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Role of Transverse Tectonics in the Himalayan Collision: Further Evidences from Two Contemporary Earthquakes

SUJIT DASGUPTA[1], BASAB MUKHOPADHYAY[2], MANOJ MUKHOPADHYAY[3] and D. R. NANDY[1]
[1]Ex Geological Survey of India, Kolkata
[2]Geological Survey of India, Central Headquarters, 27 J.L. Nehru Road, Kolkata -700 016
[3]Department of Geology & Geophysics, King Saud University, P.O. Box 2455, Riyadh 11451, Kingdom of Saudi Arabia
Email: basabmukhopadhyay@yahoo.com

Abstract: Two contemporary earthquakes originating in the central Himalayan arc and its foredeep (Sikkim earthquake of 18.09.2011, M_w 6.9, h: 10-60 (?) km and Bihar-Nepal earthquake of 20.08.1988, Mw 6.8, h: 57 km) are commonly associated with transverse lineaments/faults traversing the region. Such lineaments/faults form active seismic blocks defining promontories for the advancing Indian Craton. These actually produce conjugate shear faulting pattern suggestive of pervasive crustal interplay deep inside the mountains. Focal mechanism solutions allow inferring that large part of the current convergence across the central Himalayan arc is accommodated by lateral slip. Similar slip also continues unabated in the densely populated foredeep for distances up to several tens of kilometers south of the Main Boundary Thrust (MBT).

Keywords: Earthquakes, Transverse tectonics, Fault plane solution, Lateral slip, Himalaya.

INTRODUCTION

The Sikkim Earthquake of 18.09.2011 had its epicenter in the Kanchenjunga Conservation Area, located about 68 km northwest of Gangtok, bordering Nepal and Sikkim (Fig. 1). The earthquake produced widespread damages in the sparsely populated areas in north Sikkim and the rescuers found it difficult to reach even after 48 hours. The shock was widely felt all over eastern India, east Nepal, west Bhutan, south Tibet and Bangladesh. Human causality crossed 100 that are mostly from the epicentral tract of north Sikkim. The tragedy following the earthquake was slowly unfolded with reports of massive damage to non-engineered structures as well as due to triggered landslides blocking the main roads to Sikkim, compounded by the nagging monsoon rains. Source parameters for this earthquake reported by different agencies mostly agree on the epicentral location as well as its magnitude, but differ drastically on focal depth (varying from 10 to 60 km, Table 1). Estimates are computed using both the first arrivals (Hypocenter; USGS) and also derived through waveform modeling (Centroid; CGMT). The earthquake occurred in one of the identified potential source zones in the Himalayas given by us in an earlier study (zone F, Fig. 1 in Mukhopadhyay et al. 2011a). However, it is difficult to follow the nature of fault slip associated with the earthquake and negligible number of felt and teleseismically recorded aftershocks. Here our main objective is to investigate the role of transverse tectonics in the collision process in central Himalayan arc from the viewpoint of recent seismicity.

SEISMO-GEOLOGICAL MODEL AND TRANSVERSE FEATURES IN HIMALAYA

The Himalaya came into existence due to collision of Indian shield with Eurasian/Tibetan plate, accompanied by compression and thrusting along major faults such as Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) (Valdiya, 1976; Le Fort, 1986). The deformation front propagated southward from north with MFT as the most recently activated one in the entire sequence of thrusting. Seeber et al. (1981) was the first to suggest a tectonic model of the Himalaya from the seismic data analysis and suggested a gently dipping Indian slab, overriding Tethyan slab and sedimentary wedge (see general cross section across Himalaya; Fig. 2). The sedimentary wedge is decoupled from the Indian and Tethyan slabs. Simultaneous activation of MCT and MBT is also proposed in this model. Later, Ni and Barazangi

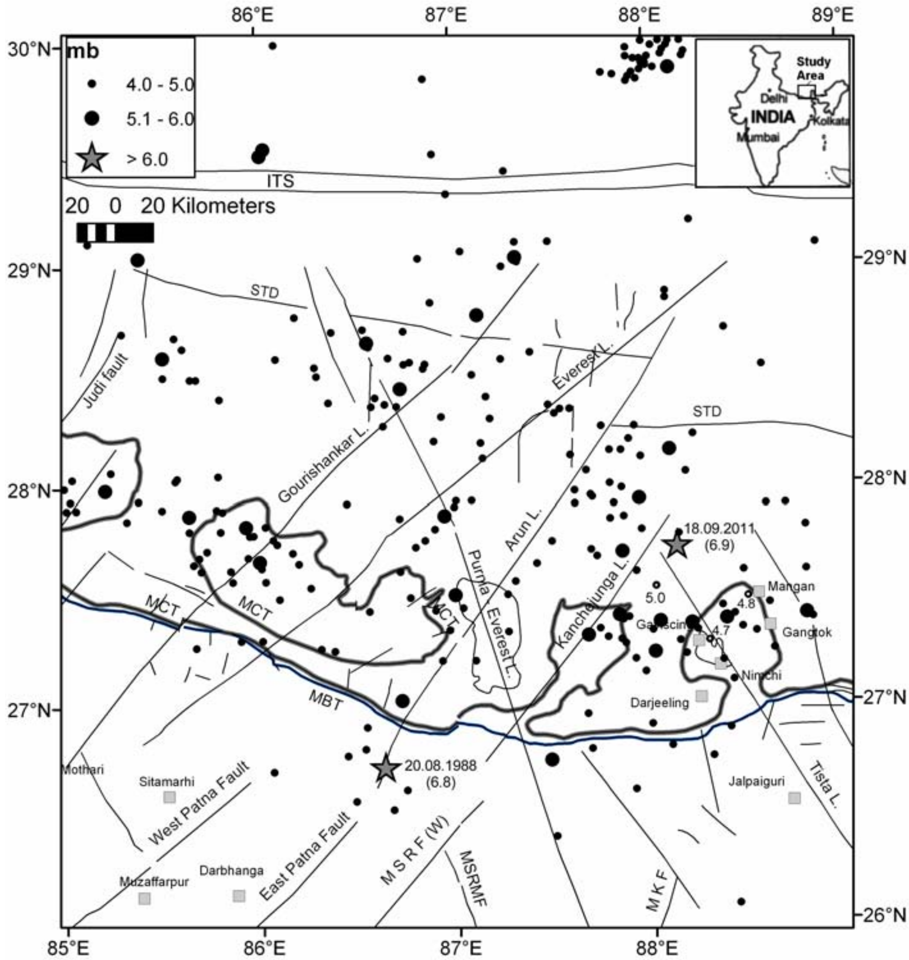

Fig.1. Earthquake magnitude distribution map (mb ≥ 4.0; 1963 – 2011) on tectonic elements in Sikkim – East Nepal area (*after* Dasgupta et al. 1987). The earthquake marked with 5.0 is the foreshock and with 4.7 and 4.8 are aftershocks (source NEIC). Note the interplay of subsurface faults in Himalayan foothills and its counterpart as lineaments/ strikeslip faults in Himalaya forming several active crustal blocks. MBT: Main Boundary Thrust; MCT: Main Central Thrust; ITS : Indus–Tsangpo Suture Zone, MSRF (W): Monghyr – Saharsa Ridge Fault (west), MKF: Malda – Kishanganj fault, MSRMF: Munger - Saharsha Ridge Marginal Fault, STD - South Tibet Detachment.

(1984) argued that presently MCT is dormant and MBT is active. In their model, the interface between the subducting slabs and sedimentary wedge is a 'plane of detachment' and further north, the contact between the Indian and Tethyan plates is marked by a Basement Thrust (BT). The zone between 'plane of detachment' and BT roughly coincides with high topographic gradient between Lesser and Higher Himalaya and characterised by steep dip of MCT and ramping of the Himalayan crust at the northern edge of the Indian plate (Lyon-Cean and Molnar, 1983; Schelling and Arita, 1991; Lave and Avouac, 2000). Further north, below the higher range of Himalaya, a mid crustal reflector at a depth of ~25 to ~40 km has been imaged in the INDEPTH profile (Zhao et al. 1993; Nelson et al. 1996) and was named as Main Himalayan Thrust (MHT). In the extreme southern end of the Himalaya below the Ganga fore-deep, the major detachment surface of MFT is located at a much shallower depth (~5 km) and extends sub-horizontally north-ward. The MFT in the frontal belt joins with the splays of MBT and MCT below the Lesser Himalaya, and further connect to MHT below the Higher Himalaya. The wedge-shaped Himalayan collision boundary defines crustal scale fault bend folds, formation of Lesser Himalayan duplexes that form taper and controlled the foreland-ward propagation of the thrust sheets (Mukul, 2010). The seismo-geological sections along Nanga Parbat syntaxis in the western Himalaya shows a depth penetration of more than 200 km of Indian plate (see Mukhopadhyay et al. 2011b). Another important aspect of Himalayan seismicity is the presence of deep focused earth-quakes beyond the Himalayan seismic zone south of MBT in the Ganges alluvial plain. This zone has been identified as bi-modal seismic zone, one along the detach-ment surface and another at deeper level (Monsalve et al. 2006).

Major geological units that are recognizable from south to north in the east Nepal – Sikkim Himalaya are - (1) Quaternary alluvium cover at the edge of the Indian shield and fore-deep, (2) the Siwaliks (Mio-Pleistocene) of the Himalayan foothills, (3) the Lesser Himalayan Gondwana and Proterozoic metasediments (Precambrian to Mesozoic), (4) the Lesser Himalayan crystalline rocks (Precambrian), (5) Crystalline rocks of Higher Himalaya, (6) Tethyan sediments (Cambrian to Cretaceous) and (7) the volcanics and sediments (Cretaceous – Tertiary) of the Indus Tsangpo Suture Zone. The Cenozoic continental collision (Honneger et al. 1982) between Indian and Eurasian plates had welded the entire litho-units described above and promoted intense crustal shortening, metamorphism, crystallisation and movement of the thrust sheets from north to south. The

Table 1. Sikkim Earthquake – Foreshock, Mainshock, Fault plane solutions and aftershock data given by different agencies

FORESHOCK PARAMETERS

No	Source	Yr	Mo	Da	Hr	Min	Sec	Lat.	Long.	Mag (mb)	Depth (km)
i)	NEIC	2011	6	3	0	53	28	27.53	88.03	5.0	51

MAIN SHOCK PARAMETERS

No	Source	Yr	Mo	Da	Hr	Min	Sec	Lat.	Long.	Mag [Mw]	Mo [Nm]	Depth (km)
1	USGS	2011	9	18	12	40	48.00	27.723	88.064	6.9		19.7
2	NEIC	2011	9	18	12	40	51.00	27.71	88.13	6.9		50.0
3	EMSC	2011	9	18	12	40	47.00	27.830	88.170	6.9		10.0
4	IMD	2011	9	18	12	40	47.00	27.700	88.200	6.8		10.0
5	USGS [CMS]	2011	9	18	12	41	18.09	28.050	88.163	6.9	2.7*10**19	35.0
6	USGS [WPMS]	2011	9	18	12	40	48.00	27.529	87.969	6.9	2.5*10**19	60.0
7	GCMT	2011	9	18	12	41	2.20	27.430	88.330	6.9	2.78*10**19	47.4
8	GFZ	2011	9	18	12	40	50.35	27.701	88.165	6.9	2.4*10**19	30.0

FAULT PLANE SOLUTIONS

No	NP1 Strike	NP1 Dip	NP1 Slip	NP2 Strike	NP2 Dip	NP2 Slip	T axis Pl	T axis Az	N axis Pl	N axis Az	P axis Pl	P axis Az	Source
5	220	78	0	130	90	168	8	84	78	309	8	175	USGS [CMS]
6	217	75	-4	308	86	-164	7	81	74	321	13	173	USGS [WPMS]
7	313	73	-163	217	74	-18	0	265	66	356	24	175	GCMT
8	309	80	-146	213	58	-11	15	77	56	324	30	176	GFZ

AFTERSHOCK PARAMETERS

No	Source	Yr	Mo	Da	Hr	Min	Sec	Lat.	Long.	Mag (Mw)	Depth (km)
i)	IMD	2011	9	18	13	11	59	27.6	88.5	5.0	16
ii)	IMD	2011	9	18	13	54	17	27.5	88.4	4.5	9
iii)	IMD	2011	9	18	21	51	52	27.6	88.4	4.2	28
iv)	IMD	2011	9	22	16	44	43	27.6	88.4	3.9	30
v)	NEIC/USGS	2011	9	18	13	11	59	27.48	88.49	4.8	35
vi)	NEIC/USGS	2011	9	18	13	54	20	27.28	88.29	4.7	35
vii)	EMSC	2011	9	18	13	11	57.0	27.56	88.61	5.0	10

Higher Himalayan sequence is thrust southward over the Lesser Himalayan rocks along MCT (developed between the Lesser and Higher Himalaya), which in turn overrides subsequently on sub-Himalayan fore-deep basin filled with Siwalik molasses (unit 2) originated from Himalayan uplift by the MBT and finally to the Indo-Gangetic plane by MFT.

The transverse structures (Fig.1) interpreted from satellite imagery and data available from surface mapping are established as faults in the foredeep region. These faults have their extension in the Himalaya and represented also

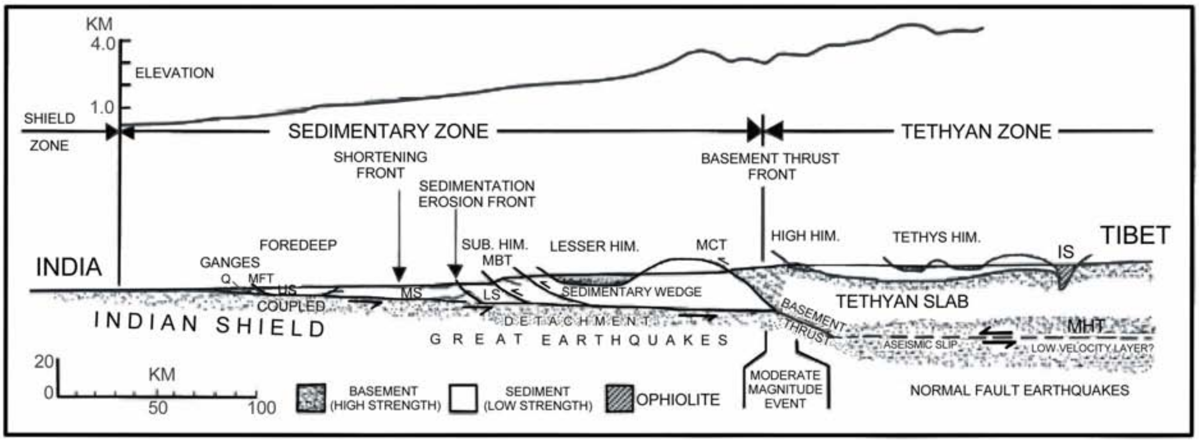

Fig.2. Generalised Seismotectonic model across Himalaya (modified after the compilation of Kayal, 2010; Kayal, 2001; from Seeber et al., 1981; Valdiya, 1976). Q – Quaternary, US, MS, LS: Upper, Middle and Lower Siwaliks, IS- Indus Suture, MBT – Main Boundary Thrust, MCT – Main Central Thrust, MFT - Main Frontal Thrust, MHT – Main Himalayan Thrust.

as active normal fault zones or grabens in the Tethyan Himalaya (see Dasgupta et al. 1987 for more details). The intersecting pattern of the transverse faults in front of subsurface wedges at the leading edge of the Indian shield is thus inferred to form a mosaic of rhombic crustal blocks bounded by possible shear planes. Some of these shear planes are pure strike-slip faults. Many transverse structures of the Himalaya are seismically active – they displace not only the MCT and MBT, but even the surface trace of the Siwalik-alluvium contact well within the foredeep (Dasgupta et al. 1987).

EARTHQUAKE DATA AND TRANSVERSE TECTONICS

Figure 1 illustrates seismic activity for the study area (lies between lat. 26° – 30°N and long. 85° – 89°E); corresponding to time domain 1963 – 2011 (source ISC: 1963 – 2004, and NEIC: 2005 - 2011). The seismicity map is overlain on a tectonic map displaying the Himalayan thrusts as well as the transverse features; the latter are adopted from satellite imagery interpreted by us in an earlier work (Dasgupta et al. 1987). The area contains 251 earthquakes (mb ≥ 4.0; focal depth up to 116 km), including two major earthquakes: Bihar – Nepal earthquake of 20.08.1988 [Mw 6.8; h 64.5 km (ISC); EHB 57 km] (Dasgupta, 1993) at the Himalayan foredeep and the recent Sikkim earthquake of 18.09.2011 [Mw 6.9; h ~ 50 km (NEIC)] between the Indus-Tsangpo Suture (ITS) and Main Central Thrust (MCT) below the Higher Himalaya. Both these earthquakes are located close to the transverse strike-slip faults (the East Patna Fault and its continuation as the Arun lineament in case of 20.08.1988 Bihar – Nepal earthquake and the Tista lineament for 18.09.2011 Sikkim earthquake). Most of the significant NNE-NE to NNW-NW trending crustal faults identified by aeromagnetic and seismic surveys under foredeep (west Patna, east Patna, Monghyr – Saharsa pair fault, Malda – Kishanganj fault etc) have its direct continuation northward in the Himalaya and presently accommodating a substantial part of the Himalayan convergence. These observations (Dasgupta et al. 1987; Dasgupta, 1993) are later supported by NGRI team (Hazarika et al. 2010) working with local station earthquake data in Sikkim Himalaya and stated - "crustal shortening in the Sikkim Himalaya has been substantially accommodated by transverse tectonics rather than underthrusting in recent times". In response to the differential pressure (N-S compression and E-W extension) the inhomogeneous geological bodies in the Himalayan front generate conjugate sets of fault planes with strike-slip geometry (Figure 4 in Dasgupta et al. 1987). These strike-slip faults are represented as large lineaments/faults developed between the foothills and ITS, trending NW to NE parallel to the outline of subsurface fault/ridge and offsets MCT, MBT and the Siwalik sediments at places (Dasgupta et al. 1987). They a lineup with basement faults in foredeep and also outline the active normal fault zone/graben in the Tethyan Himalaya. Examples of such lineaments / faults in the study area are Gaurishankar lineament, Everest lineament, Arun lineament, Kanchenjunga lineament (all trending NNE-NE) and their conjugate counterparts like: the Purnia-Everest lineament, Tista lineament trending NW-NNW (Fig. 1). These transverse lineaments produce cross faulted seismically active blocks in the Himalayan collision zone placed over the wedge shaped promontories of the Indian Shield.

CONVERGENCE MODEL AND LATERAL SLIP IN THE CENTRAL HIMALAYAN ARC

The Sikkim Earthquake (Mw 6.9; Table 1) with one foreshock (03.06.2011; mb 5.0; h 51 km NEIC) unlike other Himalayan earthquake of similar size [1991 Uttarkashi (Mw 6.8) and 1999 Chamoli (Mw 6.6) earthquakes with thrust solutions occurred further west in Garhwal Himalaya and 2009 Bhutan earthquake (Mw 6.1) further east in Bhutan Himalaya] has only two aftershocks (NEIC, USGS) recorded so far that occurred in the same day with magnitude 4.7 and 4.8 (Fig. 1) with epicenter at 35 km depth in north Sikkim. IMD has, however, recorded four aftershocks (magnitude 3.9 to 5.0, depth 9 - 30 km) three belong to the same day of mainshock and another on 22nd September (Table 1) in the north Sikkim. Disposition of the mainshock and aftershocks reveals a probable NW-SE trending rupture that is supported by the nodal fault plane defined by CGMT solution (No. 17 in Table 2). Small number of aftershocks for such a relatively large event is thus regarded characteristic for the central Himalayan arc, despite the fact that such events are strike-slip in nature, occurring in lower crust at about ~50km depth. It appears that the huge overburden load at the epicentral zone contributes in a manner to dampen the rupture propagation, thereby, hindering the process of aftershock generation. As Moho depth is around 60 km in and around source zone, the warm slab may have incurred high stress drop, slow rupture velocity resulting in small number of aftershocks. Future investigations may throw light on this aspect.

Available 17 numbers of CMT (HRVD) solutions for earthquakes in the study area (Table 2) are schematically plotted as beach-ball over the tectonic map for correlation (Fig. 3). It shows that the transverse lineaments/faults are

Table 2. CMT (HRVD)/GCMT solutions for 17 earthquakes within the area. Locational parameters from the ISC/NEIC catalogue, EHB data given where available. The solution parameters are discussed in the text in relation to the active faults. The value of the first column (No.) is plotted on the map (Fig.3)

No	Y	M	D	Hr	Mn	Sec	Lat.	Long.	Depth	Mag (Mw)	T axis plunge	T axis Azimuth	N axis plunge	N axis Azimuth	P axis plunge	P axis Azimuth	Nodal Plane Strike	Nodal Plane Dip	Nodal Plane Slip	Aux plane Strike	Aux plane Dip	Aux plane Slip
1	1979	6	19	16	29	12.4	26.74	87.48	20 EHB 19	5.0	11	84	4	353	78	243	179	34	-82	350	57	-95
2	1980	11	19	19	0	55.9	27.40	88.80	47 EHB 39	6.2	25	68	51	302	28	172	209	51	-2	301	89	-141
3	1986	1	10	3	46	43.7	28.65	86.56	53 EHB 60	5.1	20	96	43	206	40	349	140	46	-163	38	78	-45
4	1988	8	20	23	9	15.9	26.72	86.63	65 EHB 57	6.8	41	69	23	317	40	207	230	23	2	137	89	113
5	1988	10	29	9	11	0.8	27.87	85.64	15 EHB 14	5.2	71	352	10	112	16	205	309	30	109	106	62	79
6	1993	3	20	14	52	10.8	29.03	87.33	15 EHB 12	6.2	3	93	22	184	68	355	161	46	-121	22	52	-62
7	1993	3	20	21	26	49.1	29.01	87.34	21 EHB 15	5.1	30	83	4	175	60	273	160	16	-106	357	75	-86
8	1996	7	3	10	10	41.6	30.00	88.10	33 EHB 50	5.0	18	80	3	349	72	249	175	27	-83	347	63	-94
9	1997	11	3	2	29	56.8	29.04	85.39	14 EHB 11	5.5	15	277	10	184	72	61	21	31	-70	178	61	-102
10	1998	9	30	2	29	59.1	29.64	88.25	33 EHB 31	5.1	14	65	12	158	71	286	139	32	-112	345	60	-76
11	2005	3	26	20	32	15.7	28.26	87.93	70 EHB 73	4.7	20	68	62	202	19	331	109	62	179	200	89	28
12	2006	2	3	1	57	51.7	27.25	86.38	14 EHB 18	4.7	75	6	0	98	15	188	279	30	91	98	60	90
13	2006	2	14	0	55	28.8	27.38	88.39	30 EHB 17	5.3	63	311	16	74	21	170	287	27	126	68	68	73
14	2007	5	20	14	18	21.6	27.33	88.24	42 EHB 20	4.9	19	65	57	302	25	165	204	58	-4	296	86	-148
15	2009	11	7	20	8	54.5	29.50	86.02	5.7	5.5	2	89	1	179	88	304	178	43	-92	0	47	-88
16	2010	2	26	4	42	29.6	28.44	86.73	35	5.1	4	239	64	140	25	331	12	69	-16	108	75	-158
17	2011	9	18	12	40	51.0	27.71	88.13	50	6.9	0	265	66	356	24	175	313	73	-163	217	74	-18

responsible for most of the seismicity in the study area producing a varied style of faulting – from top crustal (< 20 km) thrust seismicity of probable MBT origin (CMT plot nos. 5, 12 and 13 in the Nepal and Sikkim Himalaya); normal fault related crustal – subcrustal seismicity at the Himalayan foredeep (CMT plot no. 1) or South Tibet Detachment Zone (CMT plot nos. 6, 7 and 9) / graben related extensional structure (CMT plot nos. 8, 10, 15) north of ITS in Tibet. Sikkim earthquake (14^{th} February 2006; Mw 5.3; EHB 17 km, plot no 13) has been correlated with the decollement plane of the MBT dipping northward in Sikkim Himalaya (Raju et al. 2007). Major transverse structures like, the Purnia-Everest lineament, Arun Lineament and Tista lineament are seismically active, mostly generating relatively deep crustal strike-slip earthquakes (with focal depths 50 km or more). The Purnia- Everest lineament with (CMT plot nos. 3 and 16) has shown right lateral strike-slip motion at the focal depth of 35-60 km. Whereas, seismically active Arun lineament (CMT plot nos. 4 and 11) exhibits left lateral strike-slip motion for earthquakes having crustal/sub-crustal focal depths 57-73 km. Similarly, 20.08.1988 Bihar – Nepal earthquake (having ~ 57 km focal depth) has originated in association with the Arun lineament and the East Patna subsurface fault below the foredeep (GSI, 1993). More recently, Monsalve et al. (2006), based on precision digital seismic data in the Central Nepal Himalayas, has identified a bi-modal seismic zone south of MBT, one along the detachment surface and another at the deeper zone at 40–50 km level. Similar views are also shared by Kayal (2010) as he argues that the deeper event of 1988 in the foothill is related to a deeper seismic zone and is not connected to the main Himalayan seismicity along the plane of detachment.

The Sikkim earthquake (CMT plot no. 17) and the Rangit Valley Tectonic Window earthquake of 20.05.2007 in Sikkim (h 42 km, EHB 20 km, CMT plot no. 14) together, better define the slip motion for the Tista lineament as they occur on either side of it (Fig. 3) at focal depth of 20–50 km. Both these earthquakes show right lateral strike-slip motion along NW-SE trending high dipping fault plane with steep plunging neutral axes, shallow plunging compression and extension axes along N-S and E-W respectively. Though there are variable first nodal plane solutions of 2011 Sikkim earthquake (Table 1) advocated by different agencies, we prefer the CGMT solution for tectonic interpretation as it is in parity with the other CMT solutions of Table 2. The orientations of stress axis for the Sikkim earthquake indicate active shearing at focal depths ~ 40-60 km (as indicated by de la Torre et al. (2007) from first motion data in Eastern Nepal Himalaya). Its foreshock also came from

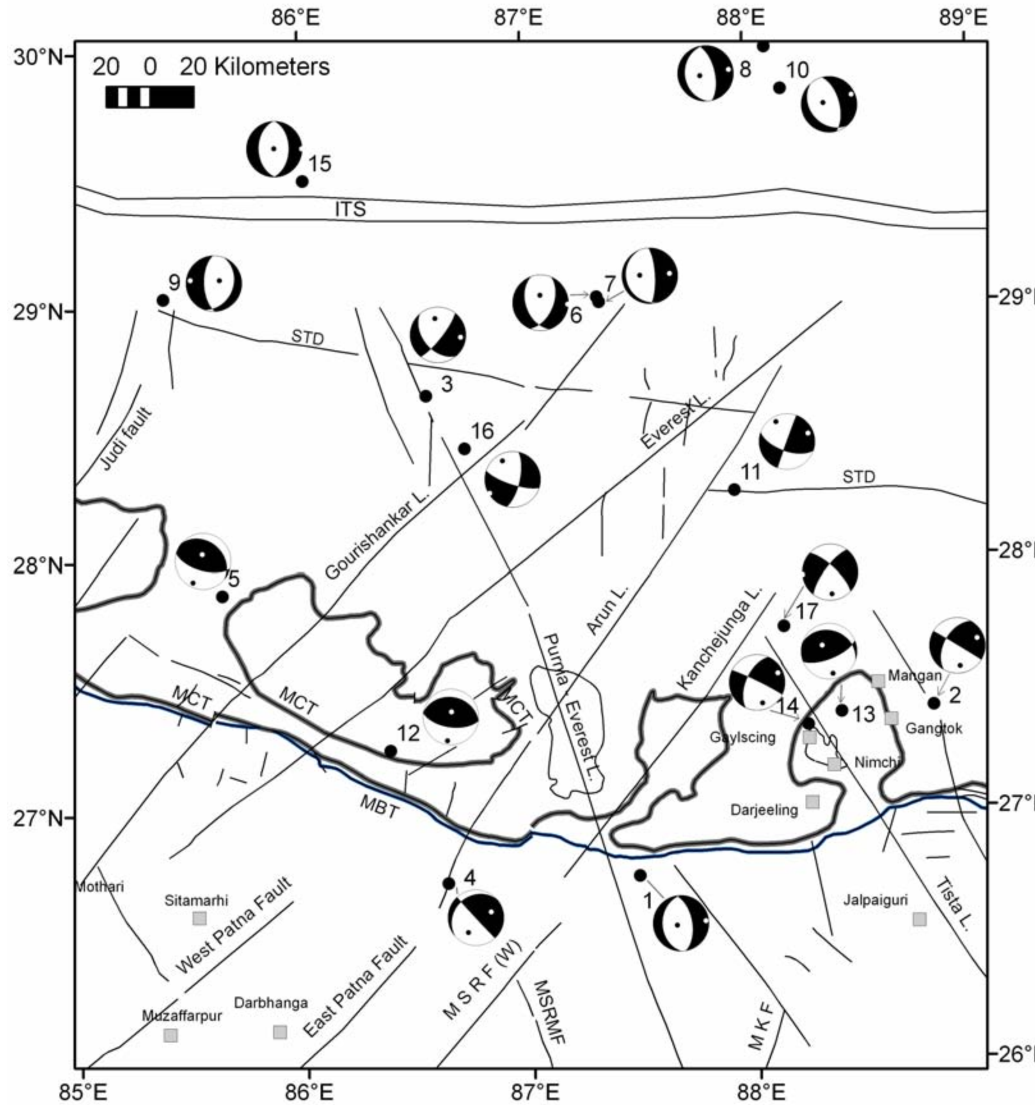

Fig.3. Tectonic map with location of fault plane solutions. Beach ball diagrams with number represented in Table 2 are plotted to infer the fault geometry. Abbreviations are as in Fig.1.

the same depth (51 km). Distribution pattern of aftershocks for the Sikkim earthquake and its fault plane solution thus permit us to infer that the earthquake was produced in association with the Tista lineament/fault. The conjugate shear faults at depths are activated by northward motion of the Indian plate and subsurface structures along its leading edge below the Himalayan collision zone, thus generating strike-slip earthquakes at depth and thrust-type earthquakes in shallower crust. Some support to this observation is accorded by the results of moment tensor inversion and first motion polarities obtained by the Himalayan Nepal Tibet Seismic Experiment which reports that the strike-slip earthquakes dominate at Moho depths >60 km in the Himalayas (de la Torre et al. 2007).

CONCLUSION

Transverse lineaments/faults from foredeep to Tibetan part of Himalaya form rhomb shaped active seismic blocks in the Himalaya defining promontories for the advancing Indian Craton. These lineaments/faults actually produce conjugate shear faulting pattern suggestive of pervasive crustal interplay deep inside the mountains. Two contemporary earthquakes originating in the central Himalayan arc and its foredeep (Sikkim earthquake of 18.09.2011 and Bihar-Nepal earthquake of 20.08.1988) are associated with such transverse lineaments/faults (the East-Patna Fault and its continuation as the Arun lineament in case of 20.08.1988 Bihar – Nepal earthquake and the Tista lineament for 18.09.2011 Sikkim earthquake) traversing the

Himalayan tectonic zone. Focal mechanism solutions of the contemporary earthquakes in the east Nepal – Sikkim Himalaya suggest that large part of the current convergence across the central Himalayan arc is presently accommodated by lateral slip. The major lateral slip movement on transverse faults/lineaments plus the minor thrust type of slip movements along the major thrusts define the crustal dynamics along east Nepal – Sikkim Himalaya.

Distribution pattern of aftershocks for the Sikkim earthquake (M_w 6.9) of 18.09.2011 and its fault plane solution allow us to infer that the earthquake was produced in association with the transverse Tista lineament/fault. Though the earthquake is large in magnitude, it has not evaded entirely the seismic risk and the possibility of occurrence of an earthquake of still higher magnitude (see seismic potentiality of zone F, Table 3, Mukhopadhyay et al. 2011a). The crustal movements also suggest that occurrence of an earthquake by reverse slip in this zone may not altogether be ruled out. Ground documentation of co-seismic features (faults/fissures/landslides) will certainly constrain the deformation pattern caused by the Sikkim earthquake of 18.09.2011.

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