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Geology, Structural and Exhumation History of the Higher Himalayan Crystallines in Kumaon Himalaya, India

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Abstract: The crystallines in the Kumaon Himalaya, India are studied along Goriganga, Darma and Kaliganga valleys and found to be composed of two high-grade metamorphic gneiss sheets i.e. the Higher Himalayan Crystalline (HHC) and Lesser Himalayan Crystalline (LHC) zones. These were tectonically extruded as a consequence of the southward directed propagation of crustal deformation in the Indian plate margin. The HHC and its cover rocks i.e. the Tethyan Sedimentary Zone (TSZ) are exposed through tectonic zones within the hinterland of Kumaon Himalaya. The HHC records history of at least one episode of pre-Himalayan deformation (D_1), three episodes of Himalayan deformation (D_2, D_3, D_4). The rocks of the HHC in Kumaon Himalaya are thoroughly transposed by D_2 deformation into NW-SE trending S_m (S_1+S_2). The extent of transposition and a well-developed NE-plunging L_2 lineation indicate intense strain during D_2 throughout the studied portion of the HHC. Ductile flow continued, resulting in rotation of F_1 and F_2 folds due NE-direction and NW-SE plunging F_3 folds within the HHC. The over thickened crystalline was finally, superimposed by late-to-post collisional brittle-ductile deformation (D_4) and exposed the rocks to rapid erosion.

Apatite Fission Track (AFT) and Zircon Fission Track (ZFT) studies from the Kumaon Himalaya suggest reactivation of the Main Central/Munsiari Thrust (MCT/MT) and Vaikrita Thrust (VT), rapid exhumation and a system that has been in topographic and exhumation steady-state since at least 4 Ma.

Keywords: Higher Himalayan Crystallines, Deformation, Exhumation, Kumaon Himalaya.

INTRODUCTION

Continued northward movement of the Indian plate at a rate of approximately 5 cm /yr suggests that about 2500 km of post collisional shortening has taken place since the collision between the Indian and Eurasian plates at 50-55 Ma (Patriat and Achache, 1984; Garzanti et al. 1987; Rowley, 1996). Shortening has been accommodated by crustal-scale imbrications of the Indian crust along a series of sub-parallel SW-directed major thrust faults which resulted in a series of parallel tectono-metamorphic units, along the length of Himalayan chain (Gansser, 1964; Molnar and Tapponier, 1975; Hodges, 2000) (Fig.1). One of these, the HHC zone is a high grade poly-metamorphic unit comprising rocks of possible Precambrian, Palaeozoic and early Mesozoic ages, metamorphosed during the late Eocene to early Miocene and intruded by granites of Miocene age. This is out cropped, throughout the Himalaya. It is recently described to be evolved due to ductile extrusion during earlier Miocene since 23 Ma along a broad northeast dipping intracontinental ductile shear zone between coeval MCT in the south and South Tibetan Detachment System (STDS) in the north (Frank et al. 1977; Jain and Anand, 1988; Hubbard and Harrison, 1989; Burchfiel et al. 1992; Hodges et al. 1992; Jain and Manickavasagam, 1993; Patel et al. 1993; Coleman, 1998; Dezes et al. 1999; Robyr et al. 2006).

Kumaon Himalaya is located near the central part of the Himalayan orogen (Fig.1) and is, therefore, a critical area for studying the typical characteristics of the Himalayan tectonics, in contrast to the areas in close proximity to NE and NW- syntaxes where complications arise due to complex tectonics. Despite the significant amount of research on geology and deformation history of the HHC that has been undertaken in different parts of the Himalaya, the Kumaon Himalaya is among the least studied parts of the Himalayan orogen. Although numerous studies have been carried out in different parts of the Kumaon Himalaya, only a few studies have dealt with geology and structural history of the HHC (Heim and Gansser, 1939; Powar, 1972; Valdiya, 1980; Valdiya and Goel, 1983; Roy and Valdiya, 1988;

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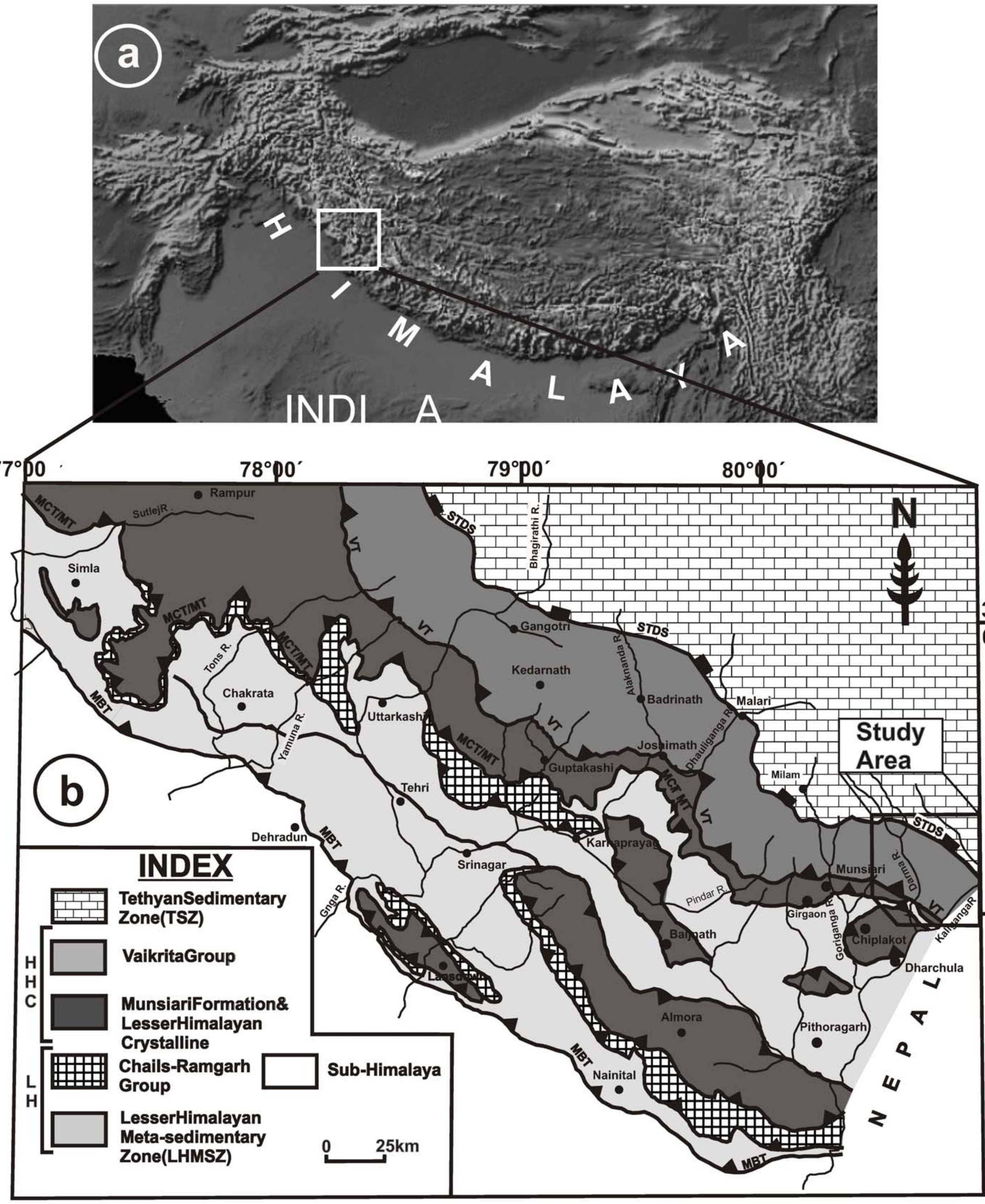

Fig.1. (a) Geological setting of the study area in the Himalaya (topography based on the GTOPO30 digital elevation model, U.S. Geological Survey. (**b**) Geological map of the Garhwal and Kumaon Himalayan region of India showing the tectonic setting of the Higher Himalayan Crystalline (HHC) in the overall lithostratigraphic framework of the region (modified after Valdiya, 1980). The study area in the Kumaon Himalaya is shown in the square box. STDS: South Tibetan Detachment System, VT: Vaikrita Thrust, MCT: Main Central Thrust, MT: Munsiari Thrust, MBT: Main Boundary Thrust, HHC: Higher Himalayan Crystalline and LH: Lesser Himalaya.

Dubey and Paul, 1993; Paul et al. 2000). Recently, few studies on exhumation history of the Kumaon Himalaya have been done (Bojar et al. 2005; Patel and Carter, 2009). In this paper, current geological, structural and exhumational knowledge of HHC of Kumaon Himalaya has been incorporated. The geological investigations have been carried out along Kaliganga and Darma valleys (Fig.1). This is supported by a new geological map of the area based on previously published map (Valdiya, 1980; Dubey and Paul, 1993; Paul, 1998), unpublished map and data collected during this study (Scale 1:50,000) and structural observations made during fieldwork between 1999 and 2002 along Kaliganga and Darma valleys. To get a complete regional geological and structural account of the HHC of the Kumaon Himalaya, the published work of Patel and Kumar (2009) along the Goriganga valley is also discussed here. AFT and ZFT data (Patel et al. 2007, Patel and Carter, 2009) are discussed here to comment on the exhumation history of the Kumaon Himalaya.

GEOLOGY

Rb-Sr ages 1800-2000 Ma, 1100-1000 Ma and 500 Ma (Singh et al. 1985; Singh et al. 1994; Rao et al. 1995) of the granite gneisses of the Kumaon-Garhwal-Himachal Himalaya strongly suggest the involvement of the Middle Proterozoic basement of the northern margin of the Indian plate in Himalayan collision. This is named as Himalayan Metamorphic Belt (HMB) (Manickavasagam et al. 1999 and other references therein). Since the collision at about 55 Ma (Klootwijk et al. 1992; Hodges, 2000) continued convergence has been accommodated by multiple folding and major faulting. Initially, the HHC was extruded during the Early Miocene (~20-15 my ago) (Burchfiel et al. 1992; Srivastava and Mitra, 1994; Dezes et al. 1999; Searle, 1999; Hodges, 2000) between the NE-dipping STDS in the north (Burg and Chen, 1984; Herren, 1987; Burchfiel et al. 1992; Patel et al. 1993) and MCT in the south (Heim and Gansser, 1939; Pecher, 1977; Thakur, 1987; Jain and Manickavasagam, 1993; Jain et al. 2000). The deformation front was then gradually propagated to the south along the Main Boundary Thrust (MBT) during Late Miocene (~10-5 Ma) (Meigs et al. 1995; DeCelles et al. 2001; Huyghe et al. 2001) and most recently along the Main Frontal Thrust (MFT) (Valdiya, 1992; Thakur et al. 1995; Lave and Avouac, 2000; Patel and Kumar, 2003). These thrusts bound orogen-parallel tectono-lithostratigraphical domains such as the TSZ, the HHC, the Lesser Himalayan (LH) zone and the Sub-Himalayan zone (Gansser, 1964; Le Fort, 1975; Thakur, 1992; Hodges, 2000) (Fig.1). Contemporaneously, the HHC was thrust over the LH zone as nappes and more and more units of the LH zone were detached from the under-thrusted Indian continent, and incorporated into the Himalayan wedge forming the LHC. These crystalline nappes were stacked and exhumed forming the Lesser Himalayan nappes (Valdiya, 1980; Thakur, 1992) and Duplexes (DeCelles et al. 2001, Srivastava and Mitra, 1994; Vannay et al. 2004; Patel and Kumar, 2006).

Recent studies show that the HMB is composed of three distinct lithotectonic units: (1) Tso-Morari Crystalline (TMC) unit in the northwest, (2) HHC unit in the middle and (3) the LHC belt in the south exposed within the Lesser Himalayan Meta-sedimentary (LHMS) zone (Vannay et al. 2004; Jain et al. 2005; Patel and Kumar, 2006). The study area in the Kumaon Himalaya comprises segments of the HHC in the north and LHC (Chiplakot Crystalline Belt (CCB)) in the south (Valdiya, 1980; Srivastava and Mitra, 1994; Ahmed et al. 2000) (Fig.1). A 20 km thick segment of LHMS is sandwiched between the MCT/MT in the north and North Chiplakot Thrust (NCT) in the south separate these two metamorphic units (Fig.2).

Previous Geological Information

The area along Kaliganga, Darma and Goriganga valleys has been studied by very few workers (Heim and Gansser, 1939; Powar, 1972; Valdiya, 1980; Dubey and Paul, 1993; Paul, 1998; Paul et al. 2000; Patel and Kumar, 2009). The tectonostratigraphy given by them is given in Table 1.

Higher Himalayan Crystallines (HHC)

Heim and Gansser (1939) described the geology of the Higher Himalayan metamorphic zone. They described a NE-dipping low to medium grade metamorphic sequences intruded by tourmaline bearing granites as stocks and apophyses. The contact between the metamorphic sequences of rocks of the HHC and the TSZ was described by them as a gradational contact through Budhi schist and overlying Martoli Formation.

Powar (1972) named the southern part of the HHC as the Rungling crystalline mass. Valdiya (1980) identified two metamorphic sequences within the Higher Himalayan metamorphic belt as (i) southern sequence named as the Munsiari Formation and (ii) northern sequence named as Vaikrita Group of high-grade metamorphic rocks.

The name 'Munsiari Formation' is designated by Valdiya (1973), after the township in the Goriganga valley to the lower part of the Central Crystallines exhibiting low-grade metamorphism in greenschist to amphibolite facies rocks. All workers except Valdiya (1977; 1979; 1980) include the

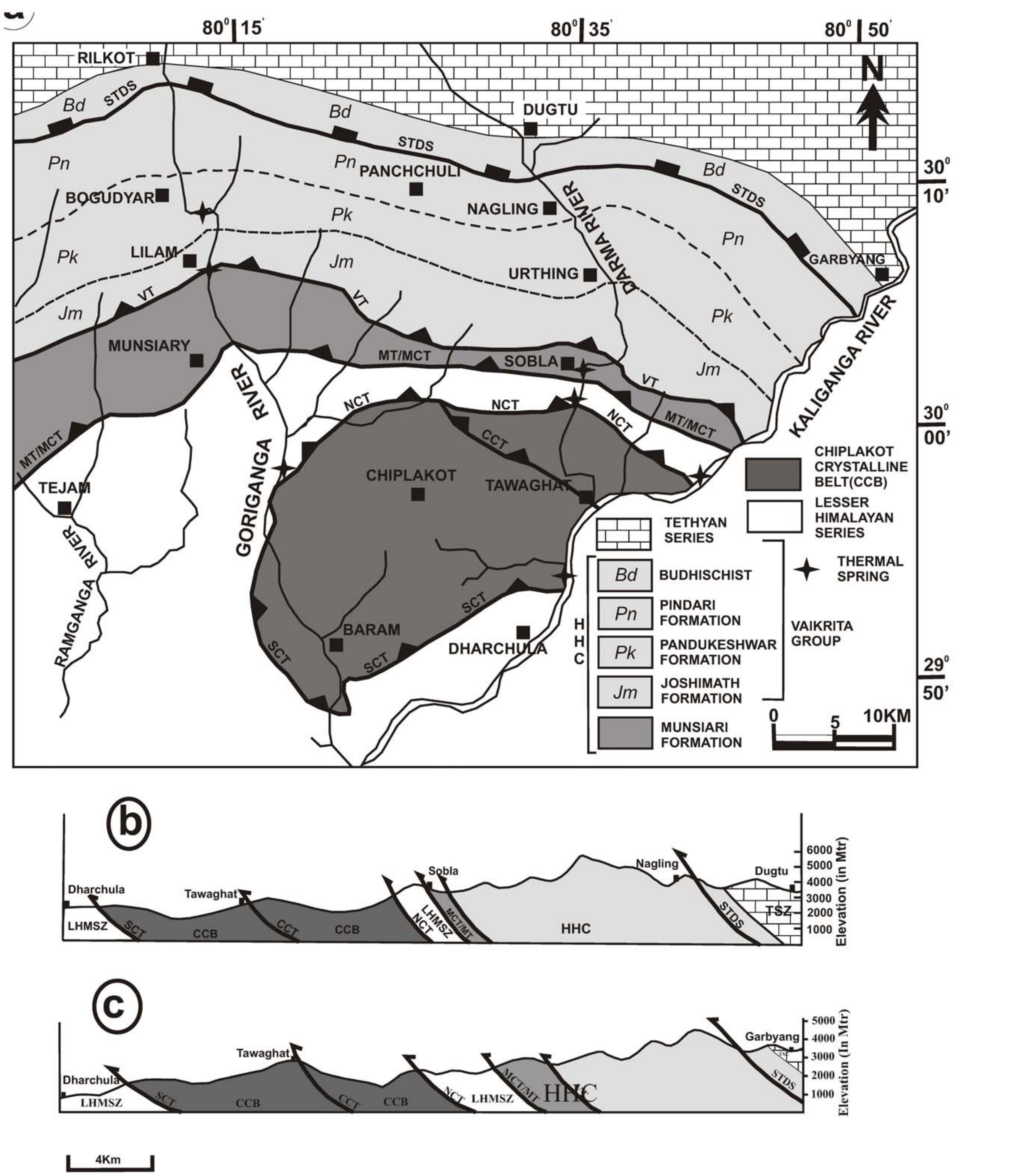

Fig.2. (a) Geological map of the Kumaon Himalaya along the Goriganga, Darma and Kaliganga valleys, **(b,c)** Geological cross-sections along the Darma and Kaliganga valleys.

Munsiari Formation within the HHC (Dubey and Paul, 1993; Thakur and Choudhury, 1983; Kumar and Patel, 2004). Valdiya (1973; 1980) studied this formation between Girgaon and Lilam along the Goriganga valley. Lithologically and petrologically, the Munsiari Formation is related with the Almora, Askot-Baijnath nappe and CCB (Valdiya, 1980; Patel and Kumar, 2006; Patel et al. 2007). Therefore, Valdiya (1980) regarded them as one and the same lithostratigraphic unit as originally described by Heim and Gansser (1939). The lower limit of the Munsiari Formation is defined by the Munsiari Thrust and the upper limit is marked by abrupt change in lithology and grade of metamorphism: the rocks of the greenschist to lower amphibolite facies are succeeded without the

Table 1. Detailed Tectonostratigraphic studies in Kumaon Himalaya showing the comparison with the studies of Powar (1972), Valdiya (1980), Paul (1998), Thakur and Choudhury (1983) and present study. The terms stand for MCT: Main Central Thrust; MT: Munsiari Thrust; T-HT/T-HF: Trans-Himadri Thrust/ Trans-Himadri Fault; STDS: South Tibetan Detachment System; NCT and SCT: North and South Chiplakot Thrusts respectively

Thakur and Choudhury (1983)	Powar (1972), Valdiya (1980) Paul (1998)	Present work
Tethys Himalayan Zone (Lower Proterozoic) - - - - No apparent break- - - -	Tethyan Sedimentary Zone (TSZ) - - - - - - - -T-HT/T-HF - - - - - -	Garbyang Formation (Tethyan Sedimentary Zone) - - - - -No apparent break- - - - -
Central Crystallines (Rb/Sr whole rock ages 1830 Ma (Bhanot et al. 1977)).	VAIKRITA GROUP: Martoli Formation Pindari Formation Pandukeshwar Formation Joshimath Formation	VAIKRITA GROUP: Budhi Formation - - -T-HT/T-HF - - - - (STDS) - - Budhi Formation Pindari Formation Pandukeshwar Formation Joshimath Formation
- - - - - - - MCT - - - - - - - Sirdang Sedimentary Zone (Belong to Calc-zone of Pithoragarh) - - - - - Thrust - - - - - Chiplakot Crystalline (correlated with Chail Nappe) - - - - - Thrust - - - - - Calc zone of Pithoragarh (Shali-Deoban para- autochthon)	- - - - - MCT/ Vaikrita Thrust- - - - Rungling Formation / Munsiari Formation - -Rungling Thrust/Munsiari Thrust (MT) - Berinag Formation - - - - - -Pangla Thrust - - - - - - Munsiari Formation - - - - - Munsiari Thrust- - - - - Berinag Formation	- - - -Vaikrita Thrust- - - - - Munsiari Formation - - - - - -MCT/MT - - - - - - Tejam Group (LH) Berinag Formation - - - - - NCT - - - - - - Chiplakot Crystalline Belt (CCB) - - - - - - SCT - - - - - - - Berinag Formation

transition by kyanite-garnet bearing two-mica-psammitic gneisses and schists that exhibit plastic flowage folding. The style and orientation of the first generation folds (isoclinal reclined with axis trending NE-SW and having 25° plunge in the Munsiari rocks) are considered different from those of Vaikrita Group (also isoclinal to reclined having variable trend from E-W to ENE-WSW) (Valdiya and Goel, 1983). This contact is named as the Vaikrita Thrust (VT) as the plane of separation of the two (Valdiya, 1980).

The name Vaikrita was first time introduced by Griesbach (1891) after the Sanskrit word meaning ‘transformed vicariously’ to a pile of higher grade metamorphics intruded by young Tertiary granites. In Kumaon, these crystallines were included as integral part of the “Central Crystalline Zone” by Heim and Gansser (1939). This group of rocks is separated from the Munsiari Formation along NE-dipping VT in the south around Dar along Darma valley and around north of Mangti along Kaliganga valley. At the top of the Vaikrita Group is the TSZ. Different workers describe the contact between the Vaikrita Group and the TSZ differently. Valdiya and Goel (1983), Roy and Valdiya (1988), Valdiya, (1989) described it as a tectonic contact and named it as Trans-Himadri Thrust/ Fault (T-HF) while Thakur and Choudhury (1983), Arita et al. (1984) described no apparent break between the Vaikrita Group and the TSZ. The kyanite gneiss, staurolite, garnet and biotite schists are followed by phyllite and quartzite succession of the Martoli Formation/ Garbyang series (basal part of the TSZ). Virdi (1980) described the contact as a thrust.

Thakur and Choudhury (1983) described progressive regional metamorphism from chlorite to sillmanite grade across the HHC. In the north, the Malari Fault /Thrust are described as the contact between the Vaikrita Group rocks and the TSZ (Valdiya and Goel, 1983). They described it as a reverse fault.

Present Geological Study

Higher Himalayan Crystallines (HHC)

The traverses from Mangti to Garbyang along the Kaliganga valley and Sobla to Dugtu along the Darma valley have been studied (Fig.2). The detailed geological studies show that the HHC is made up of low-grade metamorphic rocks of the Munsiari Formation and the higher-grade metamorphics of the Vaikrita Group. The Munsiari Thrust is considered as MCT in this study that separates the LHMS zone from the medium to high-grade metamorphic rocks of the HHC (Patel and Kumar, 2009; Patel and Carter, 2009). The VT is considered as another thrust within the HHC that separates the higher-grade Vaikrita Group from the low-grade metamorphics of Munsiari Formation. In present study, the HHC in the Kumaon Himalaya is divided into two distinct groups of metamorphics showing diverse characters and petrological compositions. The complete sequence of the HHC is exposed along the Kaliganga and Darma valleys (Fig.2). The details of these units are shown in Table 2.

Munsiari Formation

Rocks exposed between Mangti and Jipti (Brindakot) along the Kaliganga valley and Sobla to Dar along Darma valley (Fig.2) represents the Munsiari Formation. It is comprised of biotite schist and gneiss, garnet and staurolite bearing schist and augen gneiss. Small bands and layers of amphibolite and quartzo-feldspathic rocks are present within these rocks. The thickness of this belt is about 0.5–1.0 km. No major granitic intrusion is found in this formation. These rocks are highly mylonitised.

Vaikrita Group

The upper part of the HHC comprising of medium to high-grade metamorphic rocks is known as the Vaikrita Group. The Vaikrita Group forms the bulk of the HHC and represents the basement of the TSZ. The VT marks the southern limit of this group and its northern limit is a gradational one. The rock units from south to north are described below and shown on map (Fig. 2). Here the nomenclature of different formations is same as Valdiya (1977, 1980) i.e (1) Joshimath Formation; (2) Pandukeshwar Formation; (3) Pindari Formation and (4) Budhi Schist.

Joshimath Formation

The Joshimath Formation is exposed in the southern part of the Vaikrita Group along both the Kaliganga and Darma valleys. Along Kaliganga valley, it is exposed between Bindakoti and Nazyang Gad and along the Darma valley between Dar and Urthing. It consists of biotite augen gneiss, kyanite-sillimanite psammitic gneiss and kyanite bearing augen gneiss. At some places, migmatite and quartzite bands are found. In this zone, the biotite content decreases towards Pandukeshwar Formation. The stretching lineations are widely developed in rocks and are defined by preferred orientation of kyanite, sillimanite, biotite, tourmaline etc. and preferred orientation of augens.

Pandukeshwar Formation

This formation is exposed around Malpa along the Kaliganga valley and between Urthing and Nagling along the Darma valley. It consists of massive, compact, white or fawn coloured quartzite interbedded with mylonitic gneiss, layers of garnet and kyanite bearing schist. Granite gneiss band of about one kilometer is also exposed along the Darma valley. Leucogranite and pegmatite dykes are intruded in rocks of Pandukeshwar Formation. Xenoliths of granite gneiss are present within the leucogranite and pegmatite. Along Kaliganga valley, the calc-silicate bands are also found within the Pandukeshwar Formation. Virdi (1980) described the Pandukeshwar Formation at the core of a large isoclinal anticline and considered it older than Joshimath Formation. The grade of metamorphism increases towards the center of the HHC.

Pindari Formation

Pindari Formation is exposed between Nagling and Badring along the Darma valley and between Uindon gad and Patan gad along the Kaliganga valley. It is mainly comprised of thick sequences of migmatite gneiss and intrusive granitic bodies and mylonitic gneiss/ augen gneiss along with calc-silicate rocks consists of calcite, diopside, quartz, hornblende, actinolite and tremolite. These rocks are extensively intruded by pegmatite veins, granite, aplite veins and dykes. Asymmetric augens of different sizes show top-to-SW shearing. A mappable unit of leucogranite is exposed along the contact between the Pindari and Budhi schist formation. It appears as a lensoid shape. The detailed rock types are described below.

Budhi Schist

Towards north of the Pindari Formation is the Budhi schist. It is comprised of biotite porphyroblastic calc-schist interbedded with micaceous schist and phyllites towards the top. The schist and phyllite are locally carbonaceous, pyritic, staurolite, garnet bearing. The gneisses and schists at Baling in the Darma valley are intercalated with thick bands of calc-silicate rocks and thinly foliated schist. The pegmatite veins and dykes intrude the Budhi schist in Kaliganga valley. The

Table 2. Tectonostratigraphy along the Kali-Darma valleys of Kumaon Himalaya

Tectonic Units	Tectonic Subunits	Formation	Lithology/ Rock type
Tethyan Sedimentary Zone (TSZ)		Garbyang Formation	Garnetiferous schist and phyllites
Higher Himalayan Crystalline (HHC)	Vaikrita Group	Budhi schist	Phyllite, porphyroblastic (phlogopite) biotite schist, calcareous schist, intrusion of pegmatite veins.
		SOUTH TIBETAN DETACHMENT SYSTEM (STDS)	
		Budhi schist	Phyllite, porphyroblastic (phlogopite) biotite schist, calcareous schist, intrusion of pegmatite veins.
		Pindari Formation	Calc-silicate rocks with sub-ordinate biotite-psammitic gneisses and schists, extensive intrusion of dykes and veins of pegmatite
		Pandukeshwar Formation	Massive garnet-kyanite bearing quartzite, schist and psammitic gneiss.
		Joshimath Formation	Coarse-grained ky-silli-gt-ms-bt schist and banded sill-bt gneiss, migmatites, biotite schist
	VAIKRITA THRUST (VT)		
	Munsiari Formation	Munsiari Formation	Biotite-garnet schist and garnetiferous gneiss.
MAIN CENTRAL THRUST (MCT)			
Lesser Himalayan Metasedimentary Zone (LHMZ)	Calc- zone of Tejam (North)	Tejam Group Berinag Formation	Quartzite, amphibolite and chlorite schist Carbonaceous phyllite, Schistose quartzite, amphibolite, arenaceous marble, calc-schist, marble
NORTH CHIPLAKOT THRUST (NCT)			
Lesser Himalayan Crystallines Zone (LHC)	Chiplakot Crystalline Belt (CCB)	Upper unit	Augen gneiss, banded gneiss, mylonitised gneiss and schist, granitic gneiss
		CENTRAL CHIPLAKOT THRUST (CCT)	
		Lower unit	Highly mylonitised gneiss, mylonite bands, biotite gneiss
SOUTH CHIPLAKOT THRUST (SCT)			
Lesser Himalayan Metasedimentary Zone (LHMZ)	Calc- zone of Tejam (South)	Berinag Formation	Massive quartzite, Schistose quartzite
		BERINAG THRUST	
		Tejam Group: Mandhali Formation	Dolomitic limestone, Carbonaceous phyllite, Slate
		Tejam Group: Deoban Formation	Massive and bedded marble, Dolomitic phyllite, carbonaceous phyllite and slate

rocks are metamorphosed to amphibolite grade (Powar, 1972). This unit is formed by metamorphism of original calc-argillaceous sediments (Powar, 1972).

TECTONICS

Previous Structural Information

Very few workers have studied the deformation history and carried out the structural analysis of the HHC rocks in the Kumaon Himalaya (Bhattacharya, 1982, 1987; Thakur and Choudhury, 1983; Roy and Valdiya, 1988). Thakur and Choudhury (1983) have reported only three phases of deformation (D_1, D_2 and D_3) whereas Roy and Valdiya (1988) have described two categories of folds based on broad orientation with respect to dominant lineation marking the direction of tectonic transport: (i) folds with their hinges sub-parallel to the lineation and (ii) folds with their hinges at high angle to lineation. Dubey and Paul (1993) described two groups of folds: (i) early group of folds (F_{1a}, F_{1b} and F_2) which developed simultaneously with thrusting along MCT and (ii) later group of folds (F_3). No detailed studies of the structures developed during different phases and no detailed structural analysis of the HHC have been carried out so far.

Present Structural Study

Deformation Pattern

The relative chronology of the poly-phase structural evolution observed within the HHC is well constrained by cross cutting relations but it is more difficult to establish the temporal correlation between the deformation episodes.

The age data of the Kumaon Himalaya confirm the HHC as a Proterozoic basement of the northern margin of the Indian Plate over which the cover of Palaeozoic and Mesozoic sediments (TSZ) deposited (Bhanot et al. 1977; Singh et al. 1985; Jain et al. 2000) and got involved in the Himalayan deformation and metamorphism. Observations in the study area led to the recognition of several structures, mainly folds, foliations, stretching lineations, shear zones, and faults. Mutual relations among these structural elements, at the outcrop scale, indicate the occurrence of four tectonic phases (D_1, D_2, D_3 and D_4) (Fig.3). Out of these D_1 is the pre-Himalayan tectonic phase. It means the basement had undergone at least one episode of deformation (D_1) (Fig.3a) before Himalayan orogeny. Later, as a consequence of Himalayan orogeny, the basement along with the cover TSZ was deformed simultaneously by three major phases D_2, D_3 and D_4 (Figs.3b,d and e). The relative chronology of these phases is revealed by fold interference patterns as well as by folded S_1 schistosity in the hinge zone of F_2 and S_2 schistosity and L_2 lineation in the hinge zone of F_3 folds (Figs.4a and b).

The earliest D_1 phase has produced rarely noticeable, isoclinal F_1 folds with an axial plane foliation S_1. These parallel the lithological layering (S_0). A few occurrences of isolated F_1 folds depict their coaxial nature with the later F_2 folds (Fig.3a), suggesting a re-orientation of D_1 structures during the dominant D_2 deformation. Although a shear deformation may have reoriented the earlier F_1 folds (Fig.3a) towards co-axial later F_2 folds (Fig.3b), contemporaneous development of ubiquitous NE-plunging F_2 folds, mineral stretching lineation L_2 on the axial plane foliation S_2 developed during D_2. S_2 foliation is a pervasive ductile S-C shear fabric with a consistent NE-plunging mineral stretching lineation. This lineation plunges at 30-40º with very high pitch on the S_2 foliation surface. F_2 folds along with L_2 lineations maintain their consistent orientation irrespective of the attitude of the composite foliation containing them, indicating insignificant changes in kinematics during the deformation of the HHC and its subsequent shearing. These plunge orthogonally to the Himalayan trend and is characterized by preferred orientation of kyanite, staurolite, tourmaline, mica and by stretched, elongated augen megacrysts of quartz and feldspar.

At the top of the HHC, however the deformation D_2 is associated with the extensional movement along the STDS. The D_2 phase is interpreted to record the ductile stage of exhumation of the HHC, controlled by combined SW-directed thrusting along the MCT/MT and VT, and NE-directed extension along the STDS. D_2 deformation is associated with regional metamorphism between 40Ma and 15 Ma under 6-11kbar pressure and 500 - 750°C temperature along with leucogranite intrusion (Seitz et al. 1976; Stern et al. 1989; Hubbard and Harrison 1989; Metcalfe 1993; Dezes et al. 1999; Searle et al. 1999; Manickavasagam et al. 1999; Hodges, 2000; Bregar et al. 2001; Vannay et al. 2004; Yin, 2006; Jain et al. 2008).

In the later part of structural evolution, overprinted compressional D_3 deformation was associated with development of open to close F_3 folds on quartz-veins, quartzo-feldspathic layers, migmatite, amphibolite and metamorphic layers parallel to S_2 foliation in the rocks of the HHC (Fig.3d). It folded the earlier fabrics and the NE-plunging mineral/stretching lineation. The associated axial plane foliations (S_3) are defined by alternating quartz-feldspar and muscovite-biotite rich layers. These foliations are superposed on earlier planar surfaces S_1 and S_2. The overprinting of S_1, S_2 and S_3 formed the composite planar foliation, which defines the main foliation S_m in the whole HHC.

Non-coaxial superposition of F_3 on F_2 folds resulted in type-2 (Fig.4a) and co-axial superposition of F_2 on F_1 resulted type-3 (Fig.4b) interference patterns within the HHC.

Throughout the HHC, contractional ductile fabrics are overprinted by brittle-ductile to brittle extensional structures (D_4) (Fig. 3e). Such extensional tectonics studied elsewhere in the Himalaya (Patel, 1991; Patel et al. 1993; Carosi et al. 1999; Jain and Patel, 1999; Kumar and Patel, 2004) is described due to syn-to-late collapse phenomena during exhumation, which initiated during ductile deformation and continued up to brittle deformation.

Shear Criteria and Sense of Displacement

The HHC is characterized by numerous small-scale structures, which are not only better developed in the shear zones, but are ubiquitous throughout the metamorphic belts.

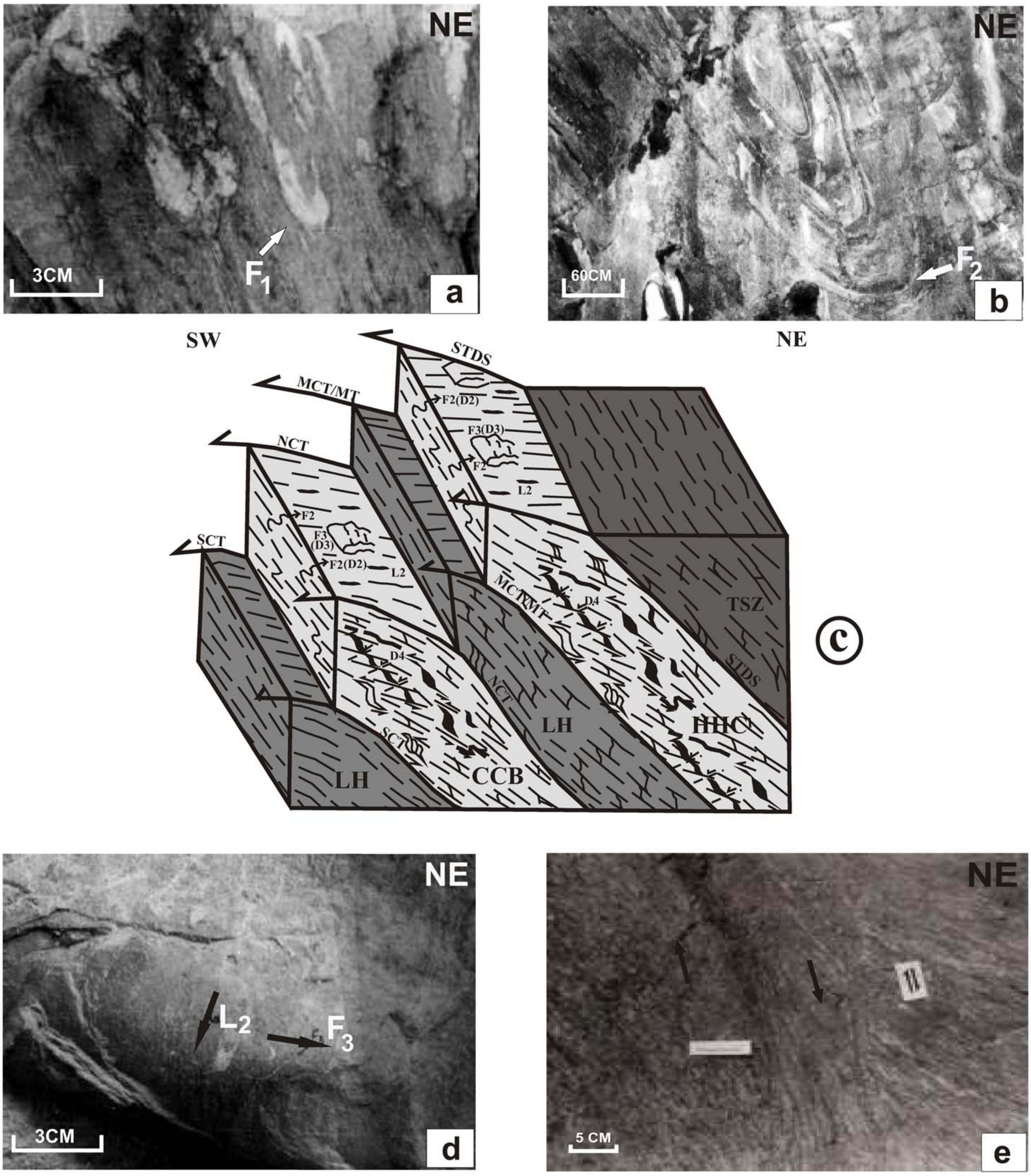

Fig.3. Representative structures of different deformation phases from the HHC along with isometric diagram showing structures of the Kumaon Himalaya. **(a)** Rootless, hook shape, sub-isoclinal F_1 folds developed in quartz veins present in the augen gneiss along the Kaliganga valley at Mangti, **(b)** Isoclinal F_2 folds in quartzites with psammite gneiss within the HHC along Kaliganga valley, **(c)** Isometric diagram showing structures of the Kumaon Himalaya, **(d)** Close-to-isoclinal F_3 fold in the HHC along Kaliganga valley. L_2 lineations are folded along the hinge zone of F_3 folds and **(e)** Extensional shear bands within the rocks of the HHC along Darma River.

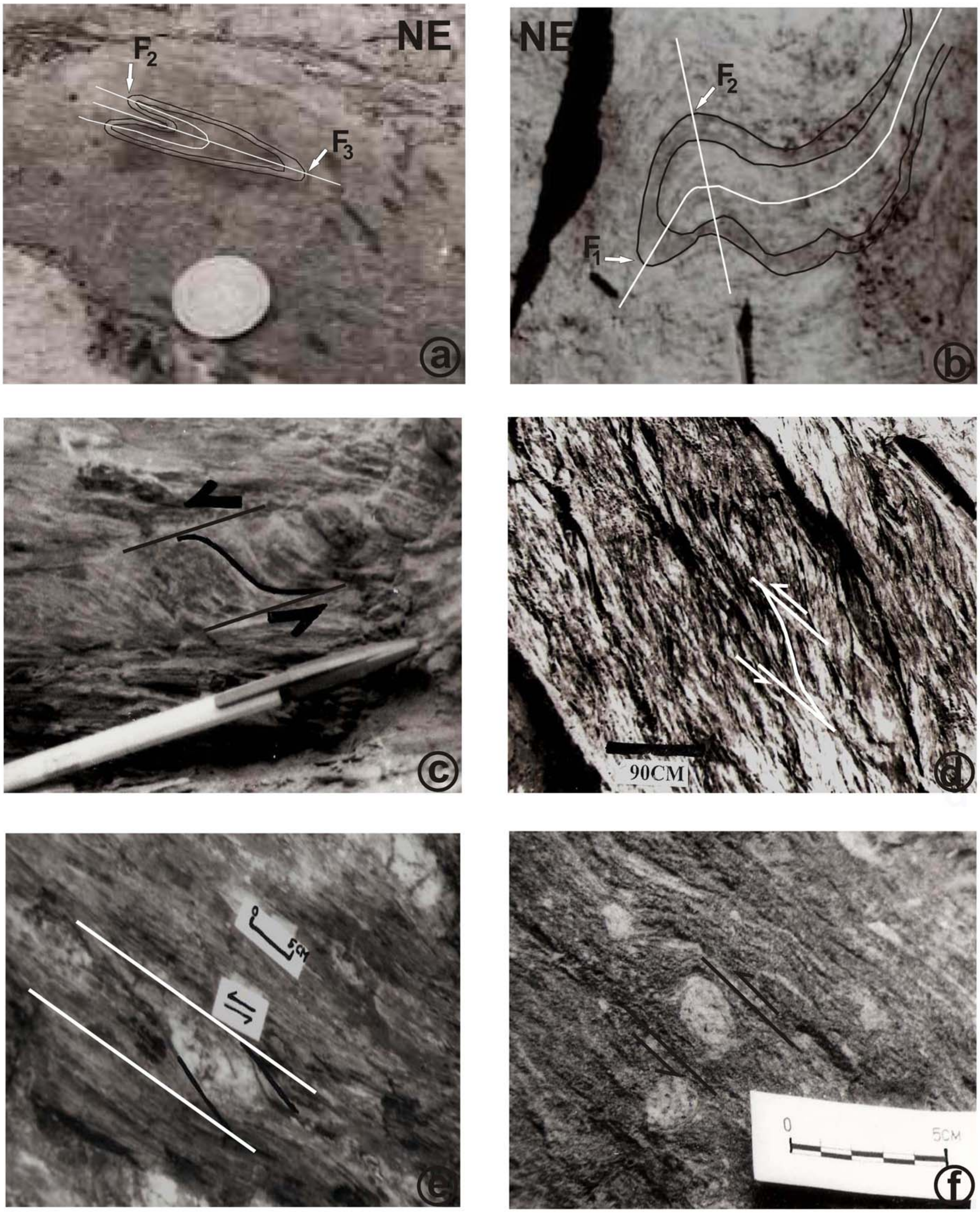

Fig.4. Representative structures of interference patterns and different stages of progressive shearing from the HHC in the Kumaon Himalaya. **(a)** Type-2 interference pattern developed due to superposition of later F_3 fold on earlier F_2 fold, **(b)** Type-3 interference pattern developed due to transposition of earlier F_1 fold during later F_2 superposed folding, **(c)** Advance stage of shearing, the angle between C- and S- is 25° to 30°, **(d)** With progressive shearing, the angle between C- and S is reduced to 15° to 20°, **(e)** Finally angle between C- and S diminishes to 0° to 5° and **(f)** Rotated feldspar augen characterized with asymmetric tails of feldspar.

Numerous shear sense indicators are present in Zanskar and Himachal Himalaya that have been used to understand the mechanism of deformation of the HHC (Herren, 1987; Patel et al. 1993; Jain et al. 2002). Similar studies have been carried out in the HHC of the Kumaon Himalaya. Shear structures belonging to two categories are present within the HHC: (a) shortening shear fabrics and (b) superposed extensional shear fabrics.

Shortening shear fabric: Shortening shear fabrics are widely present within the HHC. These structures show a consistent top-to-southwest overthrust sense of displacement developed during the pervasive D_2 deformation. S-C planer fabrics (Berthe et al. 1979; Lister and Snoke, 1984) are widely distributed within the HHC (Figs.4c, d and e). The S-C fabrics are sub-parallel to each other due to high intensity of progressive shearing along MT, VT. Different stages of progressive shearing are observed except the initial stage during which the angle between C- and S- surfaces might have been approximately 45°. During advance stage of shearing, the angle between C- and S- is 25° to 30° (Fig.4c). With progressive shearing, the angle is reduced to 15° to 20° (Fig.4d) and finally it diminishes to 0° to 5° (Fig.4e). In rocks having S-C fabric, asymmetrical pressure shadows (Simpson and Schmidt, 1983) around rigid megacrysts of feldspar with asymmetric tails of feldspar (Fig.4f) and rotated garnet show sigmodial tails in the direction of C-shears. These shadows are mostly filled with quartz and mica. Inclusions within the garnet porphyroblasts reveal continuous rotational fabrics related to ductile shearing. Both σ-Type and δ-Type of augens (Passchier and Simpson, 1986) and sheared lenses are common in granitic gneiss and mylonitic gneiss. In the zone of high strain like MCT/MT and VT, the folds are intrafolial (Fig.5a). All these asymmetric folds plunge in the NE-direction. The rootless hinges of these folds show SW-directed overthrusting sense of shear. s-slip type of asymmetric boudins (Goscombe and Passchier, 2003; Grasemann et al., 2003) are developed in quartzo-feldspathic layers. Small scale shear zones at low angles to bulk shear direction cut the foliation and competent layers into doubly tapered sigmoidal lozenges, lenses, pods or fish (Fig.5b) with distinct asymmetric geometry. The asymmetric nature of boudins shows top-to-SW shearing.

Extensional shear fabrics: Extensional shear fabrics are formed at a later stage of progressive deformation and are referred to as secondary fabric (White et al. 1980; Simpson and Schmid, 1983; Cases, 1986; Dennis and Secor, 1987; Grasemann et al. 1999). The predominant structures developed in this group are the foliation boudinage (Fig.5c), extensional crenulation cleavage (ecc) (Fig.5d), ductile shear bands (Fig.5e), brittle-ductile normal faults etc. Both symmetric and asymmetric foliation boudinage (Platt and Vissers, 1980) are found within the strongly foliated rocks of the HHC. The foliation boudinage in the HHC are formed after D_2 ductile deformation. In symmetrical foliation boudinage, foliation pinches towards the cuspate region infilled with quartzo-feldspathic materials. The asymmetrical foliation boudinage is characterized by ductile shears, which are oblique to the main foliation in the normal-fault sense. The metamorphic rocks of the HHC in Kumaon Himalaya reveal single discrete set of narrow shear zones at different localities. These shear bands are best developed in contrasting lithologies and also high-grade gneiss and leucogranite. The fabric has a remarkably consistent orientation with respect to the shear zone boundaries and occurs as a single set of structures. Shear bands trend NW-SE and dip steeply due NE.

Layers of quartzo-feldspathic composition are distinctly displaced along brittle or brittle-ductile normal fault (Fig.5f). Brittle normal faults are observed in granite, migmatite and quartzo-feldspathic rocks and in Budhi schist. These faults are parallel to ecc planes and shear bands developed in the HHC.

Structural Analysis

Structural maps of main composite foliation Sm (Sm = S_1+S_2) and lineation (Figs. 6a and b) along both the Kaliganga and the Darma valleys are prepared. On the basis of homogeneity of important structures, the whole area within the HHC was divided into 11 subareas to ascertain the regional variation in trends of structures (Figs.6a and b). The subareas K-1 to K-4 within the HHC and T-1 within the TSZ are located along traverse from Mangti to Garbyang along the Kaliganga valley and D-1 to D-5 within the HHC and T-2 within the TSZ are between Sobla to Dugtu along the Darma valley. The selective stereograms are prepared for each subarea by plotting poles to the planer fabrics, lineation, fold hinges. The oriented data are presented as lower hemisphere equal area Schmidt's projection net and subsequently contoured by Dimitrizevic net (Dimitrizevic, 1956). Details of individual subareas for different structural elements are tabulated in Table 3 and shown on Figs.6a and b.

Investigations in individual subarea as well as whole area including study along the Goriganga valley (Patel and Kumar, 2009) and CCB (Kumar and Patel, 2004; Patel and Kumar, 2006) have shown no significant change in orientation of most of the mesoscopic structures (Fig.7). S_1,

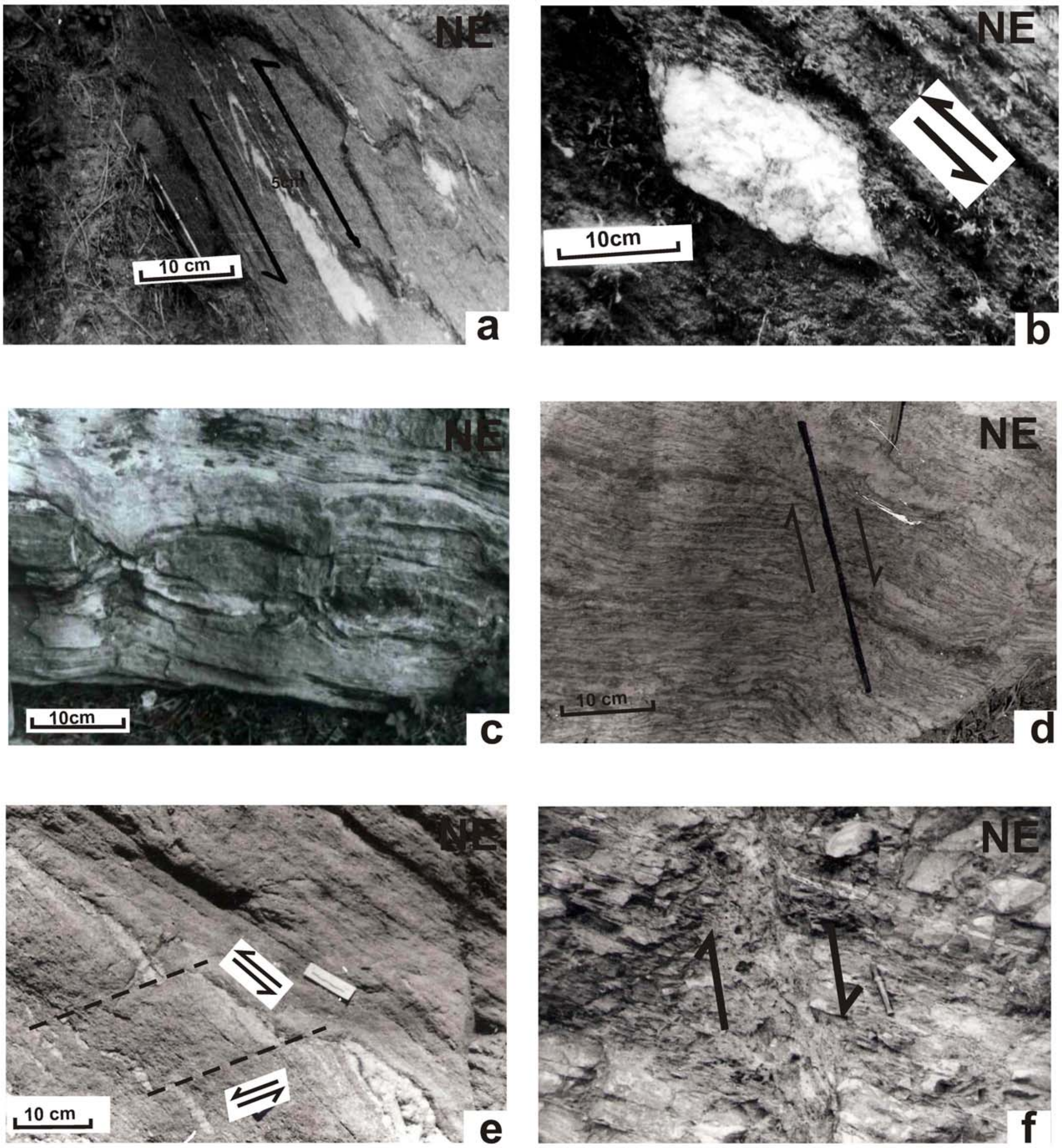

Fig.5. Representative shear fabric related to top-to-SW shearing and extensional shearing. **(a)** Intrafolial folds in quartzo-feldspathic layers showing top-to-SW shearing along Kaliganga valley, **(b)** Asymmetric quartz lense showing top-to-SW sense of movement along Kaliganga valley, **(c)** Symmetrical foliation boudinage along Kaliganga valley, **(d)** Extensional crenulation cleavage within the HHC along the Kaliganga valley, **(e)** Asymmertic lenses showing top-to-SW shearing along with superposed extensional shear bands within the HHC along the Darma valley and **(f)** Brittle normal fault at Budhi along the Kaliganga valley.

S_2 and S_m planar fabrics are found sub-parallel to each other through out the HHC (Fig.7a). Similarly, F_1 folds are also sub-parallel to F_2 folds (Fig.7b). It suggests that the S_1 and F_1 rotated parallel to S_2 and F_2 respectively during D_2 ductile deformation and developed S_m planar fabric. F_2 fold axes are strongly sub-parallel to L_2 lineation in almost whole area suggesting that they are genetically same. S_3 axial plane foliations associated with F_3 folds show a pattern, which resembles the composite S_m and S_2 foliations (Fig.7b). The scattered S_3 poles might be due to superimposition on earlier structures. F_3 folds trend obliquely to F_1 and F_2 folds. It indicates that the F_3 folds were developed on earlier planar structures due to SW-NE trending compressional stress during Himalayan orogeny.

Major Structures

The major structures present in the area are the MCT/MT, VT and STDS.

Table 3. Structural data from subareas D-1 to D-5 and T-2 along the Darma valley and K-1 to K-4 and T-1 along the Kaliganga valley within the HHC and TSZ in the Kumaon Himalaya

Fig. No.	Subarea	Structural fabric	No. of observation	Contour % area	Orientations
Darma Valley					
Fig 6a (a)	D-1	S_m	36	1-3-5	N315°/54°/NE
		L_m	22	1-3-5	54°/N42°
Fig 6a (b)	D-2	S_m	17	1-2-3	N294°/58°/NE
		L_m	14	1-3-5	50°/N62°
Fig 6a (c)	D-3	S_m	10	1-2-3	N267°/63°/NE
		L_m	3	1-2	38°/N57°
Fig 6a (d)	D-4	S_m	30	1-5-9-13	N308°/48°/NE
		L_m	4	1-3	44°/N68°
Fig 6a (e)	D-5	S_m	41	1-3-5-7-9-11-13	N281°/43°/NE
		L_m	10	1-3-5	28°/N79° N
Fig 6a (f)	T-2	S_m	12	1-2-3-4-5-6	N280°/40°/NE
		L_m	3	1-2	7°/N278°
Fig. 7a (b)	D1-D5 (Syn optic studies)	S_m	134	1-8-16-24	N297°/51°/NE
		L_m	53	1-4-7	54°/N31°
Fig. 7b (d)		S_1	6		N356°/75°/E
		F_1	7		30-50°/N176-190°
		S_2	4		N302°/54°/NE
		F_2	11		54°/N75°
		S_3	4		N273°/55°/N
		F_3	7		20-40°/N270° 37°/N329°
Kaliganga Valley					
Fig 6b (a)	K-1	S_m	39	1-4-7-10	N303°/55°/NE
		L_m	17	1-3-5	55°/N48°
Fig 6b (b)	K-2	S_m	24	1-4-8	N316°/56°/NE
		L_m	17	1-3-5	55°/N70°
Fig 6b (c)	K-3	S_m	34	1-4-7-10	N308º/50º/NE
		L_m	23	1-3-5	42°/N78°
Fig 6b (d)	K-4	S_m	14	1-3-5	N314°/38°/NE
		L_m	13		32°/N81°
Fig 6b (e)	T-1	S_m	32	1-3-5	N307°/52°/NE
		L_m	14	1-2	16°/N125°
Fig. 7a (c)	K1 – K4 (Syn-optic studies)	HS_m	111	1-5-10-15-20	N314°/39°/NE
		HL_m	60	1-5-10	48°/N73°
Fig. 7b (e)		HS_1	21	1-2-3-4-5	N14°/60°/E, N34º/12º/SE
		HF_1	27	1-3-5	22°/N85° 30°/N130°
		HS_2	28	1-2-3-4-5	N24°/50°/SE
		HF_2	31	1-2-3-4-5	53°/N30° 54°/N70° 10°/N120°
		HS_3	8	1-2	N10°/20°/SE N10°/50°/SE
		HF_3	6	1-2	12°/N125° 18°/N154° 26°/N110°

Main Central/Munsiari Thrust (MCT/MT): It is the contact between the Munsiari Formation and LHMS zone. The Munsiari Formation is thrust over the LHMS zone along this thrust. Heim and Gansser (1939) were the first to designate it as the MCT in Kumaon Himalaya. It has been correlated across the orogen (see review by Yin, 2006) and is widely recognized to be the most important structure responsible for the development of the Himalaya, but its exact location has been widely debated (e.g. Kohn et al. 2002; Searle et al. 2002). Martin et al. (2005) argued that Nd isotopic composition is the most diagnostic criterion to separate the Greater Himalayan crystallines and Lesser

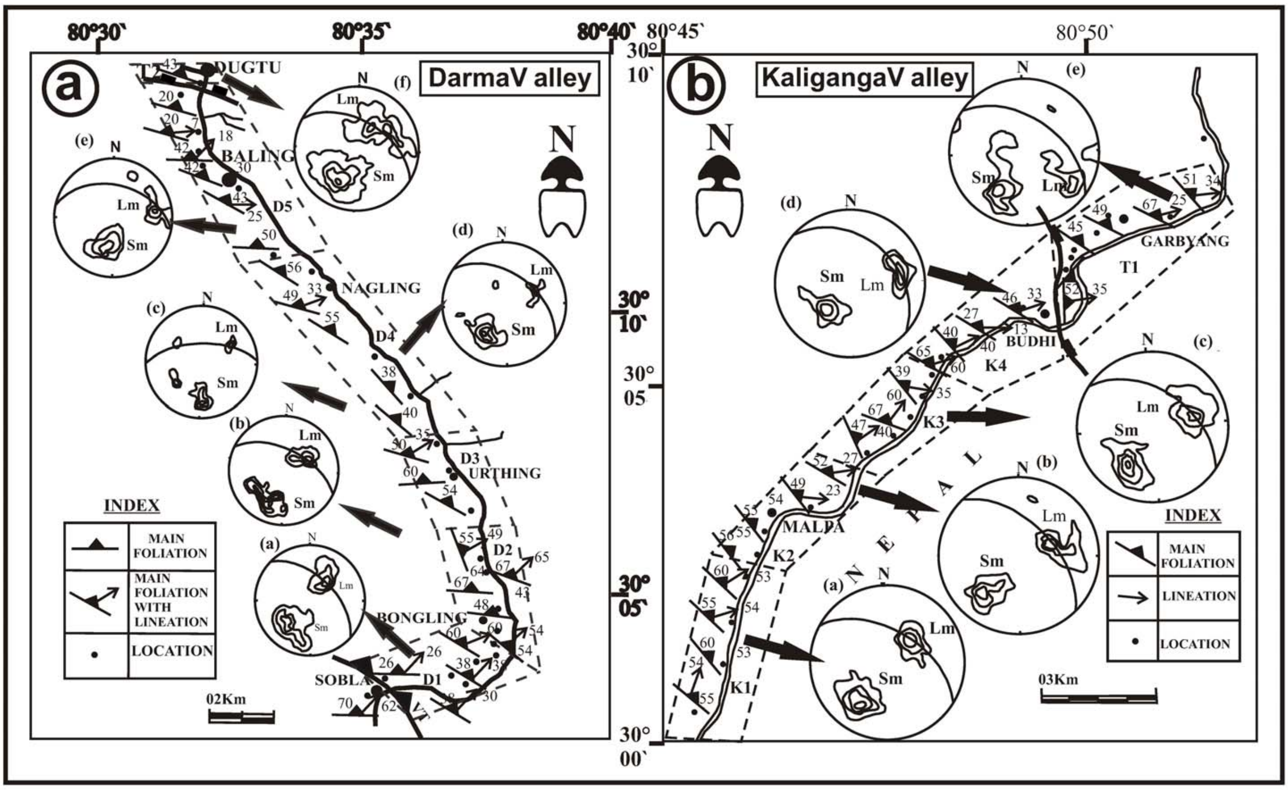

Fig.6. Structural map along the Darma valley **(a)** and Kaliganga valley **(b)** showing orientation of main foliation (S_m) and lineation (L_m) within the HHC.

Himalayan sequence above and below the MCT, while Searle et al. (2008) argue that only the location of maximum shear strain marks the trace of the MCT which falls along the Munsiari Thrust (MT). Multiple strands of the MCT have been recognized and are collectively referred to as the MCT zone (Bordet, 1961; Bordet et al. 1972). The lower and upper bounding faults of the MCT zone have been termed the Munsiari and Vaikrita Thrusts in Kumaon and Garwhal (Valdiya, 1980, Kumar and Patel, 2004, Patel and Kumar, 2006; Patel and Carter, 2009) and the MCT I and MCT II in Nepal (Hashimoto et al. 1973). The upper thrust in many parts of the Himalaya generally moved in the early Miocene, whereas the lower thrust moved in the late Miocene and Pliocene (Harrison et al. 1997; Catlos et al. 2004).

In the present study area along the Kaliganga and Darma valleys, the MCT is defined by sudden change in lithology, alternate bands of amphibolite, quartzite and gneiss. It can be traced near Mangti in the Kaliganga valley and near Nyu in the Darma valley. It is demarcated on the basis of change of meta-sedimentary rocks to gneissic rocks and sudden appearance of moderately to steeply dipping continuous augen and banded gneiss rocks above the quartzite of calc-zone of Tejam (north). A thin amphibolite band around Nyu village also characterizes it. Powar (1972) named it as Nyu Thrust. It is also marked in the field by a sharp break in slope and height and boundary between meta-sedimentary rocks such as quartzite, limestone and slate of Lesser Himalaya to medium grade gneissic rocks of the Munsiari Formation.

Vaikrita Thrust (VT): This term was introduced by Valdiya (1980) for a tectonic boundary within the HHC to distinguish a high-grade sequence from low-grade metamorphics. In the present study, VT is marked as the thrust that separates the Munsiari Formation and the Vaikrita Group. The VT is observed near Dar village in the Darma valley and Bindakoti (near Jipti) in the Kaliganga valley where gneisses of Munsiari Formation change into high-grade garnet-kyanite-sillimanite-gneiss. It is also supported by presence of hot spring near Dar village indicating its close association with the VT. Another important observation is the change in folding in the hanging wall and footwall. In the footwall (Munsiari Formation) the folds developed in quartz and quartzo-feldspathic layers are tight to isoclinal whereas in the hanging wall side (Vaikrita Formation) the folds developed in psammitic gneiss, migmatites are ptygmatic, sigmoidal disharmonic in nature. The VT is

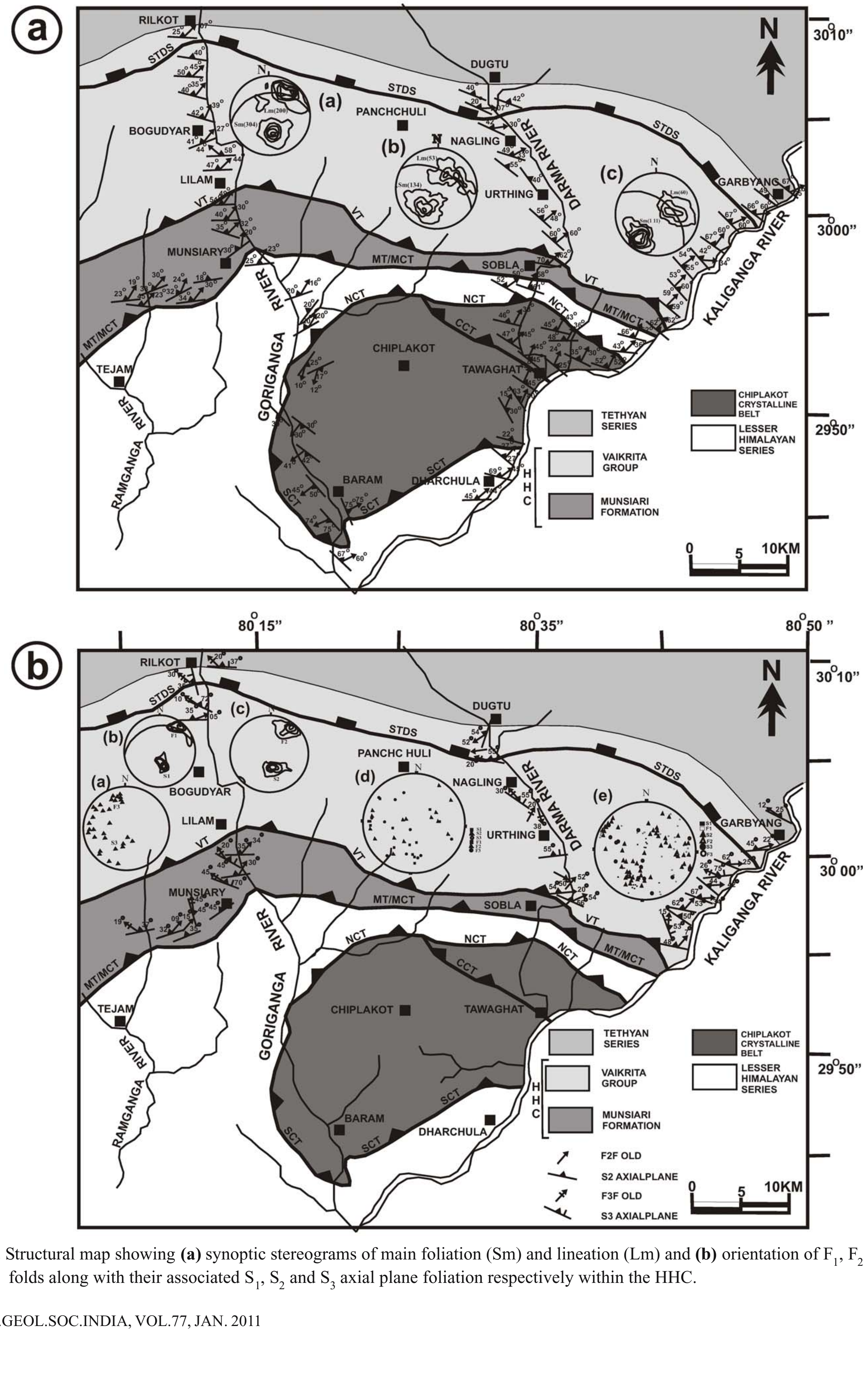

Fig.7. Structural map showing **(a)** synoptic stereograms of main foliation (Sm) and lineation (Lm) and **(b)** orientation of F_1, F_2 and F_3 folds along with their associated S_1, S_2 and S_3 axial plane foliation respectively within the HHC.

similar in tectonic position and interpretation of French workers in Nepal Himalaya, where the tectonic boundary has been placed between the medium grade and high-grade metamorphic rocks (Le Fort, 1975) and also named as MCT-II by Arita (1983).

South Tibetan Detachment System (STDS): In the Kumaon region the northern boundary of the HHC is demarcated as Maleri Fault/ Trans-Himadri Fault (T-HF) (Valdiya, 1979, 1989). Investigations in the Nepal, Kumaon and Zanskar regions demonstrated that the boundary between the HHC and TSZ is a large detachment fault of regional dimension. It is named as South Tibetan Detachment System (STDS) (Burg et al. 1984; Burchfiel and Royden, 1985; Searle, 1986; Herren, 1987; Patel et al. 1993). We did not observe such tectonic contact along the HHC and TSZ along the Goriganga valley (Patel and Kumar, 2009) and in the present study area in the Kumaon Himalaya. Our present study supports the previous studies of Thakur and Choudhury (1983), i.e. there is a transitional contact between the Vaikrita Group (HHC) and the TSZ. The upper unit of the Vaikrita Group is distinguished from the basal part of the TSZ by the presence of quartzo-feldspathic intrusive bodies within the Vaikrita Group and the absence of these bodies within the TSZ. A zone characterized by many brittle northward dipping extensional shear zones, recent land slides, pronounced changes in topography within the upper part of the HHC and abrupt changes in channel gradient of the Kaliganga and Darma Rivers is marked within the Vaikrita Group of the HHC near Budhi along the Kaliganga and near Dugtu along the Darma valleys. It is marked as the extension of the STDS (Fig.2). Along this zone both contractional and extensional shear fabrics are observed. It appears that the extensional shear fabrics are cutting across the contactional shear fabrics indicating that the extensional tectonics is younger that the contractional tectonics. The planes along which contractional shearing (top-to-SW) took place trend NW-SE and dip around 35°-40° due NE while extensional fabric trend NW-SE and dip around 70° to 80° due NE.

Seismicity and Active Tectonics

Several observations demonstrate that tectonics along the MCT/MT and VT is still active but since ~2 Ma no major disturbance in the region has taken place: (1) Thermochronological results indicate rapid but constant cooling rates across the whole HHC during the past ~2 Ma, (2) the MCT/MT and VT zones are characterized by high near-surface geothermal gradients, as revealed by the presence of several thermal springs (Fig. 2) (Kumar, 2005), (3) neo-tectonic results indicate tectonic uplift of the HHC along the MCT/MT and VT (Paul, 1986; Paul et al. 2000) and (4) the present day seismic data of the region reveals that the area has been affected by very few strong earthquakes in comparison to other parts of the NW-Himalaya. The region has not experienced a major earthquake at least in the last 500-700 years (Paul et al. 2007). It indicates that the region has been experiencing constant rates of crustal uplift since a long time.

LOW-TEMPERATURE THERMOCHRONOLOGY

Sampling and Analytical Procedures

Samples (8 samples each from the Darma and the Kaliganga traverses) were collected between elevation 1.5 and 3.5 km for fission-track analysis. Transects, along which the sampling was done are about 20 km long along north-south direction and extend between MCT/MT in south and STDS in north. Both transects cut one major tectonic boundary (VT; Fig. 8). Apatite and zircon concentrates were obtained by crushing and standard heavy liquid and magnetic separation techniques. Out of these sixteen samples, all yielded apatite but only four had good concentration of zircon. Mounting, polishing and etching were carried out using standard procedure at Low-temperature thermochronological Lab., Kurukshetra Uni-versity (apatite etching with 1% HNO_3 at 30°C for 60s, and zircon etching with KOH-NaOH at 220°C for 36 h). Mounts were irradiated with muscovite external detectors at the thermal neutron facility of the Bhabha Atomic Research Centre, Mumbai. Dosimeter glass CN-1 was used for apatite samples while CN-5 was used for zircon samples. Fission track densities were measured using optical microscope at 1500X magnification. Ages ($\pm 1\sigma$) were calculated using zeta approach (Hurford and Green, 1983) with a zeta factor of 110.6±2.86 (for CN-1 glass) for apatite and of 296.96±8.18 (for CN-5 glass) for zircon. The zeta factor is determined by multiple analyses of apatite and zircon standards following the recommendation of Hurford (1990). Only crystals with prismatic sections parallel to the crystallographic c-axis were accepted for analysis.

The ages were calculated using the following age equation (Hurford, 1990):

$$t = 1/\lambda_d \ln [\, 1 + \lambda_d \zeta \rho_s / \rho_i g \rho_d \,]$$

where λ_d = Total decay constant for uranium (1.55125×10^{-10} yr^{-1}); ζ = Zeta factor; ρ_s = Spontaneous track density measured on the mineral surface; ρ_i = Induced track densities measured on mica detectors attached to mineral surface; g = Geometry correction factor. For an internal crystal surface this will be 4π and for an external surface, as in mica detector will be =2π. Thus for external detector method g = 0.5 (2π /4π) (Gleadow and Lovering, 1977); ρ_d = Induced track densities measured on glass dosimeter.

Estimate of Exhumation Rates

AFT and ZFT analysis are commonly used to evaluate the exhumation history of regions. With these data, exhumational rates are calculated in different ways. If the depth of closure isotherm of the sample is known, then sample age (A), which represents the time since cooling through the closure isotherm (Dodson, 1973), T_c is used with an assumed geothermal gradient (dT/dz) to calculate exhumation (or erosion) rate, E_r :

$$E_r = [(T_c - T_s)/A]/(dT/dz)$$

Where T_s is the average temperature at the surface. The closure temperatures of ZFT and AFT are considered to be 250±30° C and of 125±10° C respectively (Thiede et al. 2009) that corresponds to the young FT ages of the HHC. Keeping in mind already published work in NW-Himalaya, geothermal gradient of 35° C/km has been taken in the present work while mean annual surface temperature of 10± 5° C has been adopted by several workers in the Himalayas (Kumar et al. 1995).

The mean exhumation rates and mean age for each thermo-chronometer system are used to determine the transient exhumation rates. Mean AFT ages along the Darma and Kaliganga valleys are 1.9±0.3 Ma and 2.0±0.2 Ma with mean exhumation rates 2 and 1.7 mma^{-1} respectively and ZFT ages are 4.3±0.3 Ma and 4.9±0.2 Ma with mean exhumation rates 1.6 and 1.4 mma^{-1} respectively. These values are used to estimate transient exhumation rates as described by Thiede et al. (2009). In case of AFT and ZFT thermo-chronometer system along Darma valley E_0 = 1.6 mm a^{-1}, t_0 = ~4.3 Ma, E_1 = ~2 mm a^{-1} and t_1 = ~ 2 Ma, along Kaliganga valley E_0 = 1.4 mm a^{-1}, t_0 = ~4.9 Ma, E_1 = ~1.7mm a^{-1} and t_1 = ~ 2 Ma and Goriganga valley E_0 = 2.7 mm a^{-1}, t_0 = ~2.6 Ma, E_1 = ~2.1mm a^{-1} and t_1 = ~ 1.2 Ma (Patel and Carter, 2009) are used in the following equation to calculate E_2.

$$E_2 = [(E_0 t_0) - (E_1 t_1)]/ (t_0 - t_1) \quad (1)$$

Exhumation rates of (E_2 =) 1.3 mm a^{-1} along Darma and Kaliganga valleys between ~5 and 2 Ma and 3.2 mm a^{-1} along Goriganga valley between ~2.6 and 1.2 Ma have been calculated.

RESULTS AND INTERPRETATION

The FT ages of sixteen apatites and four zircons are given in Table 4. This data along with published FT data from the Goriganga valley (Patel and Carter, 2009) are shown on the cross sections (Fig.8). One common feature in FT ages from all the three valleys is that age data show no relationship to either structural position or elevation.

Previously, low temperature thermochronological study from the Kumaon Himalaya has been carried out along Goriganga valley and AFT data found is ranging between 0.7±0.2 Ma and 2.9±0.6 Ma and ZFT data between 1.6 ±0.1 to 4.4±0.4 Ma (Bojar et al. 2005; Patel and Carter, 2009). The AFT age from Darma valley is between 1.0±0.1 Ma and 2.8±0.3 Ma and from Kaliganga valley is between 1.4±0.2 Ma to 2.4±0.3 Ma (Kumar, 2004) (Figs.8a,b and c, Table 4). Study from these valleys indicates a zone of young cooling ages between the MCT in the south and STDS in the north. To the south of the MCT i.e. within the CCB (LHC) AFT ages are quite older (7.6±0.6 to 17.9±0.9 Ma) (Patel et al. 2007). When the FT ages are compared, taking into account local structural position i.e. sample location with respect to the MCT/MT and VT, it is found that there is no first order difference in exhumation history along entire traverses in the Kumaon Himalaya. Cooling was clearly simultaneous in whole Kumaon Himalaya. The AFT data from all traverses show no systematic trends with respect to distance from MCT/MT or VT. Two distinct apatite age groups can be identified, separated by the VT (Patel and Carter, 2009). Young AFT ages are confined in the hangingwall while old AFT ages are in the footwall of the VT. The ZFT data (Goriganga valley: 1.6±0.1 to 4.4± 0.4 Ma, Patel and Carter, 2009, Darma valley: 4.0±0.2 and 4.5±0.3 Ma and Kaliganga valley: 4.5±0.2 Ma and 5.2±0.2 Ma) show similar trend as AFT data. The pattern of ages appears to show thrust sense displacement along the VT in the Kumaon Himalaya since at least ~4 Ma. Exhumation rates along Goriganga (2.1mm a^{-1}), Darma (2 mm a^{-1}) and Kaliganga (1.7 mm a^{-1}) valleys are approximately similar (Patel and Carter, 2009) indicating that the whole Kumaon Himalaya is exhuming and uplifting uniformly and as a single block.

AFT ages in the Kumaon Himalaya do not change significantly between the MCT/MT and VT and increasing distance due north from VT despite difference in elevation of samples (Figs. 8a, b and c). ZFT ages show a similar pattern as AFT ages. Similar pattern of AFT ages within the CCB is observed (Patel et al. 2007). It can be explained by a system of equilibrium whereby isotherms are parallel to each other or to the surface. It means the distance travel from isotherm to surface by the samples, at different locations having different elevation is constant and with constant velocity (Fig.8d). It implies erosion rates are in

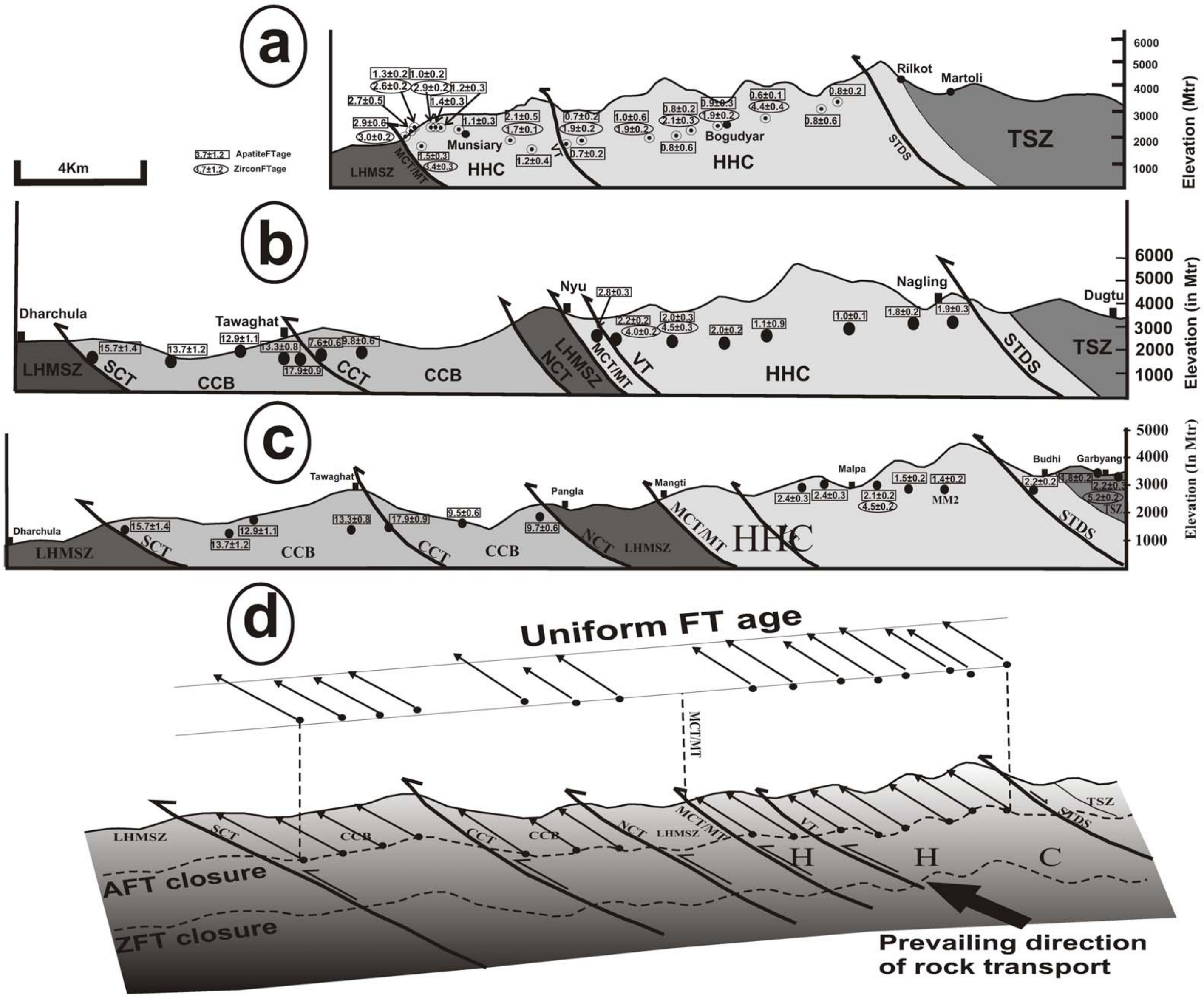

Fig.8. Geological cross section along the **(a)** Goriganga, **(b)** Darma and **(c)** Kaliganga valleys showing Fission Track ages at their respective location and elevation and (d) Cartoon to show relationship between surface and FT closure isotherms and sample exhumation path. In topographic and exhumation steady-state the distance a sample travels from closure to surface remains broadly the same.

Table 4. Lithology, Altitude and FT ages with exhumation rates along the Darma and Kaliganga valleys between the MCT in the south and STDS in the north, Kumaon Himalaya

Sample Ref.	Tectonic Unit	Altitude (in Mtr)	Age (Ma)	Mean age (Ma)	Exhumation rate (mma^{-1})	Mean Exhumation rates (mma^{-1})
Darma valley						
Apatite						
DS-2	Munsiari	2200	2.8±0.3		1.2	
DS-3	HHC	2200	2.2±0.2		1.5	
DS-8	HHC	2000	2.0±0.3		1.6	
DS-10	HHC	2000	2.0±0.2		1.6	
DS-12	HHC	2200	1.1±0.9	1.9±0.3	3.0	2.0
DS-15	HHC	2550	1.0±0.1		3.3	
DS-17	HHC	2720	1.8±0.2		1.8	
DS-20	HHC	2800	1.9±0.3		1.7	
Zircon	HHC	2200	4.0±0.2		1.7	
DS-3	HHC	2000	4.5±0.3	4.3±0.3	1.5	1.6
DS-8						
Kaliganga valley						
Apatite						
MM-9	HHC	2800	2.4±0.3		1.4	
MM-8	HHC	3000	2.4±0.3		1.4	
MM-5	HHC	2900	2.1±0.2		1.6	
MM-4	HHC	2700	1.5±0.2		2.2	
MM-2	HHC	2700	1.4±0.2	2.0±0.2	2.4	1.7
MM-14	HHC	2762	2.2±0.2		1.5	
MM-15	HHC	3350	1.8±0.2		1.8	
MM-16	HHC	3300	2.2±0.3		1.5	
Zircon						
MM-5	HHC	3350	4.5±0.2	4.9±0.2	1.5	
MM-16	HHC	3300	5.2±0.2		1.3	1.4

balance with tectonically driven rock uplift. For the higher temperature zircon data, ZFT ages north of the VT are also consistent indicating erosion rates balancing tectonic uplift. It suggests a system that has been in topographic and exhumation steady-state since at least 4 Ma within the HHC and since at least 8 Ma within the LHC (i.e. within the CCB).

DISCUSSION AND CONCLUSIONS

The Himalayan Mountain Arc like the Alps and the Apennines has been the subject of numerous studies, which provide us a good overview of intra-continental crustal shortening. The Himalayan Mountain Arc is characterized by crustal shortening, resulting from the collision between the Indian and Eurasian plates. It is widely accepted that complete closing of the Tethys ocean along the Indus Tsangpo suture zone during mid to late Eocene at approximately 50-45 Ma (Searle et al, 1988) was followed by the propagation of tectonic activity towards the foreland crustal shortening and stacking along the MCT and MBT (Gansser, 1964; Bouchez and Pecher, 1981; Mattauer, 1986).

Results of the present investigations in combination with the studies from the Goriganga valley (Patel and Carter, 2009; Patel and Kumar, 2009) and from the Chiplakot Crystalline Belt (Kumar and Patel, 2004; Patel and Kumar, 2006; Patel et al. 2007) are significant and useful in understanding the process of the intracontinental crustal shortening of the HHC in the Kumaon Himalaya.

In the whole region, the metamorphic / lithological layering / banding within the HHC represents the oldest structural feature that is dated to be 1800 ± 200 Ma old (Bhanot et al. 1977). It is folded by tight-to-isoclinal F_1 folds during pre-Himalayan D_1 deformation. These structures are absent in the TSZ (Patel et al. 1993; Jain and Patel, 1999; Patel and Kumar, 2009) along with complete abruptness of gneissose component of rocks in the latter. The HHC is therefore, described as a Proterozoic basement, which was covered by the LHMS and the TSZ rocks (Fig.9a). Intraplate deformation (D_2) was initiated during collision between Indian and Eurasian plates due to which the earliest metamorphic banding/ lithological layering (S_0) and axial plane foliation (S_1) deformed into the most pervasive NE-plunging F_2 folds and the HHC started thrusting and uplifting above the LHMS zone along the MCT.

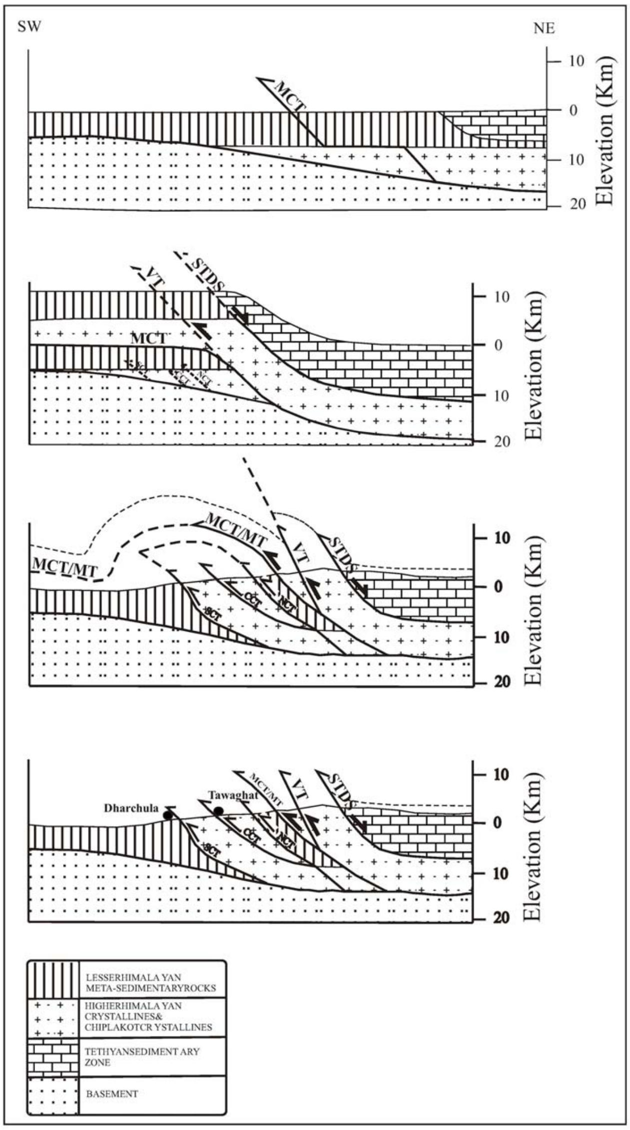

Fig.9. Schematic models for a tectonic evolution of the CCB and the HHC. **(a)** A schematic reconstruction of the sedimentary basin in the northern edge of the Indian continental marginal sea showing the respective positions of the sedimentary deposits of the three zones during pre-Himalayan phase, **(b)** The development of the MCT and thrust slicing showing displacement along the MCT during the continental collision, **(c)** Tectonic evolution is accommodated by SW-directed duplex structure through which the CCB thrust over the Lesser Himalayan meta-sedimentary Zone in the MCT and **(d)** Development of shear zone through whole of the CCB as well as HHC and eroded to evolve present topographic set up.

In the whole HHC, main penetrative S_2 foliation transposed the earlier S_0–S_1 planes that developed composite S_m foliation. The composite foliations S_m bear well-developed stretching / mineral lineations which represent extension/stretching direction during D_2 in the HHC. A few isolated occurrences of F_1 folds in the HHC depict their coaxial nature with later F_2 folds. It indicates the passive rotation of early-formed folds (F_1) into the extension direction during simple shear D_2 deformation (Sanderson, 1973); Escher and Watterson, 1974; Rhodes and Gayer, 1977; Carmignani et al. 1978). Though ductile shearing might have re-oriented the earlier F_1 folds towards later F_2 folds, contemporaneous development of ubiquitous symmetrical NE-plunging F_2 and L_2 stretching/mineral lineation has been envisaged with displacement along broad ductile shear zones of the HHC. Reorientation of early fold axes has been controlled by initial position of the (S_0/S_1) surfaces, which were folded and/or initial orientation of earlier folds (F_1).

The MCT developed within the crystalline basement, probably overlain by a cover sequence made up of LHMS rocks. It is suggested here that there was development of a long flat within the basement, followed to south by a ramp through the basement-sediment contact and a flat again at the top of LHMS rocks (Fig.9a). Emplacement of the HHC over the LHMS rocks of Lesser Himalaya took place at around 20 Ma to 14 Ma (Dezes et al. 1999) along MCT (Munsiari Thrust). Simultaneously, a duplex structure started growing in the footwall of the MCT due to development of the North Chiplakot Thrust (NCT) and South Chiplakot Thrust (SCT) in the compressional regime of the MCT zone (Fig.9b). Growth of the duplex structure caused updoming of the overlying thrust slabs, which got exposed for rapid erosion. Another shear zone i.e. the Central Chiplakot Thrust (CCT) developed in the middle of CCB along which northern part was thrust over the southern part (Fig.9c) and subsequently differential paleo-topography developed across the CCB (Fig.9d).

F_2 folds and L_2 lineation maintain their consistent orientation irrespective of the attitude of the composite foliation containing them and are orthogonal to linear trends that developed later during D_3 deformation. F_2 folds are symmetrical around the mineral/ stretching lineation. This indicates that the F_2 folds formed during ductile shearing throughout the HHC. Since F_2 folds and associated stretching lineation in the HHC have a consistent NE-plunge, continuity of the structural direction across the HHC indicates insignificant changes in kinematics during D_2 and its subsequent translation. Various shear structures such as S-C fabric, rotated feldspar megacrysts, asymmetric lenses, asymmetric intrafolial folds, duplex structures within the HHC indicate top-to-SW shearing of the HHC. The presence of NE-dipping thrust zones along the contact between the HHC and the Lesser Himalaya (i.e. MCT zone) with top-to-SW sense of shearing is similar to the observations in the

Zanskar Himalaya (Patel et al. 1993), Himachal Himalaya (Singh and Jain, 1993; Manickavasagam et al. 1999), along the Goriganga valley, Kumaon Himalaya (Patel and Kumar, 2009) and else where in the HHC and the MCT zone (Brunel, 1986; Jain and Anand, 1988). Structural relation of shear fabrics with D_2 implies that the broad shear zone played major role in crustal thickening and rock uplift during D_2 event.

Crustal shortening and rock uplift followed by erosion of the rocks of the HHC have deformed and exhumed the deeper high grade metamorphic rocks to the surface since Miocene (Hodges et al. 1992). The strongest arguments for continuous erosion of the HHC over geological time scale are (1) Once intensely deformed, metamorphosed (greenschist to amphibolite grades) and sheared HHC rocks at greater depth are now exposed at the highest peaks of the Higher Himalaya and (2) the complete removal of the HHC nappes in the Kumaon Himalaya which correlates with approximately 15-20 km of the crystalline rocks. They once covered the LHMS zone which is presently exposed between the HHC and crystalline nappes in the Kumaon region. In some segments of this region, the HHC nappes have been completely removed and today meta-sedimentary rocks of the LHMS zone are exposed in tectonic windows and half windows (Valdiya, 1980; Valdiya, 1988; Srivastava and Mitra, 1994; Thakur, 1992). These imply that efficient erosion due to the rapid rise of the Himalayan Mountain coupled with increased precipitation has removed a huge mass of rock since the MCT/MT was active. Thick, continuous sediment deposits since Paleocene-Eocene reported from the foreland basin i.e. the sub-Himalaya and the Subathu sub-basin within the LHMS zone (Richter et al. 1992; Raymo and Ruddiman, 1992; Burbank et al. 1996; Jain et al. 2008), Bengal and Indus fans (Copeland and Harrison, 1990; Metivier et al. 1999; Einsele et al., 1996), represent the HHC as the dominant provenance of detrital sediments since Miocene (Derry and France-Lanord, 1997) and sequentially deposited high-grade metamorphic index minerals (garnet and staurolite ~20 Ma, kyanite ~12 Ma and sillimanite ~8 Ma (Najman et al. 2002; White et al. 2002; Najman et al. 2003) indicate rapid exhumation, continuous erosion and transit of eroded materials to the sedimentary basins since Miocene time. Between ~23-19 Ma peak metamorphic data from the HHC suggest denudation rates > 3 mm a^{-1} (Thiede et al. 2009). Following this, between ~19-13 Ma, the denudation rates in the HHC decreased between ~0.5 and 0.7 mm a^{-1}. This was the phase of the Himalayan orogenesis during which rock uplift outpaced exhumation and hence the Himalaya rose. Low denudation rate about ~0.5 mm a^{-1} continued till 4 Ma within the HHC while to the south of it within the LHC the rate increased to ~3 mm a^{-1} between ~13 - 2 Ma. Finally, denudation rates over the last 3 Ma within the HHC have increased between ~1 and 2 mm a^{-1} (Thiede et al., 2009; Patel and Carter, 2009). The pulse of denudation between ~13-2 Ma within the LHC is the result of emplacement and denudation of the crystalline nappes of the HHC and LHC on the top of the LHMS zone (Patel et al, 2007; Thiede et al. 2009). We thus infer that maximum uplift, erosion and exhumation of the HHC occurred during Pliocene-Quaternary time.

Thrusting along the MCT (Munsiari Thrust) and along the NCT and SCT and mylonitisation of the rocks of the HHC and the CCB was followed by F_3 open folds whose axes are at high angles to F_2 folds (Fig. 3c) and superposed extension within the HHC. Extensional events began probably due to overthickening and dismemberment of the HHC along the MCT. These events modified the topography to expose the rocks to rapid erosion. Recently, thermomechanical model "the channel flow" highlights rapid exhumation of the HHC relative to the surrounding rocks and emphasize the role of ductile flow (Baumont et al. 2001). This process requires the faults and shear zones that define the boundaries to the HHC, i.e. the MCT and STDS, to be active during flow, but it is unclear how these fault zones facilitated exhumation in the brittle uppermost portion of the crust. Our AFT and ZFT analysis from this area shows rapid exhumation rates between 1.2 to 3 mm a^{-1} since at least 4 Ma. Exhumation pattern of the HHC and LHC is similar but the rate of exhumation of the HHC is rapid while it is slow within the LHC. While climate must have a major influence on exhumation in the brittle crust, local reactivation of the MCT/MT and VT has played a major role in rapid exhumation of the HHC. The absence of such reactivation along the SCT produced no new uplifted topography of the CCB to accelerate the exhumation and so exhumed slowly. Within the HHC, the exhumation rate varies temporally. Between 5 to 2 Ma the exhumation rate was 1.3 mm a^{-1} along Darma and Kaliganga valleys and then it increased to ~2 mm a^{-1} since ~ 2 Ma while along the Goriganga valley between ~2.6 to 1.2 Ma it exhumed at ~3.2 mm a^{-1} and then became ~2 mm a^{-1} since ~1.2 Ma to present. Previous studies have considered the role of Quaternary out of sequence active thrusting at the topographic front and proposed a positive feedback between focused erosion and deformation of the Higher Himalayan Ranges (Hodges et al. 2004). The acceleration of exhumation rates precludes such mechanism on the basis that slip on the VT in the Kumaon Himalaya appears to have been ongoing for nearly 2 Ma.

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