FE stress analysis and Quaternary deformation in the fold-and-thrust belt of the Garhwal Himalaya

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Abstract

The immense Himalayan arc is evolved as a consequence of the collision between Indian and Eurasian landmasses some 50 million year ago. The Indian plate converges northward at the average rate of 20.5 ± 2 mm/year (Bilham et al., 1988), and is under-thrusting beneath Tibet. This continuous northward penetration of India under Eurasia has produced the broad zone of active crustal deformation, shortening, slicing and surface uplift of the northern margin of the Indian continent; and build up the Himalaya is under very strong compressive strain that made the entire Himalayan region one of the most seismo-tectonically dynamic intercontinental regions of the world. In the present study, an approach has been made to model a NE-SW cross-section (Ram et al., 2005) extending from the Gangetic Plain to the Tethys Himalaya including potentially active major faults by means of FE method (Hayashi, 2008) considering an elastic rheology under plane strain condition with convergent boundary environment in the fold-and-thrust belt of the Garhwal Himalaya. The present study provides an opportunity to understand the neotectonic stress distribution, style of deformation and present day shortening rate in the Himalayan front. Simulation results reveal that the compressive stress of stress developed in the northern part and tensional stress fields developed in the southern part of the Garhwal Himalaya, and consequently, thrust are developed in the north and normal faults are developed in southern regions respectively, which is consistent with the characteristics of the fold and thrust belt. Furthermore, modeling results show good agreement with the Quaternary deformation, active faulting, microseismicity and focal mechanism solution of the fold-and-thrust belt of the Garhwal Himalaya.

1. Introduction

The lofty Himalaya is unique, immense mountain range of the world and represents

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one of the few tectonic zones in the Earth, where a continental crust under-thrusts over continental crust. The entire over 2500 km long Himalayan arc extending from Namche Bawar on the east to Nanga Parbet on the west is evolved as a consequence of the collision between Indian and Eurasian landmasses some 50 Ma ago (Molnar and Tapponier, 1975; Molnar and Lyon-Caen, 1988). The Himalaya was formed by huge tectonic forces which contain evidence of the complete Wilson cycle from the Mesozoic to the Eocene, followed by post-collisional deformation that is still active. Thus, the Himalaya is the best natural laboratory that provides a paramount opportunity to examine the complex geological phenomenon in which continents respond to collisional orogenesis, and to attract the attention of earth scientists from many disciplines (Johnson, 2005).

Owing to scientific interest, the Himalayan fold-and-thrust belts have been extensively studied since 1950 after the Himalayan territory opened for the foreigners. The Himalayan arc can be divided into western, central and eastern sectors on the basis of regional variation in morphology. Present study area belongs to the western part of the Himalaya

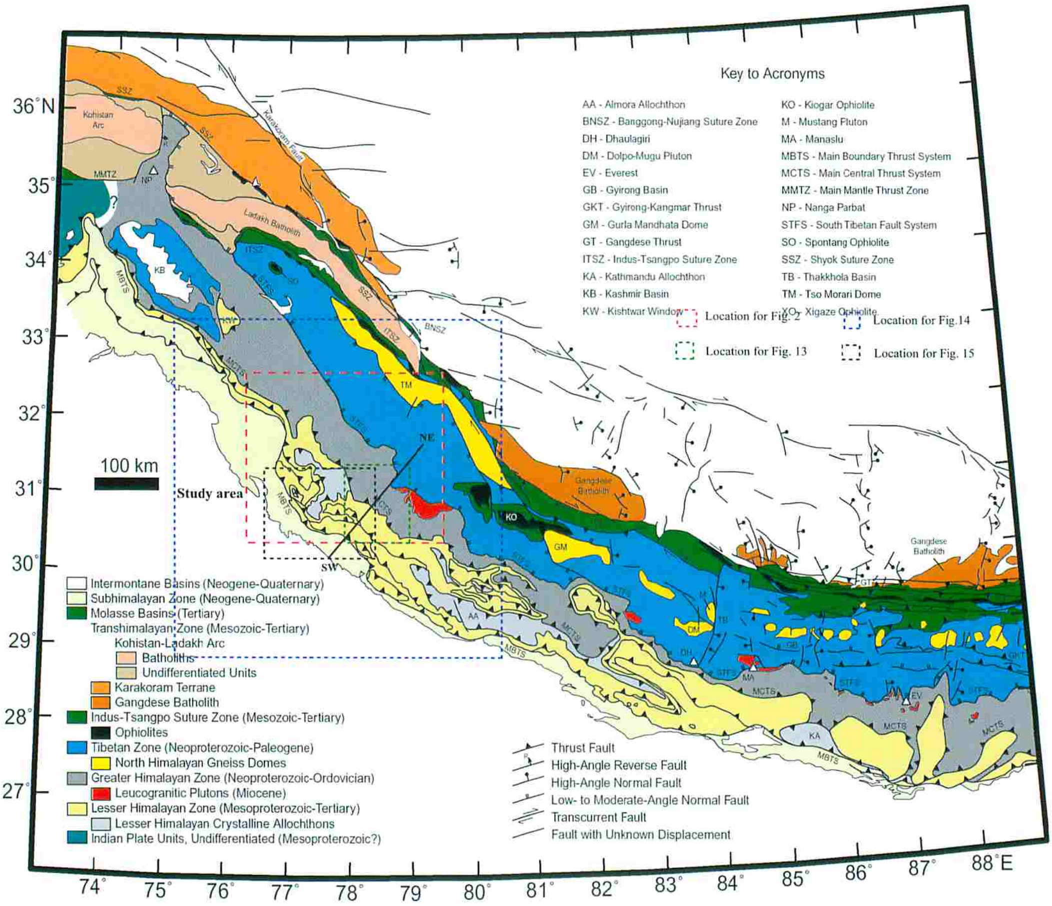

Fig. 1 Tectonic map of the Himalaya and southern Tibet (after Hodge et al., 2000).

in Garhwal region (Fig. 1). Several studies have been carried out in the region and point out complexities of the seismotectonic pattern (Verma et al., 1977; Kayal, 2001; Sharkar, 2004), intense cluster of microseismic activity in shallow depth (d <15 km) (Kayal, 2001) and high crustal deformation in the Garhwal region. Shortening rate across the Himalayan front is ~ 6-16 mm/yr from balanced cross-section (Powers et al., 1998) and $\geq 11.9 \pm 3.1$ mm/yr through the Holocene uplift records (Wesnousky, 1999). The slip rate across the Main Frontal Thrust (MFT) is $\geq 13.8 \pm 3.6$ mm/yr through the Holocene uplift records (Wesnousky, 1999) and 14 ± 1 mm/yr from GPS measurement in Dehra Dun region (Banerjee and Burgmann, 2002). Stress field of this region consistents with S_{Hmax} oriented N33°E generally perpendicular with the Himalayan arc (Gowd et al., 1992).

The study of the active fault simulation in the Himalayan fold-and-thrust belt is an important way to understand the relationship among the present observed geometries of structures, their internal deformation, the regional and local stress field and faulting pattern. The quantitative estimation of the stress field is also valuable to understand the regional geodynamic condition. In this regards, numerous studies such as active faults, lineament modeling, geomorphic (Nakata, 1989; Yeats at al. 1991; Powers at al., 1998; Valdiya, 2001; Malik and Nakata, 2003; Phillip et al., 2006; Thakur et al., 2006) and stress field (Gowd et al., 1992) analysis have been carried out to understand the regional stress field, style of deformation and type of faulting in the fold-and-thrust belt of the Garhwal Himalaya. Meanwhile, some numerical simulation studies (Alam and Hayashi, 2003; Howladar and Hayashi, 2003; Chamlagain and Hayashi, 2004, 2007) also have been applied in the Nepal Himalaya. However, neotectonic studies by numerical modeling in the NW-Himalaya have not been done so far.

In this study, an approach has been made to model a cross-section extending from the Gangetic Plain to the Tethys Zone including potentially active major fault zones by means of FE software package (Hayashi, 2007) considering an elastic rheology under plane strain condition with contractive boundary environment in the Garhwal Himalaya. Comparing other techniques numerical simulation permits the modeling of the structural features and deformation at full scale and to calculate stress and strain values a long time period by using different constitutive laws. The present study provides an opportunity to understand the deformation style, neotectonic stress distribution and present day shortening rates in the Himalayan front and compared with records of microseismicity, active faulting and GPS measurements for better understand the geodynamics of the Garhwal Himalaya.

The major objectives of the present study are as follows:

1. To explore the role of active faults in the regional stress field and faulting
2. To compare the simulated results to active faulting of the area
3. To compare overall results of the simulation with the microseismicity of the region
4. To analyze the simulated results with focal mechanism solutions of the study area
5. To find the shortening rate of the Himalayan front of the Garhwal region

2. Tectonic Evolution and Cenozoic Deformation of Himalaya

On the basis of palaeomagnetic data, Indian landmass separated from the Gondwana super-continent about 130 million years ago, and moved north-eastwards at a velocity of 18-19 cm per year and as well rotated more than 30° counter clockwise (Molnar and Topponier, 1975). For the period of this movement oceanic crust of the Tethys Ocean was subducted beneath the Eurasian continental margin, which melted at depth and formed the Transhimalayan plutonic belt. After that, the northward movement of Indian continent abruptly decreased and stabilized at ~ 5 cm per year, and that velocity persists up to present. This continuous northward penetration of India under Eurasia has produced the broad zone of active crustal deformation, shortening, slicing and surface uplift of the northern margin of the Indian continent, and the Himalaya build up the under very strong compressive strain which made the entire Himalayan range one of the most dynamic intercontinental regions of the world. This intense crustal deformation has developed over an area of several tens of million square kilometers from the Himalaya to Mongolia, and resulting several huge structural features and spectacular orogeny (Matte et al., 1997).

Whilst most of the oceanic crust was merely subducted below the Tibetan block during the northward motion of India, at least three major mechanisms have been put forward, either separately or jointly to explain what happened, since collision, to the ~ 2400 km of missing continental crust. The first mechanism is underthrusting of Indian continental lithosphere beneath Eurasia. Second is the eastwards lateral extension of Tibet and South-East Asia (Molnar and Tapponier, 1975) that seems the Indian plate as an indenter that squeezed the Indo-China block out of its way. The third proposed mechanism is that a large part of these 2400 km of crustal shortening and thickening since collision was accommodated by thrusting and folding of the sediments of the passive Indian margin together with the deformation of the Tibetan crust. Though, many scientists believed that this enormous quantity of crustal shortening perhaps results from an incorporation of these three mechanisms. It is considered that about 400-650 km of crust is under-thrusting beneath the Eurasian Plate (Patriat and Achache, 1984; Powell, 1986) however, this idea was discarded by Molnar (1984). Since then, there is controversy regarding the amount of crustal shortening and it is believed that the shortening in the suture zone is about 550 km and that in the Himalaya was probably not more then 1000 km. Furthermore, the spectacular seismic reflection profile shows that the Indian plate must have under thrust the Himalaya by at least 200 km and presumably more to the north (Zhao et al., 1993). While, Avouac and Tapponnier (1993) suggest that in so far as 50% of the convergence between India and Asia can be absorbed by the extrusion of Tibet. However, it is also controversial.

The tectonic evolution of the NW-Himalaya can be subdivided in two major episodes.

The first one is marked by compression tectonics related to the collision between India and Asia. This first event was primarily responsible for crustal shortening, thickening and metamorphism of the Indian continental margin, and deformation was accommodated by faulting, folding, and the formation of nappes (Thakur, 1987). The second major episode is marked by extensional tectonic structures related to the exhumation of the high-grade metamorphic rocks of the High Himalayan Crystalline Sequence. This second episode of syn-orogenic extension occurred while the Himalaya was still globally in compression and is expressed by ductile normal shearing, doming and brittle normal faulting (Fig. 1). The extensive crustal deformation and shortening took place along the entire northern edge of the Indian plate along the Indus Suture Zone in the north, with the process of episodic evolution of Himalaya. However, the deformation front was shifted gradually towards the south along the Zanskar Shear Zone (ZSZ), Main Central Thrust (MCT), and Main Boundary Thrust (MBT), and even in Main Frontal Thrust (MFT) (Molnar, 1975; Patriat and Achache, 1984; Valdiya, 1989; Nakata, 1989, 1990). Thus, the upper continental crust of India is sheared off and thrusts are propagating in south-westward direction along these mega thrusts. Thus, present day crustal deformation and accommodation mainly confined southern front of the Himalaya between the MFT and the MCT (Power et al., 1998; Wennouskey et al., 1999; Kumar et al., 2001; Beanerjee and Burgmann, 2002).

3. Geological Setting

The North-Western Himalaya is designated as that sector of the Himalaya, which lies west of Nepal and encompasses the Kumaun-Garhwal, Himanchal and Jammu and Kashmir regions. The principal tectonic zones of the Western Himalaya are the Sub-Himalaya, Lesser Himalaya, Higher Himalaya, Tethys Himalaya and Trans-Himalaya zones (Fig. 1).

3.1. Major Tectonic Sub-divisions of the Himalaya

According to Gansser, (1964) the Himalaya is classically divided into following tectonic units:

3.1.1. The Gangetic Plain

The southern most part in the Himalayan foothill is known as the Gangetic Plain and composed of Pleistocene to recent sediments. In the north it is delimited by the Main Frontal Thrust (MFT), and separated from the Sub-Himalayan rocks. The Gangetic Plain is one of the most extensively developed fluvial plains of the world and constitutes a major part of the Himalayan foreland basin (Fig. 2). Foreland basin is produced by the lithospheric bending in response to an orogenic load, and the asymmetric space thus created in front of the emerging mountain belt is occupied by various extents of sediment

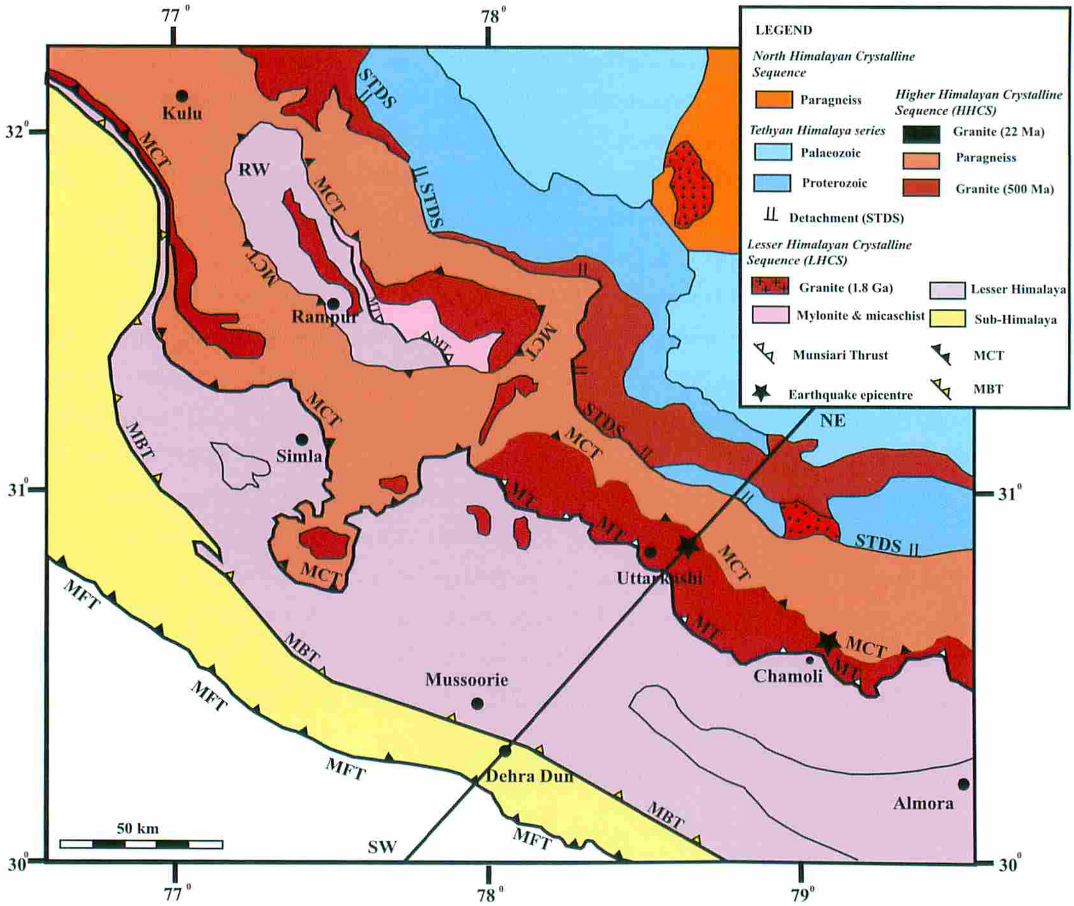

Fig. 2 Geological map of the Himanchal-Garhwal region, NW-Himalaya (modified after Vanney and Graseman, 2001).

fill (Agarwal et al., 2002). The Gangetic Plain is an example of an overfilled present-day foreland basin that has a prominent peripherals bulge where sedimentation taking place essentially by fluvial processes. The sediment fill of the Gangetic Plain is an asymmetrical sediment wedge with north-sloping lithosphere. In the NW-Himalaya, Thomas et al. (2002) classified the Gangetic Plains into Upper, Middle and Lower Plains on the basis of size and type of soil. The thickness of the sediments in the Gangetic Plain varies from north to south; only few tens of meter thick in the southern part and up to several km thick in the northernmost part. Similarly, size of the sediments gradually changes from course in the northernmost part to the finer sediments towards the south.

3.1.2. The Sub-Himalaya (SH)

The Sub-Himalaya or Siwaliks Group forms the foothills of the Himalayan Range, and is essentially composed of Miocene to Pleistocene molassic sedimentary sequences, and deposited in the foreland basin in front of the Himalaya during the Tertiary period. The

Sub-Himalaya is bounded by Main Frontal Thrust (MFT) to the south and Main Himalayan Thrust (MHT) in the north. This foreland basin constitutes a unique, present-day active foreland system in geodynamic context of intercontinental collision, where synorogenic sediments are progressively incorporated into the outer part of the thin-skinned thrust belt of the Himalaya. The Siwalik molasse basin was created by flexure of the Indian lithosphere below the load of the southward advancing of thrust sheet, and consists of an about 5 km thick, upward coarsening succession of fluvial siltstone, sandstone and conglomerate. As in other parts of Sub-Himalayan zone of Pakisthan and Nepal, Sub-Himalaya in NW-Himalayan also comprises three informal units known as the lower, middle and upper members on the basis of dominant rock types.

3.1.3. The Lesser Himalaya (LH)

The Lesser Himalaya is ~ 20 km thick pile of predominantly Early Proterozoic to Lower Cenozoic low to medium grade metasedimentary rocks with some Ordovician granites intrusion. In this zone inverted metamorphism also occurs. These low-grade sediments are thrust over the Sub-Himalaya along the Main Boundary Thrust (MBT) in the south and restricted from the Higher Himalaya by the Main Central Thrust (MCT) in the north. In the NW-Himalaya this zone is inhomogeneous and extensively wider particularly in the Kumaun-Garhwal region whereas squeezed and form a narrow belt in the Himachal-Kashmir area (Fig. 2). Furthermore, the Lesser Himalaya in the study area reveals complex seismotectonic structures, variation in stratigraphy and magmatic history. This zone often appears as several tectonic windows (Kishtwar or Larji-Kulu-Rampur) and crystalline nappes (Almora, Chamba), those bring crystalline rocks southward over less metamorphosed the Lesser Himalayan rock sequences from their root zones (Fig. 1). The geology, tectonics and stratigraphy of the Lesser Himalayan zone in the Kumaun-Garhwal, Himanchal and Chamba-Kashmir region has been documented by numerous workers including Thakur (1987), Fuchs and Linner (1995), and many others.

3.1.4. The Crystalline Nappe

The SW-directed crystalline nappes are probably formed by the High Himalayan Crystalline Sequence and were exhumed by thrust faulting along the MCT over the Lesser Himalaya. These Lesser Himalayan nappes are also known as thrust sheet, crystalline slab or wedge. It is believed that, the internal deformations within these nappes are primarily responsible for a large amount of crustal thickening. However, origin of these nappes and their relation with MCT are still controversial. The Almora and Chamba are widely known crystalline nappe in the NW-Himalaya and composed of low to medium grade metamorphic rocks especially, slate, quartzite, schist and gneiss.

3.1.5. The Higher Himalaya (HH)

The Higher Himalaya forms the backbone of the Himalayan orogen and encompasses the areas with the highest topographical relief. More or less, 30 different names exist in the literature to describe this zone; however the most frequently establish equivalents are the Higher Himalayan Crystalline, Greater Himalayan Sequence and Tibetan Slab. This zone is bounded by the Main Central Thrust (MCT) to the south and the South Tibetan Detachment System (STDS) to the north (Fig. 2). In the NW-Himalayan region, the Higher Himalaya is mainly composed of an approximately 10-30 km thick sequence of medium-to high-grade metamorphic and metasedimentary rocks particularly various gneisses, schist, quartzite and marbles which are frequently intruded by granites of Ordovician (~ 500 Ma) and Lower Miocene (~ 22 Ma) age (Thakur, 1987; Dezes, 1999). The Higher Himalayan sequence is wider in western part especially in the Kashmir-Kistwar region and much narrow in eastern side around the Kumaun-Garhwal vicinity. It is generally believed that the Higher Himalaya form major nappes which are thrust over the Lesser Himalaya along the Main Central Thrust (MCT).

3.1.6. The Tethys Himalaya (TH)

The Tethys Himalaya is ~100 km large synclinorium and ~12 km thick pile that is formed by strongly folded and imbricated, sedimentary and weakly metamorphosed rocks especially, shale, phyllites, limestones and quartzose sandstones of the Cambrian to Eocene age (Searle, 1986). An almost complete stratigraphic record ranging from the upper Proterozoic to the Eocene is preserved within the sediments of the Tethys zone in the NW-Himalaya. These Mesozoic sediment especially thick carbonates are considered to be deposited on the northern margin of the Indian continent. Some basalts are also widespread in the Tibetan sedimentary sequences of the Zanskar and the Kashmir region (Hodges, 2000). The transition between the generally low-grade sediments of the Tethys Himalaya and the underlying high-grade rocks of the High Himalayan Crystalline Sequence is marked by a major extensional structure known as the South Tibetan Detachment System (STDS).

3.1.7. The North Himalayan Gneiss Domes (NHGD)

In the Ladakh region, Tethys Himalayan passes gradually to the north in a large metamorphic dome named as Nyimaling-Tso Morari Dome (NTGD) exposed in greenschist to eclogitic metamorphic rocks. The evidence of amphibolite-facies metamorphic overprint in the core gneisses of the Tso Morari dome is well visualized. Most of the dome shows that the core of the dome mainly consists of deformed, less metamorphosed, augen gneiss (orthogenesis and paragneisses) with Carboniferous-Triassic rocks of the Tibetan sedimentary sequences (Hodges, 2000). The contact relationships of these domes to the surrounding rocks are still unclear because none of the granite-cored domes has been mapped in detail.

3.1.8. The Indus Suture Zone (ISZ)

The Indus Suture Zone (ISZ) is also known as the Indus-Yarlung-Tsangpo Suture Zone (IYTS) and composed of sedimentary and tectonic melange of carbonate, volcaniclastic and alkali volcanic rocks. The Indus Suture Zone (ISZ) that marks the zone of collision between the Indian and Eurasian plates that can be traced discontinuously throughout the Himalayan arc and represents the northern limit of the Himalaya. Further to the North is also called Transhimalaya, or more locally Ladakh Batholith, which corresponds essentially to an active margin of Andean type (Dezes, 1999). The Suture zone comprises three major rock sequences namely the Ophiolite Melanges, Dras Volcanics and the Indus Molasse. The Ophiolite Melanges are mainly composed of an intercalation of flyschs and ophiolites from the Neotethys oceanic crust, the Dras Volcanics are relicts of an upper Cretaceous to upper Jurassic volcanic island arc type and consist of basalts, dacites, volcanoclastites, pillow lavas and minor radiolarian cherts. The Indus Molasse are continental clastic sequence comprising alluvial fan, braided stream and fluvio-lacustrine sediments derived mainly from the Ladakh batholith, suture zone itself and the Tethyan Himalaya. These molasses are post-collisional deposits of Eocene to post-Eocene age.

3.2. Major Structural Elements in the NW Himalaya

From south to north, the Himalayan belt can be divided in the following major structural elements.

3.2.1. The Main Frontal Thrust (MFT)

The Main Frontal Thrust (MFT) is southernmost, youngest, NW-SE striking, north-dipping, imbricated and currently most active thrust zone (Figs. 1 and 2), which separates the Siwaliks sequences from the Indo-Gangetic alluvial plain (Nakata, 1989, 1990; Banerjee et al., 2002). The MFT represents a zone of active deformation and surface expression of shortening between the Himalaya and the Indian Plate with convergence rate of 14 $\pm$ 1 mm/yr from GPS measurement (Banerjee et al., 2002) and shortening rate of 6-16 mm/yr from balance cross-section (Powers et al., 1998). This tectonic feature has not continuously found along the southern margin of the entire Sub-Himalayan foot hill. Thus, some workers believed that the MFT is blind thrust (Yeats and Lillie, 1991). However, recent studies reveal that the MFT is active and not a blind thrust (Kumar et al., 2003; Philips and Virdi, 2007). Moreover, recent GPS data further suggest that MFT is locked over a width of $\sim$ 100 km and stress accumulating is continuous in this zone.

3.2.2. The Main Boundary Thrust (MBT)

The Main Boundary Thrust (MBT) is widely recognized, regional, steep northward dipping active thrust zone, which separates the Cenozoic foreland sediments from the Precambrian Lesser Himalayan rock sequences (Srivastava and Mitra, 1994). The Main Boundary Thrust (MBT) is sinuous in nature, thus the width of the Sub-Himalaya varies in the NW-Himalaya, about 80 km in Kangra region to nearly absence in Simla sector (Nahan salient) and again widens to about 30 km in the Dehra Dun region (Fig. 2). The brittle nature of deformation is mainly associated with this thrust, and primarily located near the thrust planes.

3.2.3. The Munsiari Thrust (MT)

In the base of the Lesser Himalayan Crystalline Sequence (LHCS) corresponds to a 1 to 2 km thick pile of mylonitic granitic gneisses which is known as Munsiari Thrust Zone (MT), and is the prominent thrust which separates the Larji-Kulu-Rampur Window from the low-to medium-grade metasedimentary rocks of the Late Precambrian-Early Paleozoic age (Fig. 2). A strong brittle-ductile to brittle deformation is well recorded by conjugate shallow, NNE and SSW dipping thrust formed during exhumation of the Lesser Himalayan Crystalline Zone (Vanney et al., 2004). This structure is widely recognized in the Himanchal-Garhwal region. Neotectonic and seismic result indicates that the Larji-Kulu-Rampur Window is uplifting and SW directed thrusting is also propagating along the MT in the Garhwal region (Kayal, 1996).

3.2.4. The Main Central Thrust (MCT)

The Main Central Thrust (MCT) is one of the most significant north dipping intra continental thrust that associated with the Himalayan orogen; and is firstly recognized by Gansser (1964). The MCT is the large-scale, high strain ductile shear zone of the distributed deformation commonly coincident with the zone of inverted metamorphism from kyanite to biotite, and places the Tertiary metamorphic rocks on the unmetamorphosed Precambrian to Palaeozoic rocks of the Lesser Himalaya (Fig. 2). It separates overlying high-grade metamorphic crystalline rocks of the High Himalayan Sequence from underlying the weakly metamorphosed Lesser Himalaya rock sequences. In the Garhwal region, it is also recognized as the Vaikrita thrust, and the lower Minsiari Thrust. This mega thrust especially responsible for significant proportion of the shortening and inverted metamorphism consequently upon the India-Asia collision (Johnson, 2005). Deformation along this structure was mainly ductile. It is believed that the Lesser Himalayan crystalline nappe or outer crystalline klippen are carried along the MCT. However, the relationship between the MCT and crystalline nappes and associated inverted metamorphism of the Himalayan orogen are still controversial issue.

3.2.5. The South Tibetan Detachment System (STDS)

The South Tibetan Detachment System (STDS) is well-known synorogenic extensional shear zone located at the top of the Higher Himalayan Crystalline Sequences, and is distributed in numerous sections all along the range (Vannay and Grasemann, 2001). The STDS is also known as the North Himalayan Shear Zone (NHSZ), represents a major system of north-dipping structural detachments which separates the High Himalayan Crystalline Sequence and the Tethys Himalaya (Figs. 1 and 2). Unlike the MCT, the STDS is not a continuous structure along the entire Himalayan belt. Deformation along this structure was accommodated either by dextral strike-slip or by extensional shearing (Dezes, 1999). The Zanskar Shear Zone (ZSZ) and the Chandra Dextral Shear Zone (CDSZ) are belonging to this structure in the NW-Himalaya.

3.2.6. The Indus Suture Zone (ISZ)

This structure marks the boundary between the Indian Plate and the Eurasian plate. The Indian plate was subducted below Eurasian continent along the Indus Suture zone (Fig. 1). Along the Indus Suture Zone in the Ladakh region scraps of petrotectonic assemblages of paleosubduction complex such as an island arcs, arc-trench gap basin and oceanic crust especially Dras volcanics, mixed with molasse deposits (Thakur, 1987; Dezes, 1999).

4. Modeling

The FE program package (Hayashi, 2008; Fig. 4 and Table.2) is used to calculate neotectonic activities, Quaternary deformation and shortening rate of the Garhwal Himalaya. In the present study, elastic rheology under plane strain condition has been adopted for modeling and gravitational force is integrated in all the models.

Primarily based on prevailing geological cross-section including structures from the Garhwal Himalaya region after Ram et al. (2005) have been adopted for modeling (Fig. 3).

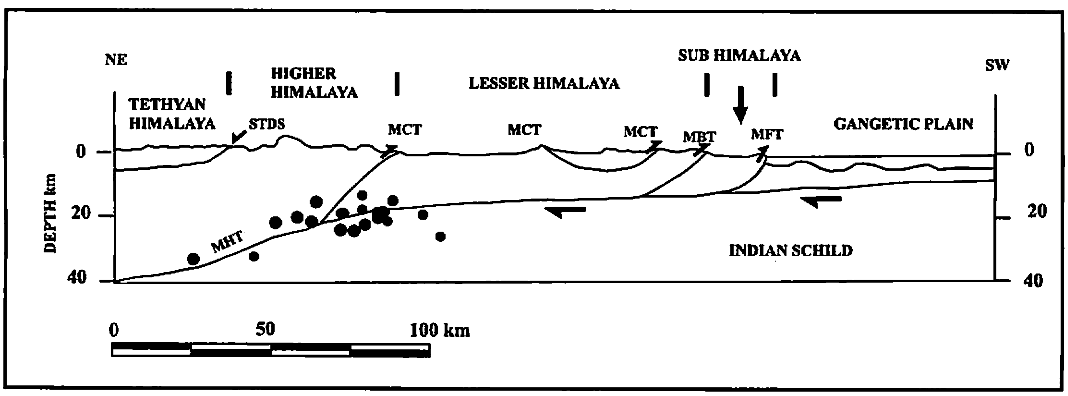

Fig. 3 Geological cross-section through the Garhwal Himalaya at true scale adopted for modeling (simplified after Ram et al., 2005).

The dimension of the model is 272 km in length and 40 km in depth that extends NE-SW and perpendicular to the cluster of microseismic activity and zone of the Uttarkashi earthquake. This model includes all tectonic zones and mega thrusts from the Gangetic Plain to the Tethyan Himalaya of the fold-and-thrust belt of the Himalaya.

On the basis of active nature and geometry of the faults, the model is divided into three types (1) model A with fault zones (2) model B with only active fault zones and (3) model C without fault zones. The Main Himalayan Thrust (MHT) is considered as a weak zone in the entire models. The dip angle and thickness of the thrust zones were considered on the basis of geological and geophysical data.

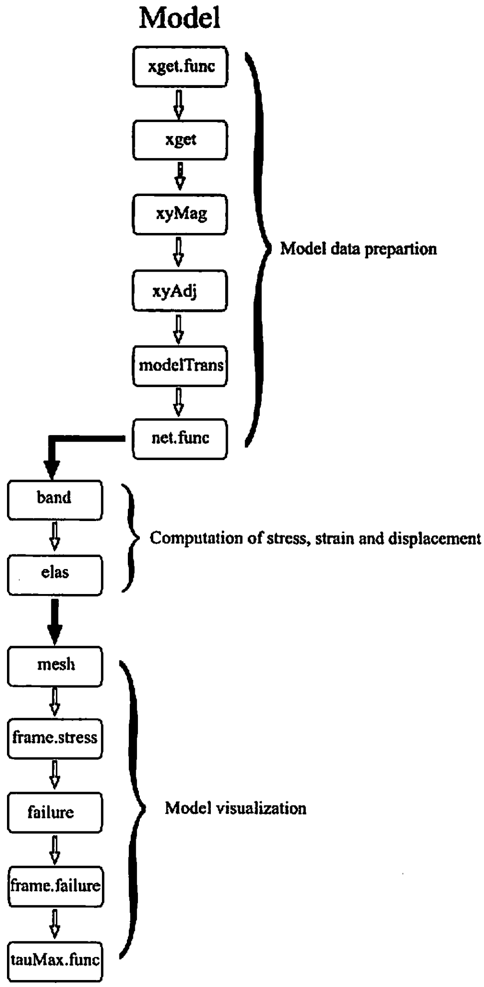

Fig. 4 Flow chart for finite element simulation (Hayashi, 2008).

Model A

It is obvious that major faults in the Himalayan fold-and-thrust belt comprise as zone rather than single plane therefore in model A all the major faults such as the Main Himalayan Thrust (MHT), South Tibetean Detachment Fault (STDF), Main Central Thrust (MCT), Munsiari Thrust (MT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) are considered as weak zones. Hence, it allows taking the value of the Young's modulus less than other rock layers.

On the basis of tectonostratigraphy of the area the model A is divided into eleven layers including major faults (Table 1).

Model B

Various neo-tectonic studies, such as active faults, lineament modeling, geomorphic analysis, satellite images and GPS measurements, suggest that the MT, MBT, MFT and associated fault systems are highly active in the Garhwal Himalaya (Nakata, 1989; Yeats at al. 1992; Powers at al., 1998; Valdiya, 2001; Thakur, 2004, 2006; Phillip et al., 2006). Meanwhile, seismic studies further show that the STDS and the MCT are not seismically

Table. 1. Physical parameters applied for the different rock units in the FE simulation.

Geological zones	Density (kg/m^3)	Young's modulus (Gpa)	Poisson ratio	Cohision (Mpa)	Friction angle (degrees)	P-wave velocity (km/sec)
Tethys Himalaya	2600.0	54.00	0.25	17	45	5.2
STDS	2100.0	01.00	0.25	10	31	-
Higher Himalaya	2700.0	58.00	0.25	19	48	5.7
MHT/MFT	2400.0	0.35	0.25	10	31	-
Indian Crust	2800.0	60.00	0.25	24	50	6.0
MCT	2300.0	01.0	0.25	10	40	-
Lesser Himalaya	2400.0	42.0	0.25	15	42	5.0
MT	2100.0	01.0	0.25	10	31	-
MBT	2000.0	01.0	0.25	10	31	-
Sub Himalaya	2200.0	18.0	0.25	10	32	3.5
Gangetic Sediment	1800.0	12.0	0.25	8	30	2.8

active faults (Kayal, 2001). Hence, in this model, only the MHT, MT, MBT and MFT are considered as active fault zones. On the basis of tectonostratigraphy of the area the model B is further divided into nine layers including major faults.

Model C

Numerous studies show that the MFT is highly active thrust (Nakata, 1989, Nakata et al., 1990; Powers et al., 1998 and Wesnousky et al., 1999) with compare to other active thrust system. The GPS measurement further suggests that high deformation and crustal shortening of the Himalaya occurs within this zone (Banerjee and Burgmann, 2002). Thus,

Table. 2 Contents of finite element software package (Hayashi, 2008).

no.	code name	function
1	xget.func	raw coordinate for each nodal points in model
2	xget	coordinate data for model
3	xyMag	scale adjustment according to model size
4	xyAdj	coordinate adjustment of model's boundaries
5	modelTrans	calculation of coordinates, nodal points and layers
6	net.func	visualization of model's mesh
7	band	calculation of band matrix
8	elas	computation of stress, strain and displacement
9	mesh	division of model into layers
10	frame.stress	visualization of stress field
11	failure	computation of failure element
12	frame.failure	visualization of failure element
13	tauMax.func	calculation of shear stress

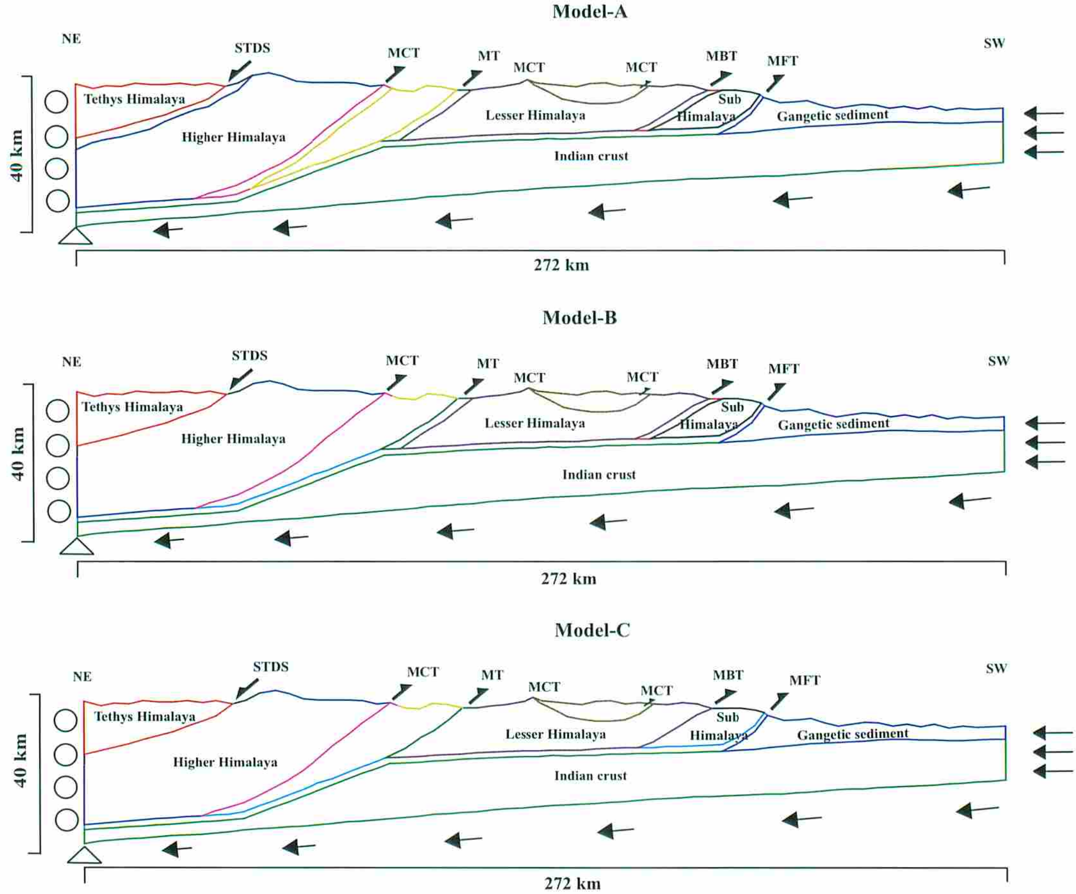

Fig. 5 Model geometry and boundary conditions.

in model C only MFT is considered as weak zone and remaining all faults are considered as without fault zone. Moreover, in this model attempt has been done to simulate all mega thrust systems without zone. On the basis of tectonostratigraphy of the area the model C is divided into seven layers.

4.1. Boundary Condition

The boundary condition plays the vital role in FE simulation, and decision of the boundary condition is one of the critical steps to simulate the tectonic process. Thus, during the selection of reasonable boundary conditions, we should consider the existing natural situation and the realistic convergent boundary conditions to characterize present day plate kinematics of the Himalayan fold-and-thrust belt. In all the models, the upper surface is free to move whereas the left side of the model is fixed horizontally. The lowermost nodal point of the left side of the model is fixed. Since, the lower boundary of the model is inclined therefore the convergence displacement is resolved into both x and y directions (Fig. 5). Reasonable uniform convergence displacement progressively increased up to 500 m at the present rate of 15 mm/yr is applied. This is consistent with the GPS measurement (Banerjee and Burgmann, 2002) and geological studies (Wesnousky et al., 1999; Powers et al., 1998) in the NW-Himalaya.

4.2. Rock Layer Properties

The mechanical properties such as density, Young's modulus, Poisson ratio, frictional angle and cohesive strength are significant and strongly influence on the result of the FE simulation. Hence, these mechanical properties were systematically varied to explore their effect on the shortening rate and style of deformation in the study area. As state previously, for the simplicity of computation, the whole models are divided into seven layers excluding major fault zones (Fig. 6), and each layer has been allocated with distinct rock layers properties on the basis of predominant rock types (Table1). For FE simulation mechanical parameter of rocks especially, independent elastic constants the Young's modulus (*E*) and Poisson ratio (υ) are essential to calculate the stress field and deformation mechanism.

Young's modulus (*E*) can be calculated by equation (i) (Timosenko and Goodier, 1970).

$$E = \rho V_p^2 \frac{(1+\nu)(1-2\nu)}{(1-\nu)} \quad \text{.......(i)}$$

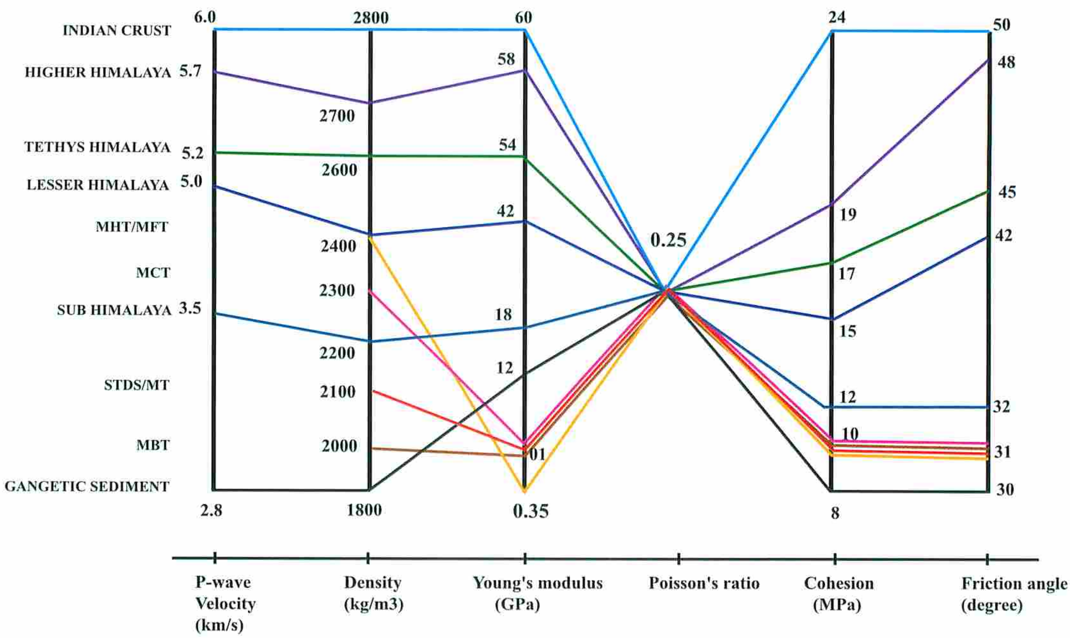

Fig. 6 Graphical illustration of the Physical parameters of the different rocks in the Garhwal Himalaya.

where, ρ and υ are density and Poisson ratio, respectively.

For simulation the static Young's modulus is used for tectonic rocks rather than dynamic Young's modulus (Fig. 6), and assuming that the static Young's modulus is 80% of the dynamic Young's modulus. These are consistent with the values for continental crustal rocks and also determined by laboratory and other published data (Sydney and Clark, 1966).

Poisson ratio (υ) is taken constant 0.25 for individual tectonic blocks. The two physical parameters, internal friction angle (ϕ) and cohesion (c) are obtained from the handbook of Physical constant (Sydney et al., 1996). Density of the rock layers of individual tectonic block is known, seismic P-wave velocity (Vp) and S-wave velocity (Vs) are obtained from the published velocity model from the Garhwal Himalaya (Cotton et al., 1996).

5. Results of simulation

State of stress is one of the widely used techniques and good proxies to understand the style of deformation of the crust and particularly depends on the geometry of the model, imposed boundary conditions and rock layer properties. The neotectonic stress field simulated for the models A, B and C are shown in Figs. 7, 8 and 9. From different (the 50 m up to 500 m) convergence displacements are imposed in the sequential order of an average velocity of 15 mm/yr for the Garhwal Himalaya. The convergence rates are consistent with the GPS measurements (Banerjee and Burgmann, 2002) and Quaternary deformation (Wesnousky et al., 1999 and Kumar et al., 2001) along the MFT in the fold-and-thrust belt of the Garhwal Himalaya.

5.1. Stress distribution

In all the models, the pattern of stress distribution reveals approximately similar nature under same convergent displacement. The special distributions of stress field with its magnitude are shown in Figs. 7, 8 and 9 where the distribution and orientation of the stress field is changed according to the structural characteristics and applied convergent displacement of the model. In compressive environment such as Himalayan fold-and-thrust belt the orientation of the maximum compressive stress (σ_1) and minimum compressive stress (σ_3) is vertical and horizontal respectively. The red bar denotes the principle stress in extension. The magnitude of σ_1 and σ_3 are increases with depth in all models. In the upper part of the entire model, the stress field shows rotation where σ_1 is deflected from its original vertical position and finally becomes horizontal. This type of stress field is indicator of the thrust faulting in the convergent tectonic environment. However, in the southern part especially in the Lesser Himalaya, Dun valley and Siwalik zone σ_1 oriented vertically together with the tensional component (red bar) of the σ_3. The stress field shows two characteristic types of regimes in the study area at low convergent displacement. An evidence of extension tectonic environment is developed in the Himalayan frontal part whereas compressive state of stress is well visualized in the northern front of the MHT ramp. Thus, the MHT ramp plays significant role to control the magnitude and orientation of the stress field in the region. Moreover, around the MHT ramp and the Higher Himalaya the dome shaped stress field is observed. This dome shaped structure is strongly developed in model A, moderately developed in model B and weekly developed in model C that is probably due to the effects of the geometry or competence contrast of rock layer properties. If the convergent displacement is increased the stress field becomes changes into compressive nature in entire models (Figs. 7, 8 and 9). This is because the stress state is a function of the convergent displacement in such tectonic environment. The mega thrust systems have significant influences in the orientation and magnitude of the stress field of the region.

5.1.1. Stress-field in model A

The stress field of the model A is almost same from 50 m to 500 m convergent displacements. In the upper part of the model, the stress field shows rotation from south

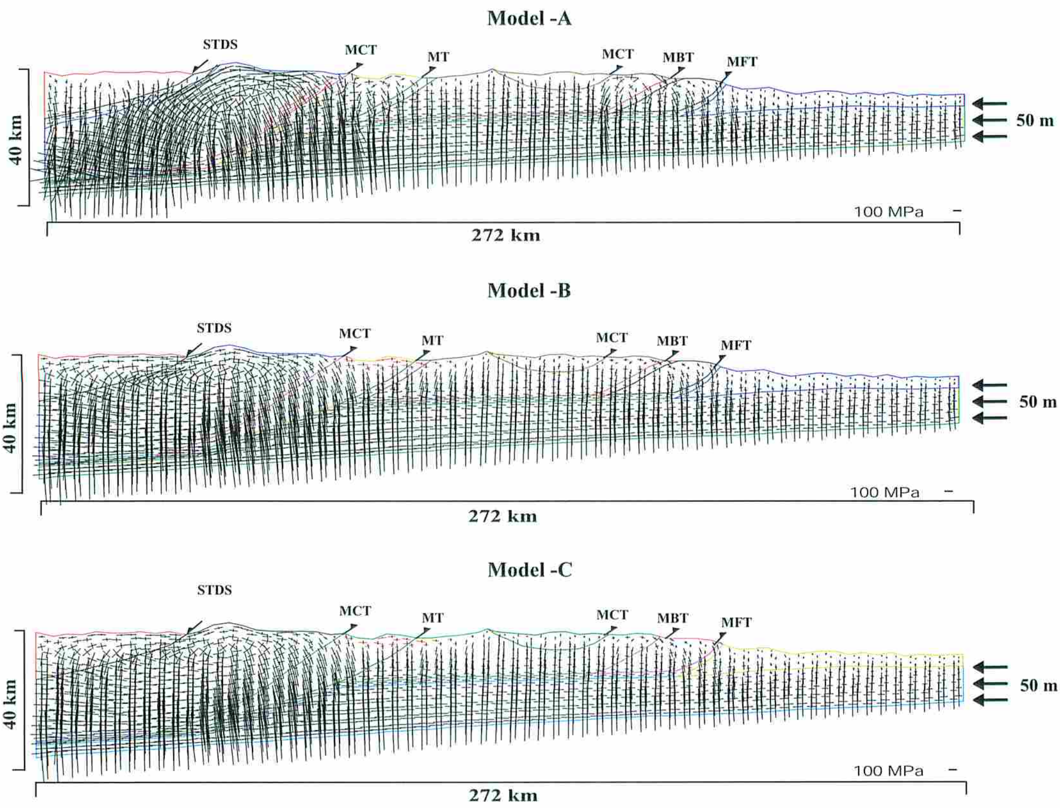

Fig. 7 Stress distribution in the Garhwal region for model A, B and C at 50 m convergent displacement.

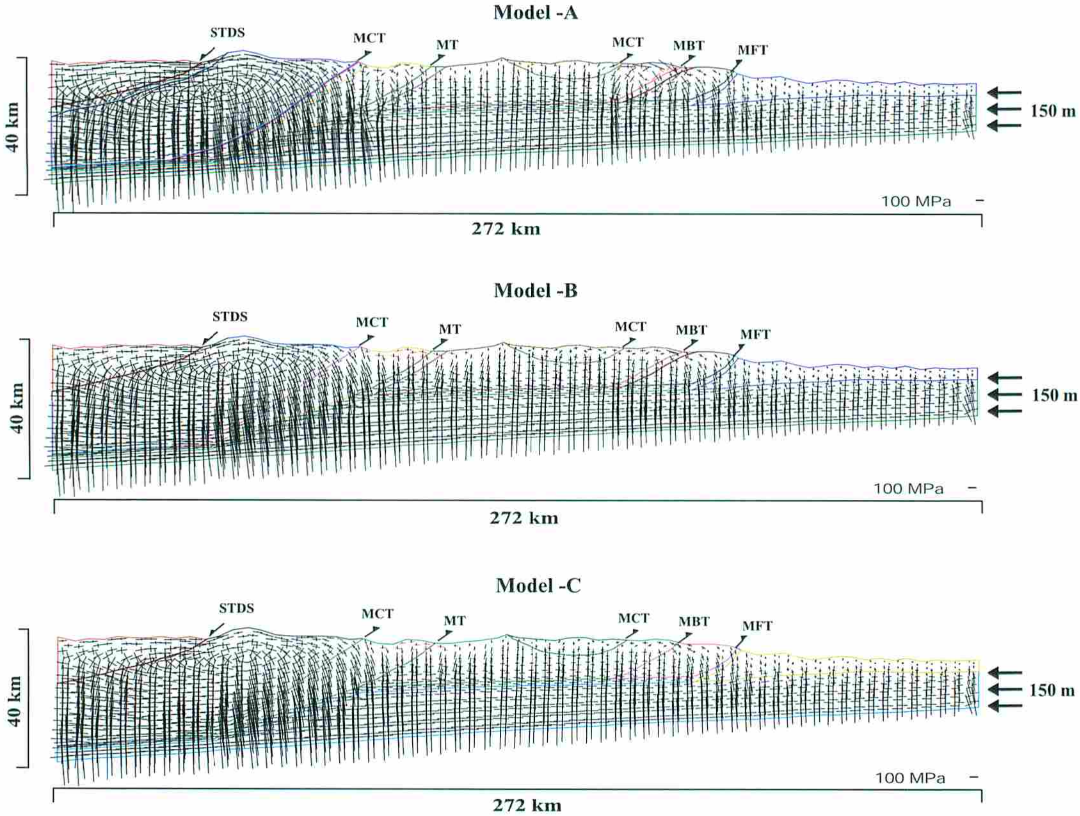

Fig. 8 Stress distribution in the Garhwal region for model A, B and C at 150 m convergent displacement.

to north where σ_1 is deflected from its original vertical position to horizontal position and made thrust faulting. This compressive nature of stress is obtained in shallow level. In the Lesser Himalaya and Siwalik Zones the orientation of σ_1 is vertical and σ_3 is in horizontal with tensional components that shows the evidence of extensional regime (Figs. 7, 8 and 9). With increasing convergent displacement, compressive state of stress is predominantly observed and shifted towards the southern front of the fold-and-thrust belt. The strong dome shaped stress field is developed around the MHT ramp and the Higher Himalaya region probably the effects of competency contrast of rock layer properties.

5.1.2. Stress-field in model B

The stress field of the model B is almost same from 50 m to 500 m convergent displacements and the compressive nature of stress is obtained in upper part of the model. Lower magnitude of σ_1 and σ_3 is found in the southern front of the Himalaya especially in the Gangetic Plain but magnitude of σ_1 and σ_3 are increases with depth. In the south of the MCT, in the Lesser Himalaya and around the MT zone the evidence of extensional

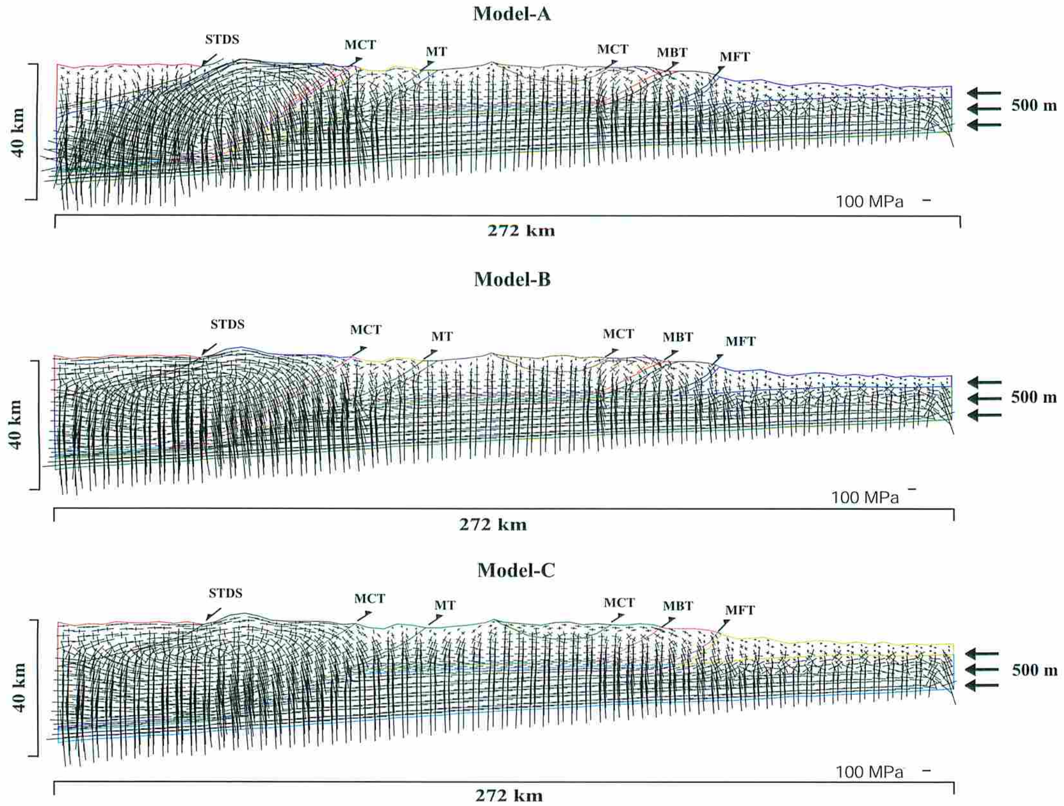

Fig. 9 Stress distribution in the Garhwal region for model A, B and C at 500 m convergent displacement.

regime is well observed at 50 m and 150 m convergent displacements, whereas in the north compressive regime is well developed. Increased the convergent displacement at 500 m thrusts were propagated towards south around the MBT and Siwalik Zone. In case of 50 m, 150 m and 500 m convergent displacements the orientation of the σ_1 remain same in the Indian Shield and only little change in southernmost part. The dome shaped stress field is moderately developed in this model (Figs. 7, 8 and 9).

5.1.3. Stress-field in model C

The stress field of the model C is almost same in 50 m up to 500 m convergent displacements, and the compressive nature of stress is obtained north of the MHT ramp and extensional regime is observed to the south of the MHT ramp (Figs. 7, 8 and 9). In the upper part of the entire model the compressive state of stress is well developed in shallow level. However, in the south of MCT especially in the Lesser Himalaya and the MT zone the evidence of extensional regime is well observed at the low (50 m and 150 m) convergent displacements but when increased convergent displacement up to 500 m compressive stress field is dominantly observed (Figs. 7, 8 and 9). The orientation of the

σ_1 in the Indian Shield is also unchanged from all (50 m to 500 m) convergent displacements. The dome shaped stress field is weakly developed in this model.

5.2. Stress distribution in failure elements

The failure elements in the stress distribution are examined with the help of the Coulomb-Mohr failure criterion coded by Hayashi (2008) in the entire models. Basically, the whole models show similar pattern of fault development at different (50 m to 500 m) convergent displacements. From 50 m to 500 m convergence displacement applied and thrust faults were mostly observed in the top of the entire models mainly in the Higher Himalaya whereas normal faults are widely distributed southern front of the MCT, within the Lesser Himalaya, Dun valley and Siwalik Zones (Figs. 10, 11 and 12). With increasing convergence displacement up to 500 m the failure elements reasonably decreased and thrusts are propagate toward south in entire models. The cluster of failure elements in all models observed in the shallow level particularly in the south of MCT where cluster of microseismic events is also observed in the Garhwal Himalaya (Figs. 11 and 12). The cluster of failure elements is mainly confined around major fault zones, northern part of

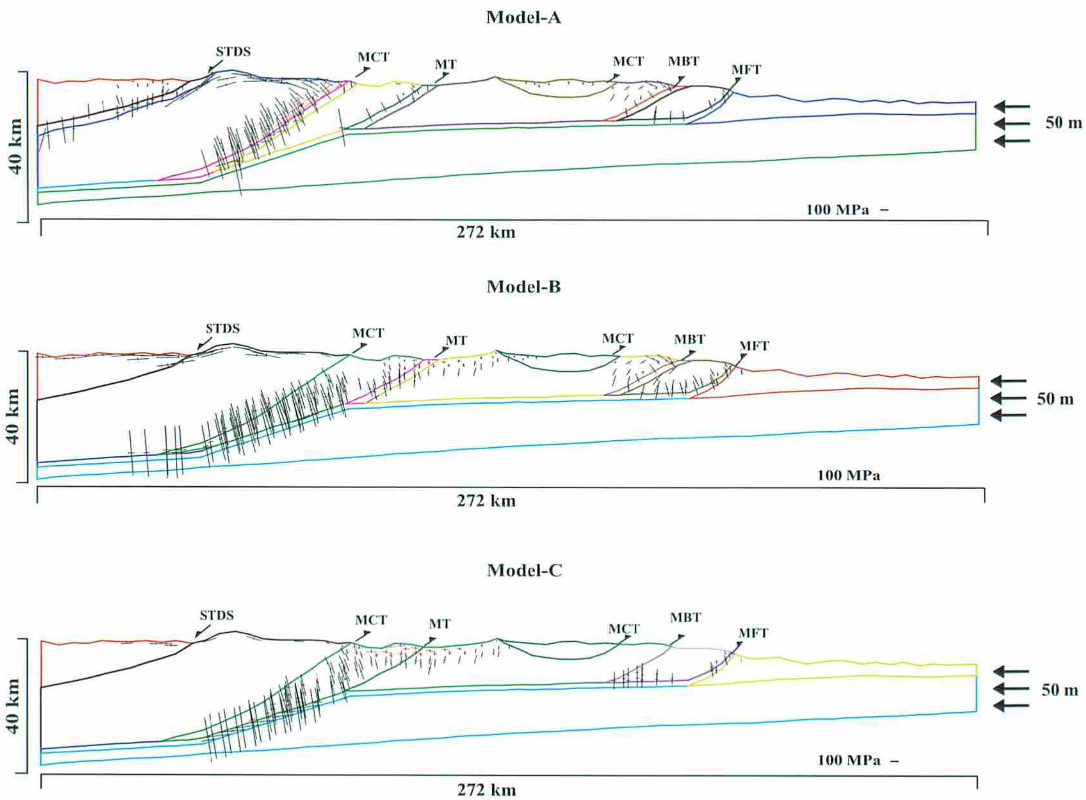

Fig. 10 Failure elements in the Garhwal region for model A, B and C at 50 m convergent displacement.

the Lesser Himalaya and Dun valley region where several highly active faults are found (Fig. 15).

5.2.1. Failure pattern in model A

The Coulomb-Mohr criterion is using for analyzed the failure pattern during progressive convergent displacement from 50 m to 500 m. In 50 m convergent displacement case most of the failure elements were observed around the MT, in the south front of the Lesser Himalaya including nappe area and Siwalik Zone whereas with increasing convergent displacement up to 500 m failure elements are gradually decreases in nappe region but concentrated around the Siwalik and MBT region. Furthermore, increasing convergent displacement up to 500 m thrust faults are predominantly observed in the Siwaliks and Dun valley area. This clearly shows when increases the convergent displacement thrusts are propagating towards south (Figs. 10, 11 and 12). Most of the thrust faults are observed in the Higher Himalaya region but normal faulting extensively developed to the southern part particularly in the Lesser Himalaya, Dun valley and the Siwalik Zone. Failure elements are concentrated along the major thrust zone in 50 m

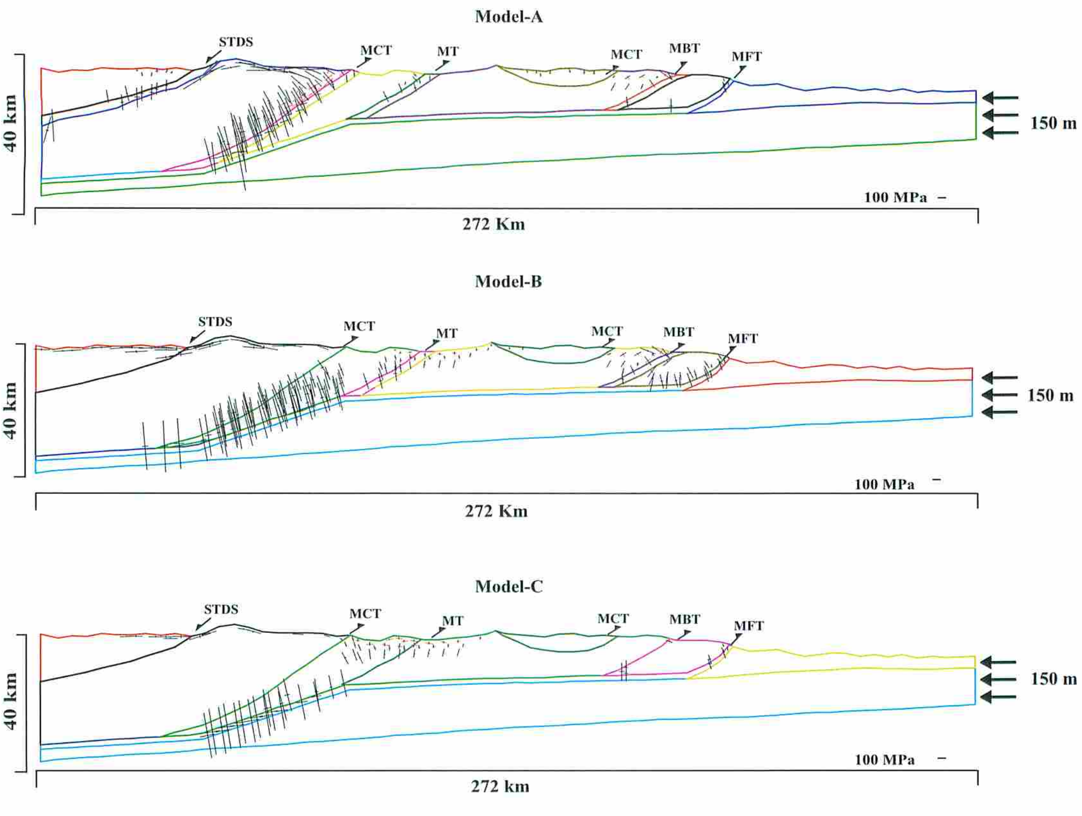

Fig. 11 Failure elements in the Garhwal region for model A, B and C at 150 m convergent displacement.

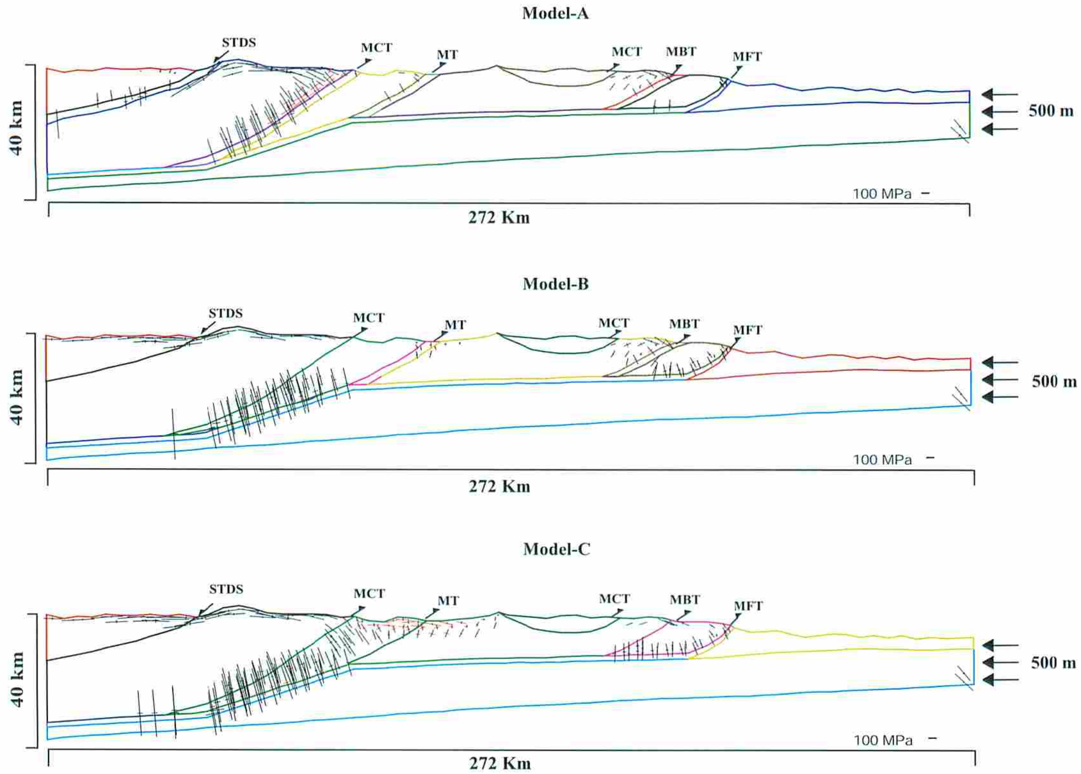

Fig. 12 Failure elements in the Garhwal region for model A, B and C at 500 m convergent displacement.

convergent displacement (Fig. 10). As the convergent displacement is progressively increased up to 500 m, numbers of failure elements decreased in the model (Figs. 10, 11 and 12).

5.2.2. Failure pattern in model B

In the case of 50 m convergent displacement, cluster of failure elements is obtained in the Lesser Himalaya, Dun valley, Siwalik and MFT zone (Figs. 10, 11 and 12), where thrust and normal faults co-exists in the southern front of the Lesser Himalaya, Dun valley and Siwalik area. Normal faulting extensively developed to the south from the MHT ramp especially upper part of the Lesser Himalaya in shallow level at 50 m convergent displacement but when convergent displacement is increased at 150 m normal faulting shifted towards MT and southern part of the Lesser Himalaya (Fig. 11). Most of the thrust faults are observed in upper part of the model especially in the Tethys zone and the Higher Himalaya in shallow depth at 500 m convergent displacement (Figs. 10, 11 and 12).

5.2.3. Failure pattern in model C

In the 50 m convergent, the cluster of failure elements is occurred in and around the MHT ramp, MT, northern side of the Lesser Himalaya and MFT zone (Fig. 10). In this model very less thrust faults are observed in the Higher Himalaya in shallow level whereas normal faulting extensively developed in the Lesser Himalaya especially northern part of the nappe around MT. However, with increasing the convergent displacement progressively up to 500 m cluster of failure elements are shifted toward south (Figs. 11 and 12). Compared with other model this model shows more failure elements concentrated in and around the MT and part of the Lesser Himalaya in shallow level (Figs. 10, 11 and 12), and the thrusts are highly propagating towards south in high convergent displacement (500 m) condition (Fig. 12).

6. Discussion

6.1. Model set up

The models presented here and used to calculate the neotectonic stress distribution, pattern of faulting and shortening rate to expand better understanding the present day tectonic activities in the fold-and thrust-belt of the Garhwal Himalaya. For modeling the structural cross-section of the Garhwal Himalaya has been taken in consideration to accomplish the elastic problem under plane strain condition coded by Hayashi (2007). The realistic boundary conditions consistent with the present-day plate kinematics of the Garhwal Himalaya have been imposed. The convergent displacements from 50 m up to 500 m have been applied. It is considered that all the rock layers are homogeneous and isotropic in the model. In nature rocks does not behave as homogeneous and isotropic body. Furthermore, it is assumed that the crust behaves elastically and able to simulate faults. However, the results are still comparable with the geology and geophysical data. Series of test calculations were carried out and finally appropriate set of rock layer parameters were adopted for the simulation. During calculation enough attention has been taken to avoid wide fluctuation of significant parameters from their natural values.

6.2. State of stress in the Himalaya

Stress orientations help us to understand the tectonic forces acting its collision boundary thus the tectonic stress field in both the regional and local scales of the Himalayan region has been computed by numerous authors (Nakata et al., 1990; Gowd et al., 1992; Shanker et al., 2002; Chamlagain and Hayashi, 2007). The maximum horizontal compressive stress $S_{H\,max}$ in the Indian subcontinent shows NNE-ENE direction and mean orientation of S_{Hmax} is N20°E (Gowd et al., 1992). However, in the Tibet region the tectonic regime is totally changed and dominated by E-W extension due to normal and strike slip faulting and WNW-ESE tension characterized by gravitational collapse (Molnar and

Topponier, 1978; Armijao, et al., 1986). From the strike and type of active fault studies Nakata et al. (1990) have deduced the direction of maximum horizontal compressive stress ($S_{H\,max}$) approximately N-S or NE-SW in the Western Himalayan front. Their studies further suggest that the direction of the $S_{H\,max}$ is changed owing to the relative motion between the Indian and Eurasian plates.

Due to diverse geological and topographic features, complex active tectonics with high rate of the plate convergence 15 mm/yr (Peltzer and Saucier, 1996) and strain accumulation made perhaps locally heterogeneous state of stress in the Garhwal region (Sarkar, 2004). However, on the broad scale the stress field in the Garhwal segment is homogeneous with maximum horizontal compressive stress ($S_{H\,max}$) oriented N33E, generally perpendicular to the Himalayan arc (Gowd et al., 1992). These studies clearly indicate that regional direction of $S_{H\,max}$ is consistent with the relative plate motion of the India-Eurasian collision.

The states of stress in various convergent displacements (50 m to 500 m) have been calculated in model A, B and C (Figs. 7, 8 and 9) and two types of characteristic regimes are well observed at low convergent displacement (Fig. 7). A compressive state of stress is developed in the north of MHT ramp especially in the Higher Himalaya and extensional regime is developed in the south part basically in the Lesser Himalaya, Dun valley and Siwaliks Zones (Fig. 7). Hence, present simulation shows realistic stress regimes in the fold-and-thrust belt of the Garhwal Himalaya. Furthermore, the stress field shows rotation in whole model, where σ_1 is gradually turn from its original vertical position and finally becomes horizontal these are the good indicators of thrust faulting (Fig. 7, 8 and 9). This is the realistic stress field in the convergent tectonic environment of fold-and-thrust belt of the Himalaya. Since, the simulated model profile is set up as NE-SW direction whose strike coincides with the horizontal maximum principal stress ($S_{H\,max}$) direction, this show results of simulation are consistent with state of stress derived from other studies in the region such as Gowd et al. (1992) and Nakata et al. (1990).

6.3. Seismic activity in the NW-Himalaya

The Himalaya is said to be one of the most active and fragile mountain range in the world, and also known as *Living Mountain* with active tectonics. Himalaya is under constant stress due to collision between the Indian and Eurasian plates. This continues penetration of India buildup high stress accumulation and manifest seismically active nature of the region. Several studies point out that the complex seismotectonic patterns, non-uniform and diversified seismic phenomenon of the entire Himalaya reveal that earthquake generating processes and their relation with tectonics is complex and varied in eastern, central and western Himalaya (Kayal, 2001). The seismicity of the Himalaya has been studied by numerous authors (Molnar et al., 1973; Chandra, 1978, Ni and Barangi, 1984; Cotton et al., 1996; Kayal, 1996, 2001; Sarkar, 2004). There are several seismotectonic models proposed by several workers which of them evolutionary model and steady state model are well recognized. However, no single tectonic model can able to explain the entire Himalayan earthquakes (Kayal, 2001).

The Garhwal Himalayas is one of the most dynamic and seismically active parts of the Himalaya. It lies in the seismic gap between the rupture zones of the 1905 Kangra earthquake (M 8.4) and 1934 Bihar-Nepal earthquake (M 8.4) region of the Himalaya.

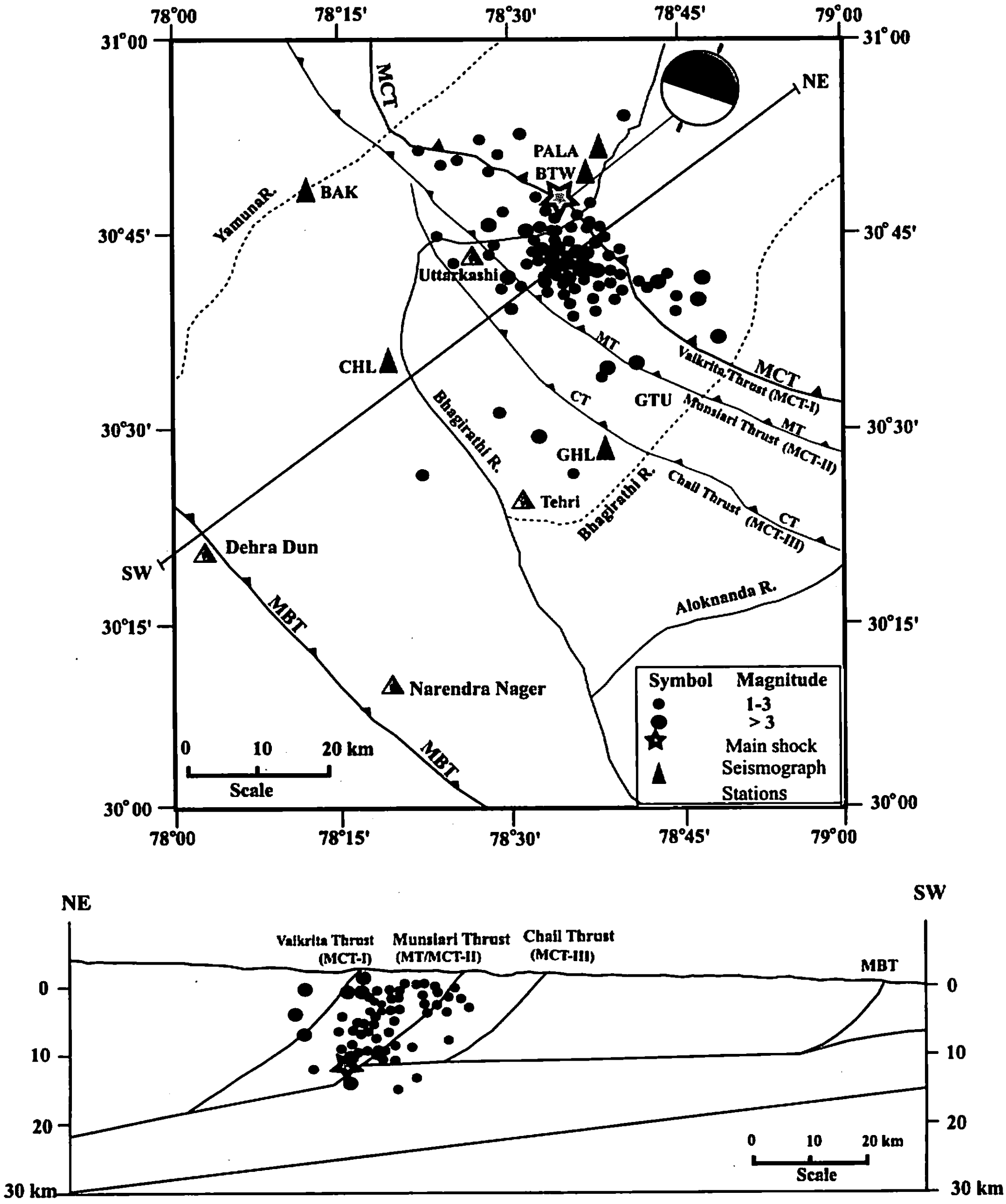

Fig. 13 Microseismicity map and NE-SW depth-section of the Utterkashi area (after Kayal, 2001).

Since 1803 the Garhwal Himalayas suffered from several moderate earthquakes (in 1809, 1816, 1966, 1967, 1969, 1976, 1978 and 1981) and recently suffered from two damaging earthquakes in 1991 the Utterkashi earthquake (*M* 6.6) and in 1999 the Chamoli earthquake (*M* 6.3). Thus, various seismic studies have been carried out by many researchers in the Garhwal Himalaya (Kayal, 1996, 2001; Cotton et al., 1996; Sarkar, 2004).

A detail microseismic study of the Garhwal Himalaya shows that the intense cluster of microseismic activity and moderate earthquakes is mainly confined between the MCT and MBT (Fig. 13). A dense cluster of microseismicity is mainly observed between the Lat 30-33 N and Long 76-79 E this indicates that a high stress accumulation exist in this region (Kayal, 1996, 2001; Cotton et al., 1996). Details study of microseismic data of the 250 earthquakes in the Garhwal region shows the focal depths for 225 earthquakes were less than 13 km and above the plane of detachment in the Lesser Himalaya (Kayal, 2001). The study clearly shows a cluster of microseismic event mainly observed in the shallow depth (Fig. 13). Present simulated results also able to simulate the realistic stress field, failure elements and fault patterns in the study area. Furthermore, modeling result clearly shows failure elements are mainly confined in and around the MT and northern

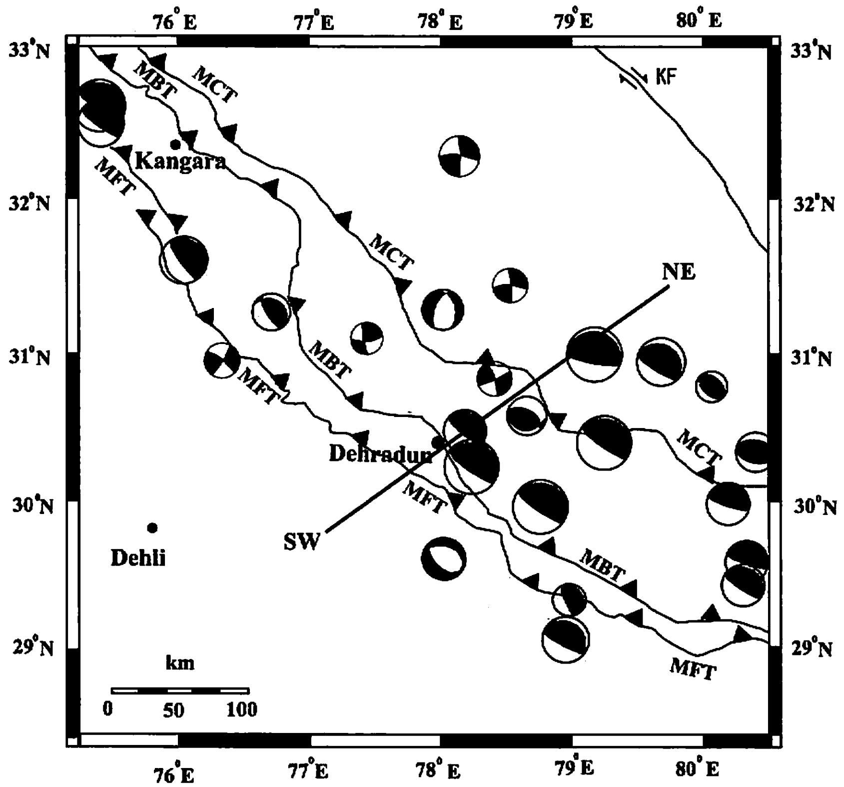

Fig. 14 Focal mechanism solutions of the NW-Himalaya (after Banerjee and Burgmann, 2002; Sarkar and Chandra, 2003 and http://www.discoverourearth.org).

part of the Lesser Himalaya (Fig. 11 and 12) where dense cluster of the microseismic activities is observed in the Garhwal region (Fig. 13). This is good agreement with the simulated results and microseismic events of the region.

In addition, the detail analysis of Utterkashi and Chmoli earthquakes (Cotton et al., 1996; Kayal, 2001) shows that microseismic events were emerge south of the MCT at shallow depth and southward propagation of rupture along this part of MHT. Similar result also suggested by Yeats and Thakur (1998) and they shows that the central part of the Himalaya moves southward as a fault-bend fold at ~15 mm/yr by infrequent earthquakes and ruptures. Seismic result indicates that the Rampur Window is uplifting, and SW directed thrusting is also propagating along the MT in the Garhwal region (Kayal, 1996).

Simulated result further able to shows that the direction of thrust faults are propagated from north to south as increases the convergent displacement (Figs. 10, 11 and 12), which is the close agreement of the southward propagation of infrequent earthquakes and rupture in the fold-and-thrust belt of the Garhwal Himalaya.

6.4. Focal Mechanism Solutions

A focal mechanism solution (FMS) is the result of an analysis of wave form generated by an earthquake and recorded by number seismographs. The complete characterization of an earthquakes focal mechanism provides significant information, including the origin time, epicenter location focal depth, seismic moment, magnitude and special orientation of the moment tensor (Cronin, 2004). Focal mechanism solution of the Himalaya have been studied by numerous researchers such as Molnar and Tapponnier (1975), Molnar et al. (1978) and Chandra (1978). The focal mechanism solutions of majority of the earthquakes located in the southern front of the MCT in the Himalayan fold-and-thrust belt reflects the overall north-south compressive state of stress and thrust type of faulting. However, locally the micro-seismic survey and the fault plane solutions in the Garhwal Himalaya indicate that the earthquakes in this part were triggered along a gently dipping, NW-SE trending thrust with a strike slip component and strike slip type (Sarkar, 2001) (Fig. 14). Furthermore, detail analysis of the ground cracks developed during the Chamoli earthquakes shows prominently tensional types of cracks exist in the region (Sarkar, 2005). The fault plane solutions map of the study area show that majority of the solutions are thrust type but thrust with a strike slip component are also observed where the P-axis for most of the solutions is consistent in NE-SW direction (Fig. 14), which is the close agreement of the results of present simulation and active faults of the region. Modeling results show that majority of the thrust faults widely distributed upper in part of the entire models (Figs. 7, 8 and 9), which are good agreement with the focal mechanism solutions of the area (Fig. 14).

6.5. Neotectonics

Neotectonics is defined as the crustal adjustment and movements of the Earth that have taken place during the Neogene and the Quaternary periods and plays a significant role to generate the contemporary topography and seismic activity. The intra continental collision between India and Eurasia made the Himalaya to be one of the neotectonically active mountain range of the world. The active faults, Holocene uplift records, geomorphic evidences, and GPS measurements indicate that the Garhwal Himalaya is one of the most neotectonically active regions in the Himalaya. Neo-tectonic studies such as active faults, lineament modeling, geomorphic analysis and satellite images further suggest that various recent movements are associated in the Himalayan front especially between MCT and MFT in the Garhwal Himalaya (Nakata, 1989; Yeats at al. 1992; Powers at al., 1998; Valdiya, 2001; Thakur, 2004; Phillip et al., 2006). Neotectonic study further indicates that the Rampur Window is uplifting along the MT. Moreover, studies reveal that the Dun valley and Siwalik Range are rising along the MFT (Wesnousky et al., 1999; Thakur et al., 2006) whereas Gangetic Plain south of MFT is progressively subsiding (Agrawal et al., 2002), corresponds MFT significantly accumulate stress in the region.

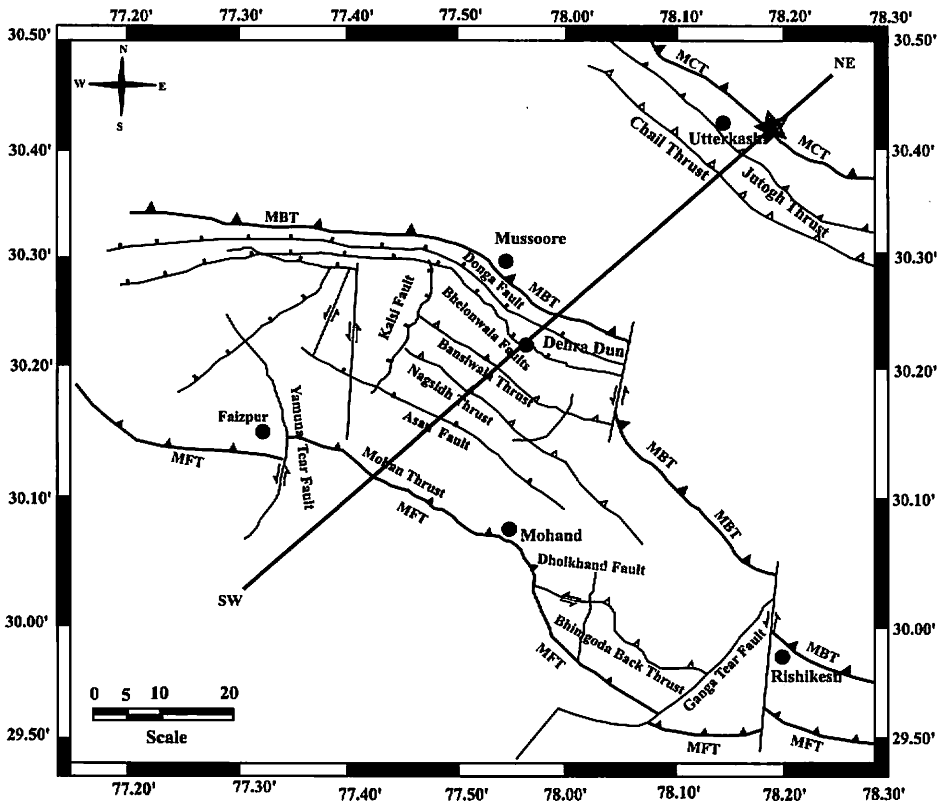

Fig. 15 Active faults map of the Garhwal Himalaya (after Valdiya, 2001, Kayal, 2001 and Thakur, 2006).

6.6. Active faults

The identification of active faults is important because active faults are considered to be the major source of earthquakes in the seismically active zones in the world. Thus, active faults play significant role to accumulate stress due to accommodation of converge in the region. For the seismic hazard evaluation the identification of active faults attained importance because most of the damaging historical earthquake occurred along active faults (Wesnouskey, 1999). Active fault studies further suggest that various recent movements e.g. normal faulting, strike-slip faulting and thrust faulting are associated along the MBT system within the Lesser Himalaya, Dun valley and MFT systems in the Sub-Himalaya in the study area (Nakata, 1989; Powers at al., 1998; Valdiya, 2001; Thakur et al., 2003; Phillip et al., 2006). It is believed that those active movements have been attributed to recent changes in the tectonic regime and seismic activity of the region. The study area is characterized by various NE-SW and NNW-SSE tending faults associated with part of the MBT and MFT systems (Fig. 15).

The MT, MBT and MFT are major tectonic features, which have been long recognized as key elements of Cenozoic shortening along the entire length of the Himalayas

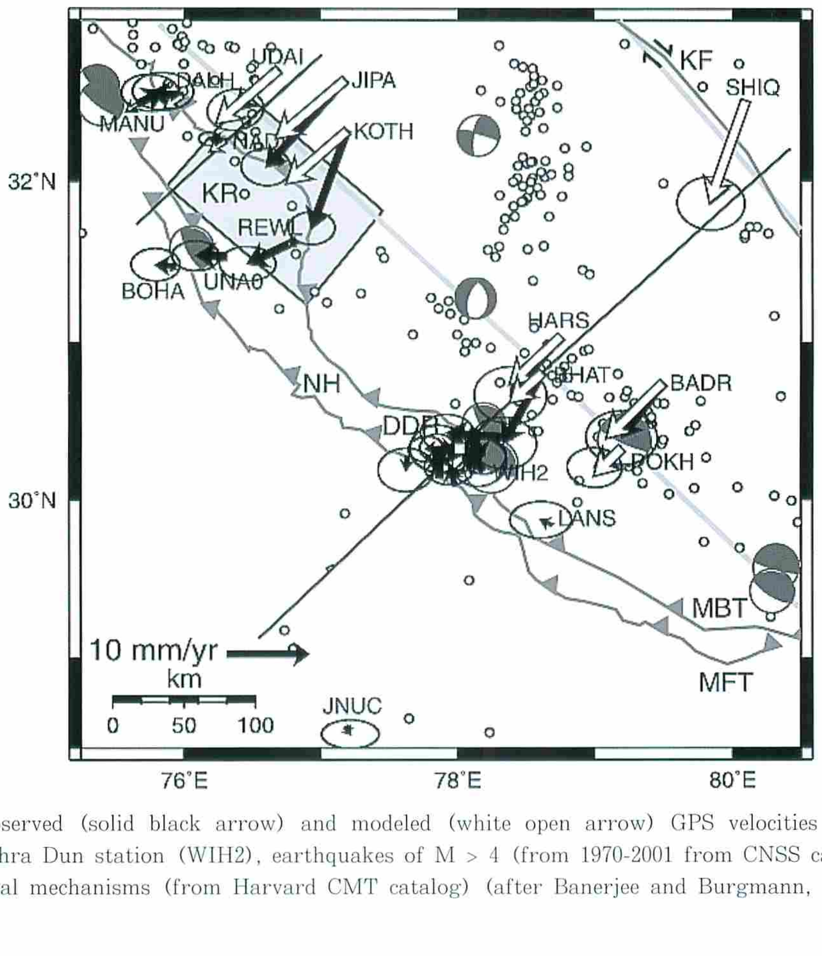

Fig. 16 Observed (solid black arrow) and modeled (white open arrow) GPS velocities relative to Dehra Dun station (WIH2), earthquakes of M > 4 (from 1970-2001 from CNSS catalog) and focal mechanisms (from Harvard CMT catalog) (after Banerjee and Burgmann, 2002).

(Gansser, 1964). The MBT forms the northern boundary of the Dun valley serves as a junction between the Pre-Tertiary of the Lesser Himalaya and the Tertiary of the Siwalik rocks. The MFT is another important tectonic feature and found at southern border of the Dun valley along the southern margin of the Sub Himalayan foothill. It is locally known as Mohand Thrust. The structural framework in the Siwalik between Yamuna and Ganga is dominated by an interesting combination of thrust and wrench faults. Mohand and Bhimgoda are two major thrusts dipping in the opposite direction in the Dun area (Fig. 15).

6.7. Geomorphic Evidences

In the Siwalik and Dun valley reactivation of active faults during late Tertiary and the Quaternary period resulted in the dislocation of various landforms and creation of several morphotectonic features such as pressure ridges, sag ponds, triangular facets and controlled drainage (Philip and Sah., 1999). Various active faults along with associated geomorphological features provide numerous evidences of recent crustal adjustments in Dun valley and the Siwaliks (Valdiya, 2003). Hence, advancement of large scale lineaments, tilting and shifting of river and piedmont, uplift of river terraces, subsidence of land and older rock sequences, overriding the younger (Holocene) sediments clearly

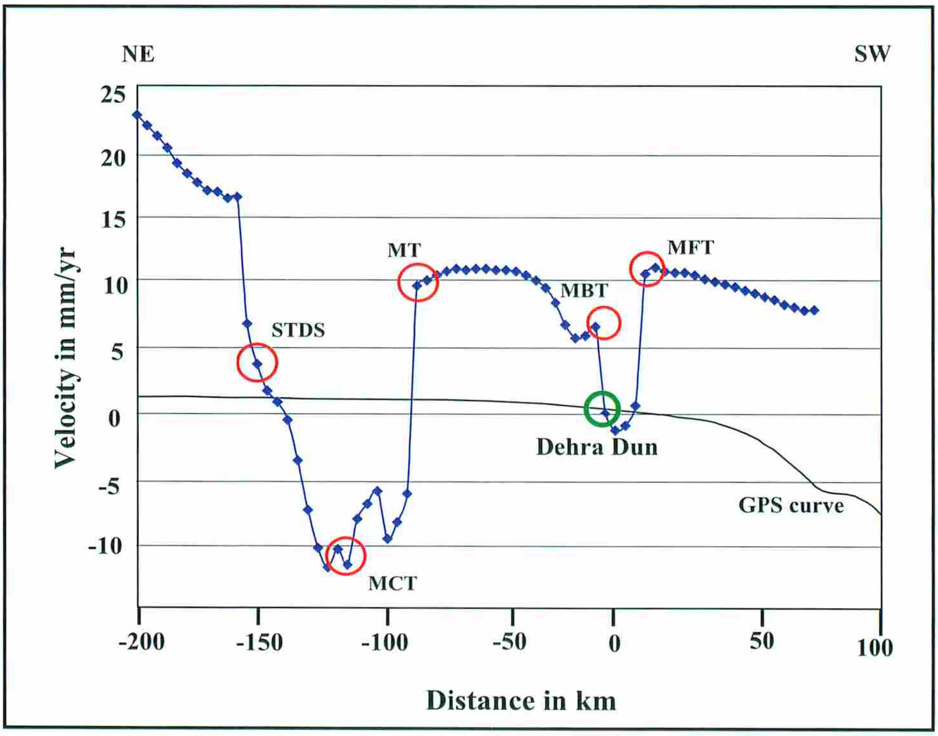

Fig. 17 Graphical illustration of the horizontal velocities from modeling (blue curve) and GPS measurements (black curve) relative to Derha Dun in the Garhwal Himalaya.

indicate that the foothill of the Himalayan fold-and-thrust belt is highly active region. Almost all thrusts that define the boundaries of lithotectonic terranes are active in the Kumaun-Garhwal region (Valdiya, 2001).

State of stress and Coulomb-Mohr failure criterion are used for better understanding of the neotectonic activities and existing stress field in the Garhwal region. Results from simulation show compressive tectonic environment in the northern part of the region and extension regime in southernmost part. Moreover, thrust faults are mainly observed in the upper part of the entire models whereas normal faults are mainly confined in the Lesser Himalaya, Dun valley and Siwalik area, which are the good agreement with the neotectonic stress field and resulting fault patterns. Hence, present modeling successfully simulates numerous active faults at their proper locations.

6.8. Quaternary deformation

The complex geological structures, intense earthquakes, steep topography of the Himalaya are the consequence of northward penetration of India beneath Asia. The process that has accommodated a huge amounts of (2000-3000 km) convergence since the Late Cretaceous (Molnar and Tapponnier, 1977) and continuous today at the rate of $\sim$ 50 mm/yr (Bilham et al., 1998). It is considered that initially the deformation front was confined along ISZ in the north whereas the deformational front was shifted progressively towards south along the ZSZ, MCT, MBT and at present deformation is going on at the foot hill of the Siwalik along MFT (Nakata, 1989). Previous studies indicate that the only a fraction of total convergence is accommodated by the shorting across the Himalaya front (Armijo et al., 1989). However, new findings clearly show that shortening mainly accommodate across the MFT.

The MFT is the youngest and most active thrust system of the Himalayan fold and thrust belt. From the balanced cross-section method in the fold-and thrust-belt of Tertiary Siwalik molasses Powers et al. (1998) observed shortening rates of 14 $\pm$ 2 mm/yr across the Kangra reentrant and 11 $\pm$ 5 mm/yr across the Dehra Dun reentrant. Meanwhile, Wesnousky et al. (1999) and Kumar et al. (2001) determined slip rate of MFT is $\geq$ 13.8 $\pm$ 3.6 mm/yr and 9.6 +7.0/- 3.5 mm/yr respectively through Holocene uplift records and the NW-Himalayan thrusting rate is 14 $\pm$ 1 mm/yr from the GPS measurements (Banerjee and Burgmann, 2002) (Fig. 17). Modeling results also able to shows that the high horizontal velocities are mainly confined along MFT zone (Fig. 17).

6.9. GPS measurement

Within the last decades several Global Positioning System (GPS) studies have provided three fundamental constrains about the tectonic framework of the Indian Plate: its overall stability (< 0.01 m strain /yr), its velocity with respect to Asia (58 $\pm$ 4 mm/yr at N 44 E) and its rate of collision with Tibet (20.5 $\pm$ 2 mm/yr) (Bilham et al., 1988).

The GPS velocity fields in the NW-Himalayan region provide new constraints on the partitioning of India-Eurasia convergence and elastic strain accumulation in and around the locked part of the Main Frontal Thrust (MFT) (Fig. 16). Moreover, GPS data further suggest that Main Frontal Thrust (MFT) is locked at the depth of 15 km, and ~15 mm/yr crustal shortening is localized within the ~100 km wide zone observed within a zone of the Siwalik Foothill (MFT) to southern edge of the Higher Himalaya (MCT) (Beanerjee and Burgmann, 2002). This zone is building up a slip at a rate of 14 ± 1 mm/yr which is consistent with geological studies (Power et al., 1998; Wennouskey et al., 1999 and Kumar et al., 2001).

The simulation results show that the high horizontal velocities are mainly confined along the Himalayan mega thrusts such as the MFT, MT and MBT zones (Fig. 17). The shortening rates calculated from the simulation are 10.6 mm/yr along the MFT zone, 9.67 mm/yr along the MT and 6.54 mm/yr along the MBT zone respectively. This indicates that the maximum crustal shortening and continues elastic strain accumulation is localized in these zones. Since, from the GPS measurements slip rate of MFT is 14 ± 1 mm/yr (Banerjee and Burgmann, 2002), which does not coincides with simulated horizontal displacement rate of 10.6 mm/yr of the MFT zone in the fold-and-thrust belt of the Garhwal Himalaya.

7. Conclusion

FE modeling is widely used to investigate the present-day crustal behavior particularly displacement, style of deformation and stress field in convergence environment. The Quaternary deformation, neotectonic stress field and style of faulting have been obtained by using FEM. FE simulation can recognize the main characteristics of present-day stress field and behavior of faulting in the fold-and-thrust belt of the Garhwal Himalaya. Furthermore, present study enhances our understanding regarding microseismic activities, active faulting and shortening rate of the region. Present simulation results demonstrate the realistic state of stress field and faulting pattern in the study area, which are consistence with the neotectonics, microseismicity, focal mechanism solutions and active faults of the fold-and-thrust belt of the Garhwal Himalaya.

On the basis of the present FE modeling results following significant points are concluded.

1. Active faults have significant influence in regional stress field and faulting of the study area.
2. In the models A, B and C thrust faults are propagated towards the south (Gangetic Plain) when increases the convergence displacement progressively, which is consistent

with the progression of thrust faulting in the fold-and-thrust belt of the Himalaya. The trajectories of the maximum principal stress (σ_1) rotates relatively horizontal position in the failure elements indicate formation of imbricate thrusts in the region.

3. Since, the cluster of microseismic activity confine south of the MCT around the MT in the Lesser Himalaya in shallow level, where simulated results also provides the cluster of failure elements in same region. Hence, simulated results show good agreement with the microseismic activity of the study area.
4. Resulted faulting pattern shows dominantly thrust faults in the upper part of the entire models, which corresponds with the focal mechanism solutions of the study area.
5. Active fault studies suggest that frequent active thrust faults, normal faults and strike slip faults have been observed in the Lesser Himalaya, Dun valley and Siwalik area of the Garhwal Himalaya. The simulated fault patterns also able to show good agreement with the active faults (thrust and normal) in the region.
6. The shortening rates calculated from the simulation are 10.6 mm/yr along the MFT zone, 9.67 mm/yr along the MT and 6.54 mm/yr along the MBT zone respectively. From the GPS measurements slip rate of MFT is 14 ± 1 mm/yr that does not coincides with simulated horizontal displacement rate of 10.6 mm/yr of the MFT zone in the Garhwal Himalaya.

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