Earthquake Mechanism and Active Tectonics of Eastern Nepal Himalayas and Vicinity

सिपक्तु माता मही रसा नः

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ABSTRACT

The tectonics of Nepal Himalaya and its adjoining Tibet region is quite complex, in which different types of faulting patterns exist. Focal mechanism solutions of earthquakes in the Himalayan region suggest the existence of thrust faults stretching along EW with one plane dipping gently north beneath the Himalaya. The dominance in thrusting appears in the Western and Central Nepal regions, whereas, in the Eastern Nepal region, it is a combination of thrust and strike-slip with large thrust mechanism. The nature of fault-plane solutions in the Eastern Nepal Himalaya shows a slightly different faulting pattern as compared to that of the Central and the Western Nepal Himalaya. Here, the solutions are mixed with thrusts and strike-slip motion with large thrust components. The observed change in the faulting pattern in the eastern parts of the thrust zone may indicate substantial movement along the transverse faults, as compared to that of the western region with the changes in the deep crustal structure. The study suggests that thrusting decreases rapidly with increasing focal depth and deformation occur due to strike-slip motion at greater depths. This may be indicative of an unstable state of the upper mantle leading to a rapid deformation in the presence of high degree of thermal regime.

Keywords: Fault-plane solution; Seismotectonics; Stress pattern; Eastern Nepal Himalaya

1. INTRODUCTION

The central sector of the Himalaya comprising Nepal and its adjoining regions has a complex tectonic history (Upreti, 1999 and Hodges, 2000) with a highly deformed upper crust that displays all major tectonic features of the Himalayan mobile belt. The region is known for its high seismic activity with the great earthquake of 1934 (M 8.4) and a number of large earthquakes of magnitude M ? 6.0 which occurred during the last century. The main Himalayan seismic belt is typically confined within the main Central Thrust (MCT) and the Main Boundary Thrust (MBT) (Ni and Barazangi, 1984) (Fig. 1). The seismicity of the region is fundamentally associated with the MBT and also with a number of thrusts, normal and transverse faults. Seismic activities in the Nepal Himalaya region are mostly confined in the upper crust; whereas clusters of a few intermediate events have been found between the MBT and the MCT in the Western Nepal region

.The seismic activity in the Eastern Nepal region is considerably high and offsets towards the north in which shallow and intermediate focus earthquakes occur frequently. Shallow events are mostly confined close to major thrusts and transverse faults; and the activities in the adjoining Tibet region lie close to north-south trending normal faults/graben structures.

Twenty fault-plane solutions (Table 1) (Ni and Barazangi, 1984; Chandra, 1978; Singh and Gupta, 1980; Zhu and Helmberger, 1996; Paudyal, 2008 and Paudyal et al., 2008) are used to infer the geodynamic processes and associated stress pattern in the Eastern Nepal Himalayan collision zone. Using WWSSN P-wave first motion data, Chandra (1978) observed that thrust type faulting is prevalent in the Central Himalaya and confirmed the underthrusting of the Indian plate towards the north along the Himalayan arc. The source dynamics of the 1934 great earthquake, observed using P-wave first motion data and surface wave polarization angle, are compatible with thrust and strike-slip components and an underthrusting of the Indian plate towards the southwest (Singh and Gupta, 1980). The high stress drop associated with the 1934 earthquake was interpreted in terms of the high tectonic stress prevailing in the region. Ni and Barazangi (1984) determined solutions using P-wave first motion and S-wave polarization recorded on long period instruments of WWSSN, and observed the shallow angle north dipping thrust environment in the Himalayan collision zone. Considering these observations, they concluded that this zone separates the under-thrusting Indian plate from Lesser Himalayan crustal block, which appears to define a part of the detachment. Zhu and Helmberger (1996) used broadband records of regional distance and pP and sP phases by waveform modelling for three small earthquakes situated in the north of the Higher Himalaya, and also observed a strike-slip mechanism with some component of normal faulting showing roughly north-south compression and east-west extension. Recently, new solutions for the Nepal Himalayan region are determined by Paudyal (2008) and Paudyal et al. (2008). The inferred unilateral stress pattern generated by the northward movement of the Indian Plate in the central part of the Himalaya reveals that the present day collision occurs roughly perpendicular to the local strike of the Himalaya. The process for the determination of the fault-plane solutions is uniform in Centroid Moment Tensor (CMT) solutions; hence two such solutions are used in the present study which could be reliable.

In addition, there are several investigators who have contributed significantly to understand the seismotectonics and the related stress pattern in Himalaya and Tibet regions (Fitch, 1970; Molnar et al., 1973; Rastogi, 1974; Gupta and Singh, 1980; Verma and Kumar, 1987; Verma and Reddy, 1988; Molnar and Lyon-Caen, 1989; Singh, 2000; Shankar et al., 2002; and Paudyal et al., 2010). Using long period records of WWSSN, Gupta and Singh (1980) determined the fault-plane solutions of the Nepal Himalaya and inferred the thrust faulting, in general, with a few cases having a small component of strike-slip faulting. Thrust faulting and the crustal shortening along the normal to the southern margin of the Tibetan plateau were derived through fault-plane solutions (Molnar and Lyon-Caen, 1989). Besides using P-wave first motion directions, the waveforms of body and surface waves have also been used by some scientists toobtain improved fault-plane solutions (Ni and Barazangi, 1984; and Rastogi, 1974). Most of the results of fault-plane solutions for the earthquakes occurring between the MBT and the MCT or slightly north of the MCT have thrust solutions, with nodal planes dipping gently towards the north however, two earthquakes in the Ganga basin showed normal fault-plane solutions. These studies were carried out on a regional scale with a limited number of fault-plane solutions. Such studies were not extended to a local scale for a highly seismic segment like Eastern Nepal using a larger number of fault-plane solution data.

In the present paper, author has tried to infer the recent trend in the faulting pattern taking place in a small region in Eastern Nepal Himalaya and its adjoining area using twenty events that occurred in the last 45 years, plus the 1934 great earthquake. Selected events include six in the range of m_b 4.7-4.9; ten in the range 5.0-5.9; and four with $m_b \geq 6.0$. The focal depths of these events lie between 9 to 57 km, and one of them at 79 km. The majority of the solutions show strike-slip motion with large thrust component and a few with thrust and normal faulting characteristics. The faulting pattern is analyzed in relation to the major tectonic features, the nature of faulting in the vertical sections along east-west and north-south directions and the prevailing stress condition using the orientation of pressure and tension axes.

2. ANALYSIS OF FAULT PLANE SOLUTIONS

The source parameters for the earthquakes considered in the present study are presented in Table 1. The azimuth and the plunges of the *P*, *T* and *B* axes and the orientation parameters of nodal planes are in degrees measured from the north and the horizontal, respectively, and the values obtained are presented in Table 2.

Table 1- Source parameters of earthquakes from Eastern Nepal Himalaya and its adjoining region

Sl. Nos.	Date	Origin time hh:mm:ss	Lat (^oN)	Long (^oE)	Mag. (m_b)	Depth (km)
A. Solutions determined by the author						
1	22/03/1973	01:06:57	87.15	28.12	5.0	33
2	24/04/1975	01:35:51	87.04	27.43	4.9	26
3	05/04/1982	02:19:41	88.84	27.38	5.0	09
4	20/04/1988	06:39:43	86.72	27.02	5.4	54
5	27/09/1988	19:10:10	88.37	27.19	5.0	28
6	09/01/1990	02:29:22	88.11	28.15	5.7	79
7	04/04/1992	17:43:20	87.98	28.15	4.9	25
8	26/04/1996	16:30:58	87.80	27.85	5.0	25
9	25/09/1996	17:41:17	88.80	27.60	4.9	32
10	30/12/1996	11:08:19	86.77	27.49	4.8	33
11	27/11/1997	16:11:57	87.31	27.56	5.0	33
12	08/12/1997	02:03:56	87.27	27.50	4.8	33
13	26/11/1998	10:14:30	87.86	27.69	5.1	35
14	02/12/2001	22:41:13	88.18	27.22	5.0	33
B. Solutions compiled from literature						
15	19/06/1979	16:29:12	87.51	26.74	5.1	24
16	20/08/1988	23:09:16	86.62	26.75	6.4	57
17	15/01/1934	08:43:18	86.50	26.50	8.3	20
18	12/01/1965	13:32:24	87.84	27.40	6.1	23
19	19/11/1980	19:00:45	88.75	27.39	6.1	17
20	21/12/1991	19:52:45	88.14	27.90	4.9	57

The beach balls of fault-plane solutions of these earthquakes are depicted in Fig. 1. The events 2 and 18 have thrust mechanism with nearly east-west striking nodal planes running almost parallel to the trend of the MBT. One of the nodal planes of these two events dip towards north and the P-axes are perpendicular to the collision direction. Further, most of the solutions (~68 percent) exhibit strike-slip faulting either with thrust (events 3-5, 8-12, 14, 16, 17 and 19) or with normal (events 1, 6, 13 and 20) nature. One event located in Southern Tibet (event 7) and one located in the Indo-Gangetic plane (event 15) show normal faulting with nearly north-south trending nodal planes. The east-west trending *T*-axis for the Tibetan event (event 7) is in agreement with the east-west flow of materials beneath Tibet. Further, it is unusual that a single earthquake (event 15) located south of the MBT also revealed normal faulting in the underthrusting environment. This solution is analogous to the events associated with oceanic trenches (Ni and Barazangi, 1984) and probably caused by flexing of the Indian plate as it bends and underthrusts beneath the Himalaya.

Table 2 - Fault plane solution parameters of earthquakes from Eastern Nepal Himalaya and its adjoining region. Strike, Dip, Dip direction (Dip dir.), zimuth (Az) and plunges (Pl) are in degrees

l. os.	**Nodal plane I**			**Nodal plane II**			**P axis**		**T axis**		**B axis**		**Ref.**
	Strike	**Dip**	**Dip dir.**	**Strike**	**Dip**	**Dip dir.**	**Az.**	**Pl.**	**Az.**	**Pl.**	**Az.**	**Pl.**	
1	048	61	138	140	86	230	008	24	269	18	148	60	**7**
2	091	44	359	091	46	179	179	02	359	88	091	00	**8**
3	011	75	282	094	66	184	054	28	322	05	220	61	**7**
4	096	76	006	169	43	259	035	21	145	44	288	39	**7**
5	018	38	108	082	72	351	327	20	211	51	070	32	**7**
6	036	54	306	118	80	209	072	36	167	14	286	52	**7**
7	163	22	073	163	69	253	073	65	252	26	163	00	**7**
8	080	71	350	012	39	103	206	50	323	20	067	33	**8**
9	086	59	176	151	54	061	206	04	301	51	115	39	**8**
10	036	38	126	096	67	006	344	16	228	56	082	30	**8**
11	066	68	336	170	58	080	299	06	204	38	037	50	**7**
12	016	40	106	087	73	357	216	48	329	19	075	36	**8**
13	004	42	094	063	66	333	198	55	309	14	047	32	**7**
14	086	70	355	153	44	243	131	49	023	15	282	38	**8**
15	179	34	-82	350	57	-95	243	78	084	11	353	04	**CMT**
16	230	23	02	137	89	113	207	40	069	41	317	23	**CMT**
17	280	30	-	154	72	-	046	24	275	58	145	22	**5**
18	090	75	-	270	12	-	181	33	001	57	271	00	**4**
19	218	59	-	119	74	-	172	12	073	35	275	54	**3**
20	-	-	-	-	-	-	157	06	252	03	-	-	**6**

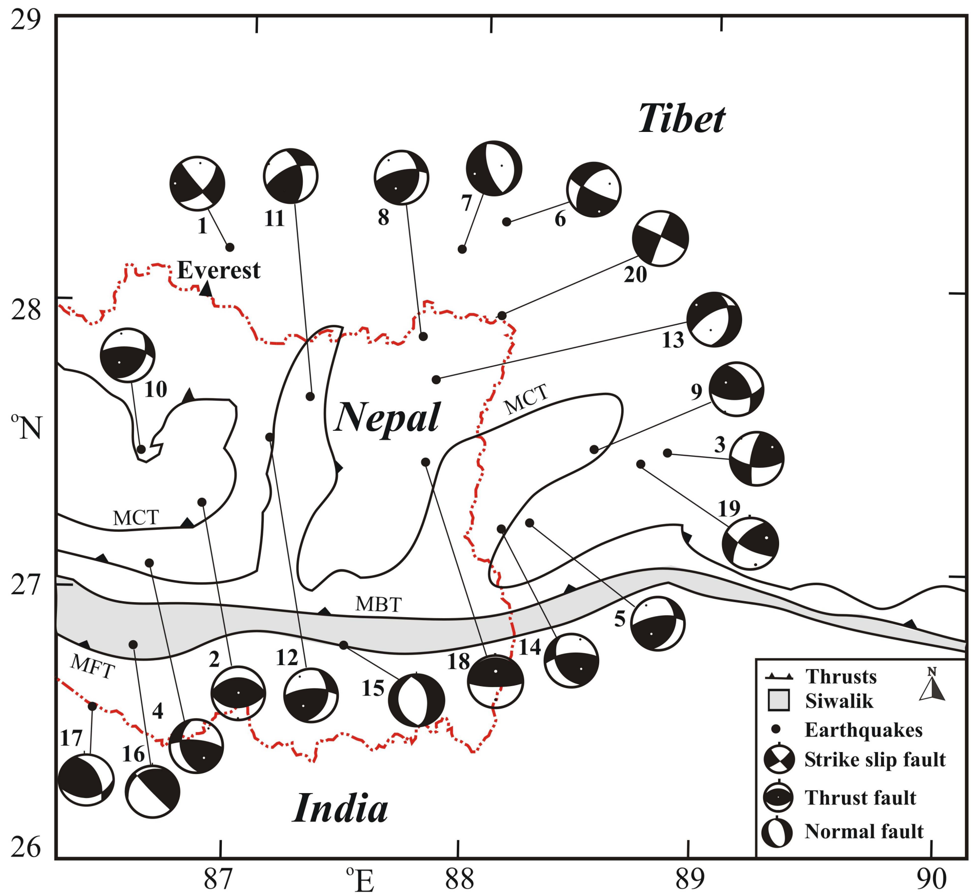

Fig. 1 - Seismotectonic map of Eastern Nepal and its adjoining region. Epicenters of the earthquakes are shown by solid circles. Shaded quadrants represent compressional first motion, and open quadrants are dilatations

The 1988 Udaypur earthquake, m_b 6.6, (event 16) occurred in the vicinity of a rupture zone of the great earthquake of 1934 (event 17) and both show a similar faulting pattern with a combination of thrust and strike-slip motion. The fault plane of the 1934 earthquake (strike 280^o, dip 30^o and slip angle 40^o) shows underthrusting towards the southwest (Singh and Gupta, 1980). Thrust faulting with a right lateral strike-slip component is reported for the 1988 Udaypur earthquake and the inferred fault plane (WNW-ESE) is compatible with the general trend of major tectonic features (Pandey and Nicolas, 1991). Another large earthquake (event 19; m_b 6.1) located near MCT around Darjeeling revealed predominantly a strike-slip faulting pattern (Ni and Barazangi, 1984). The reported north-south trending P-axis and east-west trending T-axis for this event is consistent with strike-slip and reverse motion along the existing fault in the Lesser Himalaya.

The majority of events considered here are shallow focus within 35 km, three earthquakes (events 4, 16 and 20) between 54-57 km and an isolated earthquake (event 6) at intermediate depth of 79 km (Fig. 2). The solutions can be grouped into two main depth sections: up to 35 km and 50 to 80 km. It is evident that both events associated with normal faulting (events 7 and 15) are located within 10-25 km depth, and possibly give an indication of causative factors lying at shallow depths, whereas all the thrust and most of the strike-slip faulting extend further down. A significant variation in the dip angles and strike directions of nodal planes associated with these earthquakes may represent a tectonically deformed upper crustal zone. The northerly shallow dipping nodal planes for large earthquakes (events 16, 17, 18 and 19) support continuing underthrusting of Indian landmass below the Himalayan arc. Further, the four earthquakes (events 4, 6, 16 and 20) which occurred at greater depths extending from about 50 to 80 km, show predominantly strike-slip patterns. This suggests that the thrusting decreases rapidly with increasing focal depths and deformation may occur due to strike-slip motion at greater depths in this zone, which may indicate the unstable state of the upper mantle leading to rapid deformation in the presence of high degree of thermal regime.

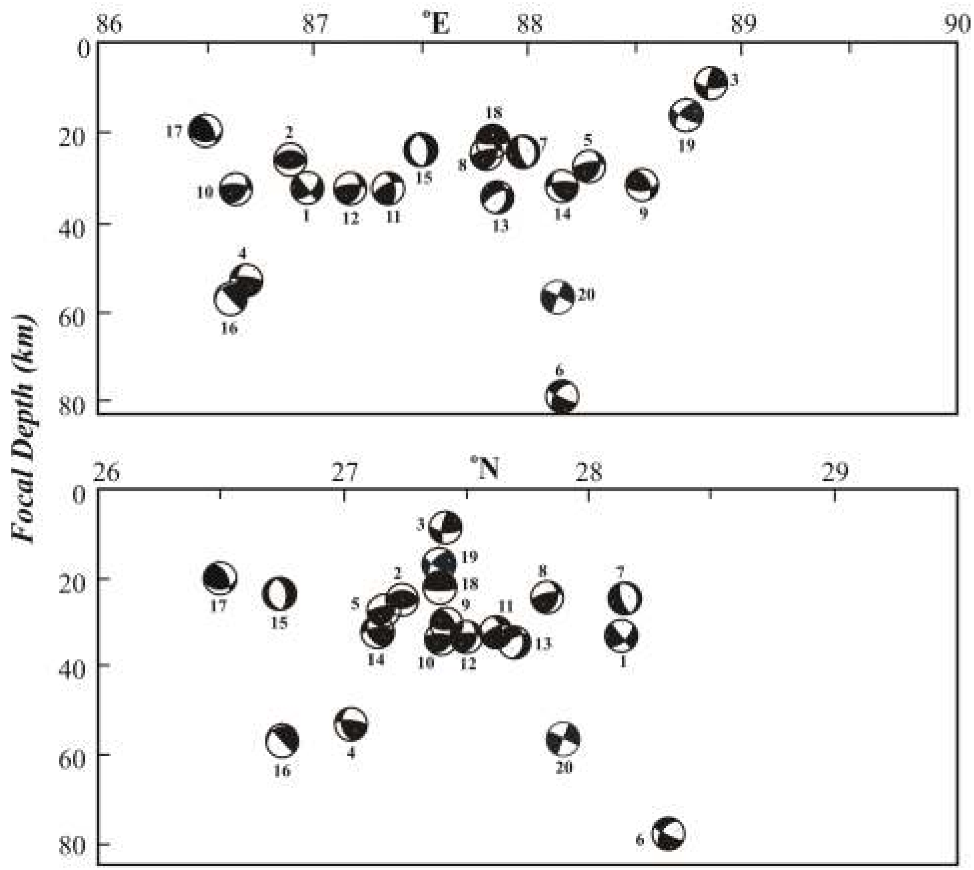

Fig. 2 - Relationship of the nature of faulting patterns with focal depth along longitude (top) and latitude (bottom) in the Eastern Nepal and its adjoining region. Shaded quadrants represent compressional first motion, and open quadrants are dilatations. The numbers attached to each solution is their respective serial number as given Table 1

The tectonics of Nepal Himalaya and its adjoining Tibet region is quite complex in which different types of faulting pattern exist. Thrust environment is dominant in the Western and Central Nepal regions (Paudyal, 2008), whereas, in the Eastern Nepal Himalayan region, it is a combination of thrust and strike-slip with large thrust mechanism. The faulting pattern in the adjoining Tibet is totally different than the Himalayan compressed belt where normal faulting is predominant with north-south trending nodal planes leading to an east-west flow of materials (Paudyal, 2008). The most predominant mode of energy release in the Eastern Nepal Himalaya region is due to thrust with strike-slip faulting (Table 3).

Table 3- Frequency of different types of fault-plane solutions observed in Eastern Nepal, Himalaya and its vicinity

Number of fault-plane solutions	Frequency of different types of fault-plane solutions				
	Thrusts	Strike-slip +Thrusts	Strike-slips	Normal	Strike-slip + Normal
20	2	14	1	1(1)	1

Note: The number shown within parentheses under the normal column is the earthquake actually located in the adjacent Tibetan part.

3. STRESS FIELD ORIENTATION

The composite plot of *P* and *T* axes will give a more robust and more general characteristic of the stress field than using individual event mechanisms. For a homogeneous medium and under the assumption that both principal stress axes make angles of 45° with slip direction, *P* and *T* axes show the direction of maximum compression and maximum tension, respectively. The azimuth and dip of *P*- and *T*-axes can be determined from the fault-plane solutions. The thrust faulting is generally associated with compressive stress prevailing in an area, while tension causes normal faulting indicating the flow of materials. If the *P* plunge is less than 45° and the *T* plunge is greater than 45°, it represents a compressive regime, and its reverse condition indicates the extensional regime. The composite solutions depict direct evidence for the main compressive stress field in the Nepal Himalaya region.

The nature of fault-plane solutions in the Eastern Nepal Himalaya shows a slightly different faulting pattern as compared to that of the Central and the Western Nepal Himalaya. Here, the solutions are mixed with thrusts and strike-slip motion with large thrust components. Using a composite stereographic projection of orientations of the compression and tension axes the nature of the stress direction acting in this region is inferred. The estimated values of the plunges and the azimuths of *P*- and *T*- axes are furnished in Table 2, and the distributions are shown in Fig. 3. Here the plunges of *P*-axis are observed to be gentle to moderately steep; whereas it is mostly steeper for the *T*-axis (within 45° to 60°). Nearly 70 percent of the *P*-plunges are less than 45° with around 50 percent lying within 24°. Further, all the *T*- plunges except one vary between 10°-60° showing gentle to steeply dipping nature of the nodal planes with about 30 percent of events having a dip greater than 45° (Table 2). The *P*- and *T*- axes show a rather diffuse distribution representing compressive stress in the field from south and north. A substantial difference in the plunges of *P*- and also in *T*- axes in this region has been observed as compared to the Central and the Western Nepal Himalaya, which may be attributed to the presence of a significant strike-slip faulting along the transverse features in the Himalayan thrust belt. The compressive stress is acting approximately along the N-S direction nearly perpendicular to the trend of the Himalaya. From the orientation of maximum compressive stress, it may be indicated that the earthquake generation process in the Eastern Nepal Himalaya is somewhat different from that in the Central and the Western Nepal Himalaya.

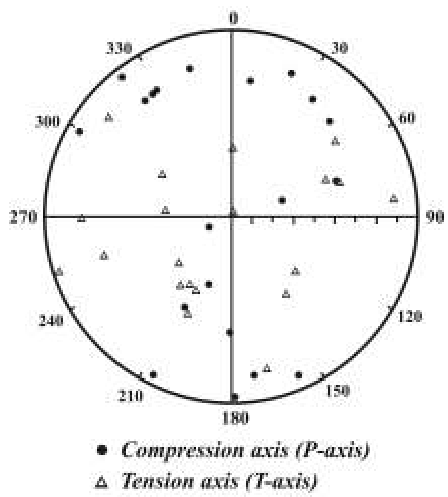

Fig. 3 - Lower hemisphere projection of P-axes (•) and T-axes (Δ) in Eastern Nepal Himalaya

4. DISCUSSIONS

The Himalaya was formed as a result of the collision of India with Eurasia. This collision was brought about by the northward migration of the Indian plate resulting in closing of the intervening Tethyan Ocean. It is generally accepted that the faulting pattern in the Himalaya and its adjoining region is the result of collision of the Indian plate with the Eurasian plate that occurred in the Late Tertiary (Powell and Conagham, 1973 and Mplnoa and Tapponnier, 1978). The present geotectonic activity in the Himalayan collision zone is the result of post collisional incident. The current information derived through fault-plane solutions testifies that the processes, which were responsible for the formation of Himalaya, are still continuing. Fault-plane solutions of earthquakes in the Himalaya, in general, imply thrust faulting and are consistent with the northward movement of the Indian subcontinent and underthrusting in the Himalaya at shallow depths.

Rastogi (1974) observed a thrust faulting environment of earthquakes with a shallow dipping nodal plane consistent with the underthrusting of the Indian plate towards north-northeast beneath the Himalaya. Baranowski et al. (1984) pointed out that there is a coherent underthrusting of the Indian plate beneath the Lesser Himalaya in the eastern half of the Himalayan arc. They inferred that slip vectors are locally perpendicular to the Himalayan mountain range with a very gentle plunge in the eastern section and more steeply in the western section. The stress system prevailing over the Nepal Himalaya thrust belt is observed to be more complex compared to the adjoining south central Tibet region. *P*-axes orientations are inferred in the north-south to northeast-southwest for the Himalaya and from north-south to east-west for the Tibet region; whereas *T*-axes change from north-south to east-west in both regions (Singh, 2000). The eastward flow of the Tibetan plateau is due to the combined action of the shear and the compressive stresses as a consequence of continued convergence of two mega plates, India and Eurasia.

In the Western Nepal region, the events located between MCT and MBT show thrust mechanism with northwest to northeast dipping nodal planes indicating northward underthrusting of the Indian plate along the major thrusts of Himalayas (Paudyal et al., 2010). Moreover, an obvious picture of the existence of under-thrusting phenomenon at a gentle angle along north dipping nodal planes is inferred from the faulting pattern of moderate size earthquakes ($m_b \geq 6$). Though the nodal planes of individual event differ marginally in their orientation, the collective dip of the nodal planes show northward underthrusting of Indian plate at shallow angle. The upper crust of this region is observed to be the most active thrust faulting zone. In the Central Nepal Himalaya region, the faulting pattern is consistent with the trend of the thrust features and the pattern of underthrusting of the Indian plate is analogous to that of the adjacent the Western Nepal Himalaya region.

In Eastern Nepal, the majority of the solutions show clearly a different trend, strike-slip motion with large thrust component and a few events with pure thrust characteristics, more solutions with sinistral and dextral motions along their inferred fault planes indicating that a major portion of the stress is being released along the existing transverse tectonic features. The most predominant mode of energy release in the Eastern Nepal Himalaya region is due to thrust with strike-slip faulting. The inferred nodal planes associated with thrust and strike-slip faulting show their orientations from NW-SE to E-W being roughly parallel to the strike of the Himalayan arc. A considerable variation in the dip angles and strike directions of nodal planes may represent tectonically the deformed upper crustal zone. The large earthquakes associated with northerly gentle dipping nodal planes of this region indicate that the underthrusting of Indian landmass below the Himalayan arc is continuing. The continuation of strike-slip faulting from upper crust to deeper levels, and the absence of thrusting at greater depths suggest that there is a deformation in the deeper parts of the lithosphere which occurs due to the strike-slip motion in the Eastern Nepal Himalaya region only. It was unusual for an earthquake that occurred on 19 June 1979 in the thrust zone located south of the MBT to show normal faulting with *T*-axis approximately perpendicular to the strike of the Himalayan arc showing nearly north-south extension.

Thrust faulting in an area is normally caused by the compressive stress due to collision and subduction of lithospheric plates whereas normal faulting indicates an extensional zone like spreading centers where materials flow perpendicular to the fault plane. The faulting pattern to the west of Kathmandu in the Central Himalaya region is thrust dominated and the pattern changes to strike-slip motion with a large thrust component to the east (i.e., beyond 85^{o} E) (Paudyal, 2008). The observed change in the faulting pattern in the eastern parts of the thrust zone may indicate substantial movement along the transverse faults as compared to that of the western region with the changes in the deep crustal structure. The strikes of the northward gently dipping nodal planes in the Nepal Himalaya region are normally parallel to the major thrust/local tectonic features as evidenced by the faulting pattern (Fig. 1) indicating under-thrusting of the Indian plate towards the north along the Himalayan arc. In the Nepal Himalaya region, it is inferred from the orientation of the P-axes that the compressive stresses are dominating along N-S to NE-SW (Paudyal, 2008). However, a considerable difference has been observed in the plunges of *P*- and *T*- axes in the Eastern region as compared to its western part which may be thought of as due to the presence of dominant strike-slip faulting with a large thrust component.

5. CONCLUSIONS

The mainstream of the fault-plane solutions signify predominantly a compressive environment with strike-slip motion having gently northward dipping nodal planes in the Eastern Nepal Himalaya region which is due to the compression exerted by the northward movement of the Indian plate and movements along the transverse faults. The Indian continental lithosphere materializes to be thrusting at a gentle angle. It may be visualized that, as this huge lithosphere descends into the upper mantle, a portion of it melts and raises upwards depositing melts at the bottom of the Tibetan crust, which results in crustal thickening and consequently increases the vertical load. The inferred direction of compressive stress is acting almost perpendicular to the Himalaya suggesting crustal shortening in the north-south direction. A concentrated pattern of sharply dipping tension axes shows that there is no mass movement in the Nepal Himalaya region contrary to that of Tibet. The prevailing stress conditions at shallower levels extend up to the deeper levels into the upper mantle, as verified by the faulting pattern in the region. Almost akin pattern of horizontal compression and vertical tension axes are inferred all along the Central Himalayan belt (Paudyal, 2008). However, the existence of a fairly diffused nature of these axes in the eastern sector is possibly due to the variation in the deep crustal structure along with the local factors including transverse faults.

Acknowledgments

The present work has been carried out within the framework of the Associateship Scheme of the Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy. The author is grateful to ICTP for providing the necessary facilities and literature for the present work. The author is thankful to Prof. H.N. Singh, Department of Geophysics, Banaras Hindu University, India and Dr. D. Shanker, Department of Earthquake Engineering, IIT Roorkee for useful discussions.

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