Earthquake source characteristics along the arcuate Himalayan belt: Geodynamic implications

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The occurrences of moderate to large magnitude earthquakes and associated subsurface geological processes were critically examined in the backdrop of Indian plate obliquity, stress obliquity, topography, and the late Tertiary regional tectonics for understanding the evolving dynamics and kinematics in the central part of the Himalayas. The higher topographic areas are likely associated with the zones of depressions, and the lower topographic areas are found around the ridges located in the frontal part of the orogen. A positive correlation between plate and stress obliquities is established for this diffuse plate boundary. We propose that the zone of sharp bending of the descending Indian lithosphere is the nodal area of major stress accumulation which is released occasionally in form of earthquakes. The lateral geometry of the Himalayas shows clusters of seismicity at an angle of $\sim 20^\circ$ from the centre part of the arc. Such spatial distribution is interpreted in terms of compression across the arc and extension parallel to the arc. This biaxial deformation results in the development of dilational shear fractures, observed along the orogenic belt, at an angle of $\sim 20^\circ$ from the principal compressive stress axis.

1. Introduction

The study area is located in the central arcuate belt of the extra peninsular India between longitude 75° and 90°E with a maximum orthogonal extension of ~ 300 km (figure 1), and fits closely with a small regular arcuate shape of radius ~ 1696 km (Seeber *et al.* 1981; Bendick and Bilham 2001). Across the Himalayan arc, the convergence front documents three main kinematic elements (figure 1; cf. Davis *et al.* 1983):

- (1) a foot-wall block (Indian cratons) that dips gently northward below the sediment-filled foredeep and has little internal deformation;
- (2) an accretionary wedge where thrusting and folding verge towards the foredeep; and

- (3) a hanging-wall block (Tibetan slab) that has prominent Neogene extensional structures in both radial and arc-parallel directions (e.g., Burg *et al.* 1984; Armijo *et al.* 1986; Gapais *et al.* 1992; Seeber and Pêcher 1998).

Recent convergence between India and Asia is assumed to be accommodated predominantly along a single fault – the Main Himalayan Thrust (MHT) (Wobus *et al.* 2005), which flattens beneath the Lesser Himalayas and roots deeper beneath the Higher Himalayas and southern Tibet (Cattin *et al.* 2001). Lyon-Caen and Molnar (1983) reported that the Indian plate was weakened and bent to $\sim 10^\circ$ – 15° at a position ~ 50 km south of the Indus Tsangpo Suture (ITS), and the crust has been detached from the mantle along MHT.

Keywords. Seismicity; plate obliquity; stress obliquity; coupling; depression, ridge.

Figure 1. Tectonic map of the Himalayas (reconstructed after Gansser 1964; Valdiya 1980). Traverses AA' to OO' were taken orthogonal to the strike of the arcuate Himalayan belt for reconstruction of topography as illustrated in figure 2. Shaded zone in the lower right inset map represents the study area. Abbreviations: MFT– Main Frontal Thrust, MBT – Main Boundary Thrust, MCT – Main Central Thrust, STD – South Tibet Detachment, ITS – Indus–Tsangpo Suture, DHR – Delhi–Hardwar Ridge, FR – Faizabad Ridge, MSR – Monghyr–Saharsa Ridge.

Studies on the mechanism of horizontal deformation in and around southern Tibet (Molnar and Tapponnier 1977; England and McKenzie 1982; Vilotte *et al.* 1986; Houseman and England 1993; England and Molnar 1997) and vertical uplift in the Himalayas (Molnar and Lyon-Caen 1989; Jackson and Bilham 1994; Bilham *et al.* 1997; Cattin and Avouac 2000; Takada and Matsu'ura 2004) provide numerous ideas about active deformation along the Himalayan orogenic belt. Thermo-mechanical numerical modelling demonstrates that the channel-flow and ductile extrusion are dynamically linked with the effects of surface denudation at the southern flank of the Himalayas (Beaumont *et al.* 2001). The mutual

coupling between the crustal deformation and erosion, which leads to mountain building along the convergence margins (Koons 1989; Molnar and England 1990; Willett *et al.* 1993; Avouac and Burov 1996; Whipple and Meade 2006), is usually caused by trade-off between tectonic uplift and denudation (Ahnert 1970; Pinet and Souriau 1988; Summerfield and Hulton 1994; Hovius 2000). The Himalayas is one of the best modern examples for such a coupling operative all along the convergence margin (Lavé and Avouac 2001). Further, the degree of crustal deformation driven by convergence, detachment, and subduction of underlying mantle lithosphere is intrinsically related with plate obliquity (Ellis *et al.* 1995). It is worth

mentioning that the processes controlling the mountain building (Harris 2007) or basal shearing and crustal flow in the hinterlands of the Himalayas and the southern Tibetan are not very clear. Occasionally, the high-strained features in the hinterlands of collisional orogens provide clues for lateral crustal flow and extrusion of material from mid-crustal depths towards the orogenic foreland (Godin *et al.* 2006). In such cases, mapping of the earthquake hypocenters in the mantle and the associated source processes are important tools for understanding the plate interactions at depth.

In this paper, we examine the variation of topography along different strike-orthogonal profiles and trench-parallel crustal discontinuities such as Main Frontal Thrust (MFT), Main Boundary Thrust (MBT), Main Central Thrust (MCT), South Tibet Detachment (STD) and Indus-Tsangpo Suture (ITS). The interrelationships, if any, between seismic activities, topography, intersecting basement ridges (e.g., Monghyr–Saharsa, Faizabad, Delhi–Hardwar), and depressions (e.g., Gandak and Sarda) (Sastri *et al.* 1971; Rao 1973; Valdiya 1976; Dasgupta *et al.* 1987; Gahalaut and Kundu 2012) are qualitatively assessed. The evenly spaced ridges and depressions intersecting the Himalayas from south, evolved through east–west compression during bending of the northern Indian margin, are correlated with the level of occurrences of seismicity (Yin 2006; Gahalaut and Kundu 2012). We further attempt to analyze the neotectonic movements of the crustal blocks along the major crustal discontinuities in terms of earthquake source processes. We find an interrelationship between topography, seismicity and plate- and stress-obliquities, and finally propose a simplified model for stress-obliquity-dependent subsurface lateral relative movements of blocks.

2. Tectonics

2.1 Regional

Plate reconstruction shows an abrupt decrease in the convergence rate from ~ 15 to ~ 4 cm yr $^{-1}$ at ca. 50 Ma (Molnar and Tapponnier 1975; Patriat and Achache 1984; Copley *et al.* 2010) following collision of the Indian plate against the Asian plate (Searle 1991; Garzanti *et al.* 1996; Hodges 2000; Yin and Harrison 2000). This rapid change in the rate of convergence coincided with a major rearrangement of plate boundaries in the Indian Ocean (DeMets *et al.* 1990; Copley *et al.* 2010). Subsequent to slow down or cessation of convergence (McKenzie and Sclater 1971; Sclater and Fisher 1974; Patriat and Achache 1984; Schluter *et al.* 2002), the Indian plate, partly coupled

with Burma plate, resumed its northward journey through early Miocene time and increased its obliquity and convergence rate in middle Miocene time (McCaffrey 1991; Diament *et al.* 1992; Hall 1997). This renewed convergence reached its critical value in the late Miocene (Levchenko 1989), and caused widespread deformation in the north-eastern Indian Ocean (Weissel *et al.* 1980; Gordon *et al.* 1990; Deplus *et al.* 1998; Hintersberger *et al.* 2010), opening of the Andaman Sea (Raju *et al.* 2004; Khan and Chakraborty 2005), reorganization of the Central Myanmar Basin (Khan 2004), initiation of grabens in southern Tibet and the Himalayas (Burchfiel and Royden 1985; Yin and Harrison 2000; Hintersberger *et al.* 2010), and rapid uplift of the Himalaya–Tibetan plateau (Harrison *et al.* 1992; Molnar *et al.* 1993). A 20° clockwise rotation of the motion vectors of India prior to 7 Ma (DeMets *et al.* 1990) coincided with the initiation of shortening between India and Australia since 7 Ma as identified from the dating of a widespread unconformity (Leg 116 Shipboard Scientific Party 1987), and marked the onset of deformation along the eastern equatorial Indian Ocean. Since the collision with Asia, India has indented ~ 3000 km into Asia, producing a combination of lateral escape and crustal thickening which have given rise to the largest uplifted topographic features, the Himalayas, on Earth with an average elevation of 5000 m (e.g., Molnar and Tapponnier 1975; Peltzer and Tapponnier 1988; Harrison *et al.* 1992; Fielding *et al.* 1994; Tapponnier *et al.* 2001).

2.2 Local

Present day convergence of the Indian plate along the Himalayan arc varies from ~ 4.2 to 5.4 cm/yr (DeMets *et al.* 1990). Nearly 33% of the convergence is absorbed by compressional deformation (Molnar and Lyon-Caen 1989; Bilham *et al.* 1997) and the remaining $\sim 67\%$ is distributed in a large area spread from Tibet to Mongolia (Molnar and Tapponnier 1977; England and Molnar 1997). Trench parallel and orthogonal partitioning of the oblique convergence resulted the radial slip, along-strike translation, and extension along this deformation front (McCaffrey and Nabelek 1998). The extension of southern Tibet was accommodated by significant east–west shortening in the western Himalayan syntaxis and eastward motions in southeast Tibet (Butler *et al.* 1989; Seeber and Pêcher 1998; Larson *et al.* 1999; Banerjee and Burgmann 2002; Khan *et al.* 2010). This Late Tertiary deformation in the Himalayas all together sliced the orogeny into five broadly parallel lithotectonic units, separated by mostly north-dipping faults (figure 1 of Godin *et al.* 2006). The two

parallel and opposite-sense shear zones, which bounded the Himalayan metamorphic core, termed the Greater Himalayan Sequence (GHS), were more active during the Miocene (Hubbard and Harrison 1989; Searle and Rex 1989; Hodges *et al.* 1992, 1996). The MCT zone marks the lower boundary of the GHS, juxtaposing the metamorphic core above the underlying Lesser Himalayan sequence. The STD system defines the roof fault of the GHS, marking the contact with the overlying unmetamorphosed Tethyan sedimentary sequence. More southerly structures the MBT and the MFT evolving sequentially (Wobus *et al.* 2005), separated the Lesser Himalayas to the north from the Sub-Himalayas to the south. The MFT (i.e., surface trace of the MHT) marks the limit between the undeformed sediments lying on the Indian basement and those that have been scraped off and involved in the Siwalik (Sub-Himalayas) fold belt (Cattin *et al.* 2001).

3. Data and analysis

3.1 Topography

We have selected 15 profiles (figure 1) at regular separation, orthogonal to the trend of the Himalayas, for reconstruction of the topography (figure 2). Topographic data were compiled from GTOPO 30, global digital elevation model (DEM) with a horizontal grid-spacing of 30 arcsec (~ 1 km). We have used tile number E060N40 under the DEM file for illustrating the topography along the different profiles (figure 2) and crustal discontinuities (figure 3). Relative variation of topography was further assessed through estimation of average elevation over 1° longitude interval with a linear moving window of 0.5° (overlapping line) along the discontinuities. The moving window has been considered for comprehensive analysis, and maintaining the inherent segment-to-segment continuity of the data points. The dimension of the linear window is selected for incorporating reasonable data points representing the elevation at the mid-point of each 1° linear segment to understand the E–W as well as N–S variations of deformation of the arcuate Himalayan segment.

Along S to N profile, a sharp rise in elevation in the east, and a relatively gradual rise in average elevation past the MCT towards the central and western parts of the study area are noted (figure 2). Wider irregular topography is also noted between MCT and MBT towards the west and central parts (profiles 3–9, figure 2). Instead, a relatively flat topography is noted beyond MCT towards east. These observations possibly account for more arc-parallel erosion rate towards west and increase in

landmass transportation towards east. The topography along MFT between Himachal and Darjeeling Himalayas is relatively uniform (figure 3). A small increase in average elevation along MBT, and a sharp rise along MCT towards east might be accounting for anomalous imbalances in mass distribution all along this zone. Guillot *et al.* (1999) and Finlayson *et al.* (2002) advocated a differential denudation along the MCT hanging wall from east to west along the Himalayas. The variable denudation was either caused by (a) an eastward increase in slip along the MCT due to counter-clockwise rotation of India with respect to Asia during Indo-Asian collision or (b) an eastward change in the dip angle of the subducting Indian plate or (c) an eastward increase in the magnitude of exhumation due to regional variation of climatic conditions or a combination of these factors. An oscillatory variation of topography existing along the MCT is further continued towards south, and decreases significantly near MFT. West to east increase in average elevation along MCT, STD and ITS, decreases sharply past $\sim 80^\circ\text{E}$, and becomes minimum at $\sim 82.5^\circ\text{E}$. It further increases sharply and almost gets saturated along STD beyond 84°E . Instead, the average elevation along MCT beyond 84°E increases sharply. It is also clear that the seismicity along this arcuate belt is not distributed evenly; rather it is concentrated in some specific blocks as illustrated in figures 3 and 4. It is also interesting to note that the maximum concentration of seismicity is apparently associated with areas of higher elevation along MCT. These typical features are either related with variable degree of southward transportation of Asian landmass over the northward underthrust Indian lithosphere or variable erosion/denudation. The local reduction in elevation (local depression, figure 3) between ~ 80 and 84°E from north to south all through the ITS, STD, and MCT might be caused by east–west increase in extension near the hinterlands of the Himalayas or trench-orthogonal extrusion of crustal wedges towards the Himalayan topographic front coupled with vertical collapse of the topography. Thus, the mutual interaction between the underthrust Indian lithosphere and the overthrust Asian landmass has a definite role behind both the erosion and generation of seismicity.

3.2 Seismicity

We have considered 611 earthquake events (magnitude $M_w \geq 4.0$) along the Himalayan arcuate belt between Himachal and Darjeeling, during the period 1902–2012, for detailed investigation of seismicity distributions (figures 4 and 5). The earthquake data were taken from the catalogues

Figure 2. Plots illustrate the reconstructed topography along different traverses from AA' to OO'. The more non-uniform topography towards the western part of the study area may be noted.

of the Indian Society of Earthquake Technology (Bapat *et al.* 1983), International Seismological Centre, and the US Geological Survey. It was noted that the activities were not uniformly distributed all along the arc; rather confined laterally in some specific blocks surrounding Chamba, Mussourie–Dehradun, near Dharchula and Kalikot, and between Kathmandu and Darjeeling (figure 4). Based on the seismicity distributions, six isolated blocks (block I: 133 events, block II: 132 events, block III: 141 events, block IV: 28 events; block V: 91 events; block VI: 86 events, figure 4) were identified. Figure 5 illustrates the source-distribution of earthquake events, concentrated at depths between ~5 and ~60 km, though events beyond 60 km are not rare. Although the variation of seismicity concentration from Himachal to Darjeeling Himalayas is apparently distinct, a significant decrease in concentration is noticed near the central part of the arcuate belt (figures 4 and 5). Although the events are mainly located between the MBT and STD, less seismic activities are also identified to

the south of MBT and north of STD, and occasionally to the south of MFT (figures 4 and 6). Six depth-sections of seismicity through the six blocks (figures 4 and 6) indicate that the activities are merely associated with MHT. Further, the geometry of the surface distribution of seismicity towards the western segment of the study area is nearly elliptical with major axis parallel to the strike of the Himalayan orogen, and the strike-parallel ellipticity reduces towards eastern part. Cluster of seismicity is significantly associated with the sharp bending segments of the Indian mid-upper crust (IMUC), Indian lower crust (ILC) or mantle lithosphere. The studies of De (2000), Kayal (2001), Monsalve *et al.* (2006) and Hazarika *et al.* (2010) show that the earthquakes are mostly clustered to the north of the MBT without following any particular trend, and a majority of the earthquakes occurred below the plane of detachment, and particularly, the MBT is seismogenic up to the mantle in the Sikkim–Darjeeling Himalayas.

Figure 3. Plots show the variation of topography along different crustal discontinuities (i.e., MFT, MBT, MCT, STD and ITS). The horizontal distributions of open triangles at the top represent the longitudinal variations of earthquake epicenters. The higher concentration of seismicity is associated with average higher topography along MCT. Also note the oscillating nature of topography along MCT. Amplitudes of oscillations sharply decrease towards south.

3.3 Source processes

A total of 64 focal mechanisms of earthquakes of magnitude $M_W \geq 4.7$ (table 1), compiled from the Harvard Centroid Moment Tensor Catalogue and the studies of Tandon (1972), Molnar *et al.* (1973), Rastogi *et al.* (1973), Chaudhury *et al.* (1974), Rastogi (1974, 1976), Tandon and Srivastava (1975), Chandra (1978), Molnar and Tapponnier (1978), Singh and Gupta (1980), Dasgupta *et al.* (1982) and Ni and Barazangi (1984), were analyzed for in-depth investigation of geodynamics of the Himalayas. Although the thrust-type movements are apparent in the area between ~ 75 and $\sim 82^\circ\text{E}$, the thrust, strike-slip, and normal faulting mechanisms are significant towards east (figure 7). Active strike-slip faulting identified towards east can be explained by increasing lateral shearing between the landmass around the MCT. An increasing number of normal faulting earthquakes from south to north past the MCT are quite phenomenal, and particularly confined between ~ 80 and $\sim 88^\circ\text{E}$. These typical faulting processes are possibly associated with topographic collapse of an overthickened crust (Molnar and Tapponnier 1978; Dewey 1988) coupled with arc-parallel extension in this part of the Himalayas. We also note

that the P-axes are nearly orthogonal with the local trend of the orogenic belt for events occurring between ~ 75 and $\sim 82^\circ\text{E}$ (figure 8). Verma and Kumar (1987) reported changes in the orientations of P-axes for all thrust-dominated movements from N–S in the part near Darjeeling Himalaya to NE–SW in the western Himalaya. Baranowski *et al.* (1984), Molnar and Chen (1982), Molnar and Lyon-Caen (1989), Molnar (1990), McCaffrey and Nabelek (1998), and Seeber and Pcher (1998) found the slip vectors perpendicular to the local trend of the range. A little anomaly in the distributions of P-axes is significant towards east of the orogen.

3.4 Indian plate obliquity and stress obliquity

The present study attempts to explore the possible role of topography, plate obliquity (i.e., φ , angle between the local trench-normal and the plate convergence velocity vector, Jarrard 1986; Ellis and Watkinson 1987; McCaffrey 1992; Liu *et al.* 1995; Kao *et al.* 1998; Seeber and Pcher 1998; Chiao *et al.* 2001; Soofi and King 2002; Khan and Chakraborty 2005; Khan *et al.* 2010), stress obliquity (i.e., ψ , angle between trench-normal

Figure 4. Seismotectonic map of the arcuate Himalayan belt shows the distributions of epicenters of 611 moderate magnitude earthquakes (solid red circles) and 11 historical damaging earthquakes (white solid stars). Four digit numbers adjacent to white solid stars represent the years of occurrences of the damaging earthquakes. Dashed yellow lines demarcate the boundary of seismically active six distinct blocks. Black solid lines along AA' to FF' represent the traverses, orthogonal to the strike of the arcuate Himalayan belt, considered for depth-probing of seismicity in different blocks. Solid black arrows indicate the velocity of convergence of the Indian plate against the Asian plate at respective locations (after DeMets *et al.* 1994). Abbreviations: KF – Karakoram Fault, others are explained in the caption of figure 1.

and eigenvector of the maximum horizontal compressive stress axis, Khan 2007) behind the incidences of moderate to great earthquakes along the arcuate Himalayan belt. Along oblique convergence margins, the convergence plate velocity vector is generally partitioned into strike-normal and strike-parallel components (Fitch 1972), giving rise to compressional and shear components of strain (Lu and Malaveille 1994; Haq and Davis 1997; Mohanty 2011; Sinha and Mohanty 2012). This may evolve a variety of structures along the collisional boundary following the ratio of compressional to shearing motion (cf. Soofi and King 2002). An assessment of variations of plate and stress obliquities along this arcuate belt reveals a positive correlation between Indian plate obliquity and stress obliquity for 32 earthquake events (figure 9). McCaffrey and Nabelek (1998) and Seeber and Pêcher (1998) have shown that the radial slip, along strike translation, and extension parallel to the deformation front are commonly associated with degree of partitioning of oblique convergence in response to the drag from the downgoing plate, and occur in the hanging-wall block of orogenic belts (McCaffrey 1992). The plate-obliquity has minimum value near 85°E

(figure 9a) and increases both towards east and west. The increase in plate obliquity is associated with increase in shear movement along the strike of the Himalayan orogen, away from the central zone in response to the convergence of the Indian plate below Asia. We advocate that the plate-obliquity over the study area possibly controls the compatibility of source dynamics and kinematics with the strike of the trench-axes. Alternatively, a small decrease in degree of coupling between the Asian landmass and the Indian lithosphere along the basal shear plane away from 85°E can be inferred. The increasing arc-parallel compression towards eastern and western termini of the Himalayan orogen supports this observation.

A distinct feature of the relationship between longitudinal variations of the plate obliquity is the distribution of 55 data points of seismic events showing gaps at different places (figure 9a). The stress obliquity also shows similar relationship (figure 9b). The correlation between the plate obliquity and stress obliquity (figure 9c) shows a linear relationship, having data distribution of mainly three types: (a) 12 data points have positive intercept on the stress obliquity axis, (b) 32 data points have zero intercept, and (c) 8 data points

Figure 5. Plots illustrate variations of concentration of earthquake events with respect to their focal depths in six different blocks. Note the occurrences of earthquakes in the Indian lithospheric mantle.

have negative intercept on the stress obliquity axis. The data distribution in the stress obliquity *vs.* longitude show the first type to be in the upper segment of the mean curve, the second type coinciding with the mean curve, and the third type in the lower segment of the mean curve (figure 9b). The first two types of data are interpreted to be the result of pure thrust to transpression stress regime, whereas the third type of data represent the transtension regime. The data cluster at point C near the central axis of the plate obliquity (figure 9a) has obliquity of 0–5°, and is separated

from the adjacent clusters B and D with obliquity between 10° and 25°. The farthest cluster at A has obliquity of 33°–45°. The cluster at C is located close to the principal compressive stress axis, representing pure thrust dominated movement. The points in B and D are located close to the orientation of the plane of shear failure predicted by the Mohr–Coulomb theory. The point A is close to the plane of maximum shear stress related to the principal compressive stress at 85°E. It may be noted that shear failure planes under uniaxial compression make an angle of $\sim 30^\circ$ with the maximum

Figure 6. Cartoon illustrating the subduction of the Indian lithosphere beneath the Himalayas (Owens and Zandt 1997; Cattin *et al.* 2001; Monsalve *et al.* 2006; Tiwari *et al.* 2006; Chamoli *et al.* 2011). Hypocentres of 611 events and 11 damaging earthquakes were projected on six vertical depth-sections along AA' to FF'. Four digit numbers adjacent to white solid stars represent the years of occurrences of the damaging earthquakes. Note the association of major concentration of seismicity with the sharp bending portion of the Indian mid-upper crust (IMUC), Indian lower crust (ILC) and Indian mantle lithosphere between MBT and STD. Abbreviations: SH – Siwalik Himalaya, LH – Lower Himalaya, HH – Higher Himalaya, TH – Tethys Himalaya, MHT – Main Himalayan Thrust, ST – Southern Tibet.

principal stress axis (figure 10a). The angle in the present analysis shows a value lower than the predicted model. This can be explained by a

deformation model in which the maximum principal stress is compressive and the minimum principal stress is extensional in nature (figure 10b). In

Table 1. *Hypocentral and source parameters of moderate to large magnitude earthquakes in the Himalayas.*

Date	Latitude (°N)	Longitude (°E)	Depth (km)	Magnitude	Fault plane 1			Source of data
					Dip	Strike	Rake	
20/05/1979	29.58	80.32	15	5.8	7	274	79	1
22/06/1980	30.1	81.59	15	5.1	36	28	−50	1
29/07/1980	28.96	81.11	10	5.5	25	278	90	1
29/07/1980	29.42	80.95	22.3	6.5	21	290	92	1
23/08/1980	32.59	75.37	15	5.5	10	293	63	1
23/08/1980	32.49	75.4	15	5.5	12	298	82	1
19/11/1980	27.42	89.05	44.1	6.2	51	209	−2	1
10/01/1986	28.6	87.09	81.4	5.1	46	140	−163	1
26/04/1986	31.59	76.06	15	5.5	19	299	57	1
16/07/1986	30.48	78.19	15	5.4	17	278	37	1
09/08/1987	29.3	83.77	34	5.6	43	81	−10	1
20/08/1988	26.52	86.64	34.7	6.8	23	230	3	1
29/10/1988	27.39	85.73	18	5.2	30	309	−70	1
19/10/1991	30.22	78.24	15	6.8	14	317	114	1
20/03/1993	28.87	87.64	15	6.2	46	161	−121	1
05/01/1997	29.43	80.29	15	5.5	19	279	68	1
28/03/1999	30.38	79.21	15	6.5	7	280	75	1
28/09/2001	33.0	75.46	40.5	4.9	32	323	105	1
27/11/2001	29.61	81.75	15	5.5	4	257	63	1
27/11/2001	28.91	81.49	15	5.4	28	280	73	1
27/01/2002	33.32	75.91	28.8	5.2	20	225	−11	1
04/06/2002	30.13	81.25	15	5.6	49	159	−130	1
26/03/2005	28.08	87.95	69.6	4.7	62	109	179	1
31/10/2005	28.38	84.88	22.5	4.7	42	120	97	1
31/10/2005	29.39	81.28	47.0	4.7	52	8	176	1
14/12/2005	30.12	78.83	34.2	5.1	23	293	86	1
01/02/2006	30.06	80.31	30.7	4.7	54	156	−141	1
03/02/2006	26.94	86.7	30.9	4.7	30	279	91	1
14/02/2006	27.22	88.64	19.2	5.3	27	287	126	1
20/05/2007	27.23	88.56	13.6	4.9	58	204	−4	1
07/11/2009	29.31	86.28	18.8	5.5	43	178	−91	1
26/02/2010	28.41	86.77	84.5	5.1	69	12	−16	1
06/07/2010	29.55	80.33	14.1	5	25	318	140	1
04/04/2011	29.37	80.69	22.9	5.4	31	321	125	1
04/04/2011	29.43	80.71	18.8	5.4	30	318	128	1
18/09/2011	27.44	88.35	46	6.9	72	216	−12	1
20/02/1967	33.7	75.3	18	5.6	45	317	91	2
16/01/1973	33.2	75.7	42	5.1	42	262	46	2
26/09/1964	30.1	80.7	50	6.2	18	301	97	2
27/06/1966	29.7	80.9	37	6.1	28	313	106	2
12/01/1965	27.6	88.0	23	6.1	12	271	90	2
27/03/1964	27.2	89.3	32	6.3	19	76	90	2
05/11/1968	32.3	76.5	33	4.9	24	325	74	2
22/06/1969	30.6	79.4	19	5.4	18	154	106	2
26/09/1964	30.1	80.7	50	6.2	60	130	90	2
20/02/1967	33.63	75.33	18	5.6	65	258	59	2
12/01/1965	27.6	88	23	6.1	2	279	90	2
16/01/1974	33.2	75.7	42	5.5	56	209	121	3
15/01/1934	26.5	86.5	20	8.4	71	334	114	4
11/12/1975	33	76.17	2	5	74	166	90	5
01/01/1976	32.97	76.12	40	5.3	56	150	86	5
14/06/1978	32.24	76.16	7	5	72	168	90	5
31/01/1975	28.1	84.72	33	5.4	80	303	−155	6

Table 1. (contd)

Date	Latitude (°N)	Longitude (°E)	Depth (km)	Magnitude	Fault plane 1			Source of data
					Dip	Strike	Rake	
16/12/1966	29.7	80.7	15	5.8	39	280	90	7
16/12/1966	29.62	80.79	15	5.8	24	280	90	7
12/01/1965	27.4	87.84	23	6.1	75	90	90	7
24/03/1974	27.73	86.11	33	5.7	88	97	90	8
19/06/1979	26.29	87.57	24	5	34	179	350	9
21/02/1967	33.7	75.4	41	5.1	30	280	90	10
01/06/1965	28.5	83.2	20	5.3	40	267	61	10
20/02/1967	33.6	75.4	25	5.1	57	156	93	10
24/10/1973	33.1	75.9	33	5.4	36	168	75	11
26/02/1970	27.6	85.7	96	5	76	287	-140	11
28/12/1958	30	79.8	30	6.2	54	102	90	11

Sources: 1. Harvard Centroid Moment Tensor Catalogue, 2. Chandra (1978), 3. Chaudhury *et al.* (1974), 4. Singh and Gupta (1980), 5. Dasgupta *et al.* (1982), 6. Molnar *et al.* (1973), 7. Molnar and Tapponnier (1978), 8. Ni and Barazangi (1984), 9. Rastogi *et al.* (1973), Rastogi (1974, 1976), 10. Tandon (1972), 11. Tandon and Srivastava (1975).

Figure 7. Map explains the subsurface geological processes through beach balls of 64 moderate to large magnitude earthquakes. Top histogram plot indicates the focal-depth distributions of the 64 events. Note the operative thrust dominated movements towards the central and western parts of the study area.

such a deformation scenario, a set of extensional fractures develops parallel to the maximum principal compression axis. Such fractures evolve into normal faults because of extension perpendicular to the fracture plane. A regional E–W extension observed in the southern Tibetan plateau and the transtension regime mentioned earlier are possibly related to this process. This aspect of extensional stress and development of normal faults in the Himalayas is discussed in the next section. The variation of obliquity also controls the

development of transpression and transtension domains (figure 10c, d). The partitioning of principal stress (σ_1) into normal component (σ_N) and shear component (σ_S) along the plate margin results in development of thrust dominated movement with strike slip (i.e., transpression) in a dominant portion of the plate, but certain segments oblique to the major part give rise to transpression (figure 10c), or transtension (figure 10d) (see also Mohanty 2011; Sinha and Mohanty 2012 for intraplate earthquakes).

Figure 8. Map shows the regime of maximum horizontal compression operative in different parts of the arcuate Himalayan belt. The lengths of stress directions are related to the plunge of the axes.

4. Discussion

Renewed convergence of the Indian plate and subsequent shear traction along the Chaman and Sagaing faults at the western and eastern ends (Patriat and Achache 1984; Yin 2006) presumably caused east–west compression, and created undulation in the Himalayan foreland. Levchenko (1989) reported that the widespread unconformity near the Late Miocene–Pliocene boundary was associated with short pulse of tectonic deformation of the Indian lithosphere, and the occurrences of major tectonic events in the collision between Indian and Asia (Weissel *et al.* 1980). The evenly spaced down- and upwarping near the foothills of the Himalayas (Sastri *et al.* 1971; Rao 1973; Valdiya 1976; Dasgupta *et al.* 1987; Gahalaut and Kundu 2012) possibly took place during this time. The entire Late Miocene deformation processes coupled with the Indian plate obliquity (Fitch 1972; McCaffrey 1991; McCaffrey and Nabelek 1998; Seeber and Pêcher 1998; Khan 2005; Khan and Chakraborty 2005; Ansari and Khan 2014) resulted the spatiotemporal variation of coupling along its convergent margin. Positive correlation between blocks of concentrated seismicity and higher elevation along MCT (figure 3) with the areas of northward-extended Gandak and Sarda depressions possibly indicates the active deformation of the descending lithosphere. Instead, the penetrating ridges (Monghyr–Saharsa, Faizabad,

Delhi–Hardwar), were likely located around the gaps of seismicity and lower topography along MCT (figure 3) in the Himalayan foothills, possibly prohibiting the occurrences of earthquakes. Similar type of episode/quiescence was also observed elsewhere by Kelleher and McCann (1976).

McCaffrey (1992) and Liu *et al.* (1995) found a positive correlation between the plate obliquity and slip obliquity. The slope in plot of plate obliquity *vs.* slip obliquity was computed to be either 1.0 or less than one. Liu *et al.* (1995) suggested that the slope value of <1.0 is linked with increased slab pull effects along different subduction margins. Although we find a positive correlation between plate (ϕ) and stress obliquity (ψ) as $\psi = 1.30\phi + 0.28$ and $\psi = 1.15\phi + 27.66$ for 32 and 12 moderate magnitude earthquake events, the values of the slopes in either cases are estimated to be more than one (figure 9c). This observation thrives towards increased downdip resistance or enhanced coupling of the descending Indian lithosphere with the overthrust landmass at different locations (Liu *et al.* 1995). This may be noted here that the operative stress fields in Indian lithosphere (Cloetingh and Wortel 1986; Richardson 1992; Sandiford *et al.* 1995) arise by collisional resistance along the Himalayan orogen. Further, the earthquake focal mechanisms in the continental interior of the Indian plate accounts for high resistance at its northern margin (Chandra 1977; Sandiford *et al.* 1995; Sinha *et al.* 2013). Besides,

Figure 9. Plots illustrate the along-strike relative comparison between Indian plate obliquity and stress obliquity. (a) Represents the variations of plate obliquity, and (b) stress obliquity against their respective longitude locations. Note the data-point clusters in B and D associate obliquity between 10° and 25° , and the farthest cluster at A has obliquity of 33° – 45° . The cluster at C is preferably located close to the principal compressive stress axis. Relationship between the plate obliquity and stress obliquity (c) shows a linear positive correlation having data distribution of mainly three types. Three open stars are apparently located as outliers.

we document larger value of plate obliquity (i.e., 30° and 40°) for more than 20% events (figure 9c), and the intercept between 0.28 and 27.66 are dissimilar to computed values (i.e., zero) of McCaffrey (1992) and Liu *et al.* (1995). These observations might be accounting for arc-parallel transportation of partially decoupled masses along this margin. Three events likely in the outlier, located at the northwestern part of the study area, show very low value of stress obliquity (figures 7 and 9), which accounts for non-correlation between plate and stress obliquities. The ambiguity in the relation possibly concealed either in the average arc drawn through the mean of MFT, MBT and MCT or local effect. It is appreciated in the literature (Liu *et al.* 1995) that the along-strike component of the oblique convergence is gradually dissipated by the interplate coupling resistance and the mantle shear as the slab subducts. This accounts for coupled deformation of the overthrust Asian landmass and underthrust Indian lithosphere (McCaffrey 1991; Malod and Kemal 1996; McCaffrey *et al.* 2000; Khan and Chakraborty 2005; Khan *et al.* 2010).

The depth-distribution of seismicity (figure 6) shows the events are more concentrated around the sharp bending segment of the descending Indian lithosphere. It was also observed elsewhere in many convergence margins that the portion of sharp bending of the subducting lithosphere is the most active zone of seismic slip accumulation (Stern 2002; Khan and Chakraborty 2009; Khan 2011; Khan *et al.* 2012). Conrad and Hager (1999) also estimated that $\sim 60\%$ of energy dissipation occurs through the bending (flexing zone) of the subducting slab. It is also postulated that the maximum bending stress of the descending oceanic lithosphere at the subduction margins is about an order of magnitude larger than the maximum strength of the oceanic lithosphere (Kohlstedt *et al.* 1996; Conrad and Hager 1999), only 10% of the elastic bending stress is supported without deformation, and the remaining stress is relieved in the form of seismicity by fracturing of rocks (e.g., Turcotte and Schubert 1982). We propose that the bending segment of the descending Indian lithosphere beneath Asia along the Himalayan margin is seismically active. Incidences of nine damaging earthquakes (e.g., 1803 Garhwal, 1833 Nepal–Bihar, 1905 Kangra, 1945 Chamba, 1975 Kinnaur, 1986 Dharmsala, 1991 Uttarkashi, 1999 Chamoli, and 2011 Sikkim, figure 5) within the sharp bending portion of the descending Indian lithosphere support this observation. The seismicity continued in the deeper part of the Indian mantle lithosphere (figure 6) is possibly caused by deformation of the overthrust Asian landmass and the underthrust whole Indian lithosphere.

Figure 10. Development of failure planes at different angles (θ) with respect to the maximum principal compression (σ_1), predicted by Mohr–Coulomb failure envelope for uniaxial compression (a) and biaxial (σ_1 compression and σ_3 extension) deformation (b). Clusters B and D in figure 9 correspond to these failure planes. The slips along these fractures can be antithetic or sympathetic giving rise to transpression (c) or transtension (d), respectively. Combined effects of conditions illustrated in (b) and (d) can explain the development of normal faults in orogenic belts.

5. Conclusions

Incidences of moderate to large earthquakes in some specific segments with apparent seismic gaps along the arcuate Himalayan Mountain Range are related to the lateral deformation of the converging Indian lithosphere initiated during Late Miocene–Pliocene period. The convergence of the Indian plate created EW axial compression during its movement along the Chaman shear zone in the west and Sagaing shear zone in the east. This distinct motion creating evenly spaced domal structures in the Himalayan foreland built-up variable degree of decoupling between the overthrust Asian landmass and underthrust Indian lithosphere. The segment-specific clustering of seismicity is identified to be the manifestation of this coupling effect. The less active seismic zone or the gaps possibly represent the areas of quiescence of recent episodes of tectonic pulse. The NNE–SSW trending ridges in the Indian plate converging towards the

frontal part of the Himalayas are presumably prohibiting the generation of moderate to large earthquakes in the Himalayas. We also advocate that the recurrences of large damaging earthquakes in some specific areas are likely related with anomalous arc-parallel compression in the Himalayas. We find a positive correlation between Indian plate obliquity and stress obliquity for reasonable number of seismic events. Slopes of correlations for three isolated dataset were estimated to be more than one and the ordinate intercepts vary between -13.81 and 27.66 . This supports the view of variable degree of coupling between the two converging plates.

Highest concentration of seismicity around the sharp bent portion of the penetrating Indian mid-upper crust, lower crust and lithospheric mantle, and less seismic activities within the less bent part apparently indicate the bending zone to be the nodal area of stress accumulation. Some of the events, continued into the deeper part of the descending Indian lithospheric mantle,

are the manifestations of active deformation along the arcuate Himalayan belt. The curved nature of the oroclinal front developed transpression and transtension in certain segments. The former zones develop prevalently along low-angle antithetic shear bends whereas the latter condition is suitable along low-angle sympathetic shear bends (figure 10). The extensional tectonics operative towards the northern part and in southern Tibet might be the effect of combination of oblique subduction, oroclinal bending, and concentrated compression in the central part of the Himalayan arc.

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