-elastic theory to study the earthquake phenomena related to natural and induced seismicity. She is a scientist with NGRI since 2000. Her studies are related to stress inversion of earthquake source mechanisms in the Indian plate boundary zones including the Himalaya, and also theoretical modeling of reservoir induced seismicity, which are well recognized. She was awarded the Indian National Science Academy (INSA) Young Scientist Medal in the year 1999. She visited the University of South Carolina, USA as a BOYSCAST Fellow during 2004.

T. Tsukuda (1945), is an Associate Professor at the Earthquake Research Institute (ERI), University of Tokyo, specializing in the field of earthquake forecasting based on geophysical field observations in Japanese Islands. He and his research group have extensive experience in monitoring micro-seismicity, quiescence, and changes in geophysical parameters, ground water regimes and other precursory geophysical characteristics that are likely to precede an impending large earthquake in the Japanese Islands. Incorporating various unconventional measurements in an innovative manner, Prof Tsukuda and his group carry out earthquake precursory studies in various tectonic regimes of the Japanese Islands.

D. S. Ramesh, (1961), obtained his Ph.D. in the field of seismic tomography in 1990. He initiated the global seismology group at NGRI and has international collaborative programs with the University of Tokyo, Japan and GFZ, Potsdam, Germany. He visited various reputed research institutions in Europe and Far East as a visiting Professor and an Alexander von Humboldt fellow. His research interests are, imaging and modeling the fine structure of the earth in complex tectonic scenarios using seismological converted waves of various scale lengths.