CHAPTER-1

INTRODUCTION

1.1 Background:

Crustal shortening, tectonic uplift and erosion have shaped the Himalayan orogen since the India-Eurasia collision ca 50-55 Ma (Patriat and Achache, 1984; Rowley, 1996; Yin and Harrison, 2000; Najman et al., 2001, 2002; Ding et al., 2005). The crustal shortening and tectonic uplift of the Himalaya is largely controlled by major thrust faults such as Main Central Thrust (MCT), Main Boundary Thrust (MBT), Main Frontal Thrust (MFT) and their associate thrust within the Indian continental crust (Fig.1.1) (Valdiya, 1980; Bouchez and Pecher, 1981; Le Fort, 1986; Mattauer, 1986; Thakur, 1987; Jain and Anand, 1988, Patel et.al. 2010; Yin, 2010a). These faults divide the Himalaya into four latitudinal lithotectonic units from south to north, namely, Foreland basin (Sub-Himalaya), Lesser Himalayan Sequence (LHS) (comprised of Lesser Himalayan meta-sedimentary zone (LHMS) and Lesser Himalayan Crystallines (LHC) belt), Higher Himalayan Crystallines (HHC) and Tethyan Himalayan Sequence (THS). During this event, the HHC, which is composed of Proterozoic-Ordovician metasedimentary rocks, orthogenesis and granitoids with pervasive ductile shear fabric (Jain and Anand, 1988; Patel et al., 1993) were thrust to the south over the LHMS zone of Proterozoic-Palaeozoic age along the MCT and its associated splays while THS, which is composed of Proterozoic-Eocene sedimentary strata, was detached from the HHC along the South Tibetan Detachment System (STDS), synchronously during the early Miocene (Gansser, 1964; Valdiya, 1980; Schelling and Arita, 1991; Patel et al., 1993; Grujic et al., 1996; Beaumont et al., 2001). The deformation front was then gradually propagated to the south along the MBT during Late Miocene (~10-5 Ma) (Meigs et al., 1995; DeCelles et al., 2001; Huyghe et al., 2001) and most recently along the MFT (Valdiya, 1992; Thakur et al., 1995; Lave and Avoac, 2000; Patel and Kumar, 2003; Patel et. al. 2011a). The LHMS along with the crystalline thrust stakes (i.e. Lesser Himalayan Sequence: LHS) were thrust over sub-Himalaya along the MBT and the sub-Himalaya has been thrusting over the Indo-Gangetic plain along the MFT.
This in-sequence thrust model of the Himalayan tectonics describes the emplacement of the crystalline thrust sheet over the LHMS by (a) the wedge-extrusion (e.g., Burchfiel and Royden, 1985; Grujic et al., 1996; Kohn, 2008), (b) the channel flow - focused denudation (e.g., Beaumont et al., 2001; Hodges et al., 2001) and (c) the tectonic wedge model (Yin, 2006; Webb et al., 2007) (Fig. 1.2).
Figure 1.2: Himalayan tectonic models for the emplacement of the Higher Himalayan Crystalline (HHC) complex, (a) channel flow/focused denudation model (e.g., Nelson et al., 1996; Beaumont et al., 2001; Hodges et al., 2001), (b) wedge extrusion model (e.g., Burchfiel and Royden, 1985; Grujic et al., 1996) and (c) tectonic wedging model (e.g., Yin, 2006; Webb et al., 2007). THS: Tethyan Himalayan Sequence; LHS: Lesser Himalayan Sequence; ITS: Indus–Tsangpo suture; E.: Early; M.: Middle.

(a) Channel flow-focused denudation:

In channel flow-focused denudation model, the HHC is described as partially molten lower/middle crust in the thickened collision zone (Fig. 1.2a). The partially molten HHC flows southwards, driven by the gravitational potential of the high plateau (e.g., Beaumont et al., 2001, 2004; Godin et al., 2006a). This partially molten HHC channel is exhumed between active faults by erosion across a narrow zone where precipitation is focused by the orography of the topographic front (e.g., Beaumont et al., 2001; Hodges et al., 2001). The initiation of rapid exhumation and development of the paired channel flow-focused denudation system is speculated to result from a precipitation increase associated with a climatic shift (e.g., Beaumont et al., 2001; Clift et al., 2008; Hodges et al., 2001).

(b) The wedge–extrusion Model:

The wedge-extrusion model describes an orogenic wedge of the HHC bounded below by north-dipping, south-directed basal MCT zone and above by north dipping STDS normal fault (Fig. 1.2b). The STDS simply formed a hinterland-dipping backstop which did not form as a consequence of large scale crustal thinning of an over thickened orogenic wedge. South-directed extrusion of the HHC rather than north-south extension was responsible for the normal fault geometry at the STDS
(Burchfiel et al., 1992). This model of extruding wedge of the HHC explains the simultaneous operation of southward thrusting along the MCT and normal fault extension on the STDS (Burchfiel and Royden, 1985; Kunding, 1988, 1989; Burchfiel et al., 1992; Hodges et al., 1993).

(c) **Tectonic-wedge model:**

In this model, the STDS is a key factor because it contains records of alternating top-south and top-north shearing (e.g., Godin et al., 1999; Grujic et al., 2002; Hodges et al., 1996; Jain et al., 1999; Patel et al., 1993; Robinson et al., 2006; Webb et al., 2007). As a gently north-dipping structure with top-north sense-of-shear indicators, the STDS has the appearance of a regional low-angle normal fault with extension parallel to the shortening direction across the orogen (e.g., Burchfiel et al., 1992; Burg et al., 1984; Herren, 1987). Shortening and extension appear synchronous, as the MCT and STDS were coevally active in the Early–Middle Miocene (e.g., Hodges et al., 1992, 1996).

In tectonic wedging models, the STDS represent 10 s of kilometers of back thrusting in the MCT hanging wall (Fig. 1.2c). The top-north displacement is kinematically linked to the north-directed Great Counter thrust system, which juxtaposes the THS rocks at top the Asian plate rocks and suture zone rocks to the north and was active in the Early–Middle Miocene (i.e., coeval with STDS motion; Yin et al., 1994, 1999). This model describes that the MCT and STDS merge to the south in the Himalaya, bounding the locally exposed leading edge of the HHC (Thakur, 1998; Webb et al., 2007; Yin, 2006). The motion along the STDS accommodated the HHC emplacement entirely below Earth’s surface, with current HHC exposure resulting from subsequent erosion and footwall deformation.

These models have mainly discussed on the Miocene mechanism of emplacement/extrusion of the HHC between the two low grade meta-sedimentary sequences: the LHS in the south and the THS in the north of the HHC but not the more recent tectonic history. During this time, the MCT was probably the frontal thrust of the system. These models also do not take into account the Miocene to present forward propagation of deformation from the MCT toward the MFT. Wedge-extrusion and channel flow models do not address the issues of emplacement and exhumation of the crystalline nappes and klippen over the LHS and their relationship with the emplacement of the HHC between the MCT and the STDS. On the other hand, the tectonic wedging model explains the emplacement of these rocks and their
relationship to the MCT, HHC and STDS in the Himachal Himalaya. In the framework of the tectonic wedging model, these klippen/nappes rocks are interpreted as the basal THS rocks sliding along the MCT to the south of a branch line merging the MCT and STDS. Through the study of the Kathmandu nappe in central Nepal, it has been reported that the crystalline klippen/nappes rocks are different from the HHC rocks as these crystalline klippen/nappes like HHC, do not display inverted metamorphism (Johnson et al., 2001). The Kathmandu nappe in the Central Nepal and Dadeldhura klippe in the western Nepal are considered as the southern representative of the THS to the south of the branch line of two merged faults i.e. the MCT and the STDS and the kyanite-migmatite gneiss as the leading edge of the HHC (Webb et al., 2007; Webb et al., 2011) (Fig. 1.3). Recent study of existence of thrust sense (top-to-the-south) shearing at the base and normal sense (top-to-the-north) shearing at the top of the Almora-Dadeldhura klippe (Antolín et al., 2013) does not support the merging of the MCT and STDS at the northern base of the klippe and so the klippe as basal THS rocks.

Fig. 1.3: Structural model of emplacement of nappe in the central Nepal Himalaya (He et al., 2015)
All these models are not clearly able to predict the available young thermochronologic ages (Ar-Ar, Fission Track ages) with in the HHC relatively well. These models also do not take into account the Miocene to Present forward propagation of deformation from the MCT toward the MFT as well as continuous rapid tectonic uplift of the HHC since Miocene to present. It therefore, two competing models have been proposed to describe the post emplacement to present day kinematics of the HHC: (1) Underplating (also Duplex model) and (2) Out-of-sequence models. These differ in their predictions of which surface breaking faults accommodate current shortening and what kinematics drive rapid exhumation in the topographic transition zone around the MCT. Avouac (2003) and Bollinger et al. (2004, 2006) described that recent deformation is concentrated along the MHT and that rapid exhumation in the MCT zone results from underplating along the MHT ramp (Fig. 1.4a). In contrast, Wobus et al. (2003) and Hodges et al. (2004) suggested active out-of-sequence thrusting in the topographic transition zone (Fig. 1.4b), possibly driven by climatically controlled localized exhumation in this area. The opposing models predict different exhumation paths for rocks in the LHS and the topographic transition zone that should be recorded by low- and medium-temperature thermochronometers such as apatite fission track (AFT) and mica Ar-Ar (Fig. 1.4). In particular, the out-of-sequence model predicts an age jump in the topographic transition zone (Hodges et al., 2004; Wobus et al., 2006), whereas the underplating model predicts a gradual decrease in ages across the Lesser Himalaya from the MBT to the MCT (Bollinger et al., 2004, 2006).

Fig.1.4: Exhumation duplex model and out-of-sequence model of the Himalaya
1.2. Higher Himalayan Crystalline (HHC)/ Greater Himalayan Crystalline (GHC):

The core metamorphic part of the Himalaya received many names such as Greater Himalayan Crystalline, Higher Himalayan Crystalline and Central Himalayan Crystalline sequences and occupies the highest elevation of the Himalayan range. It forms a continuous belt from Kashmir through Nepal and Bhutan to Arunachal Pradesh. It is characterized by a 15-20 km thick sequence of Paleoproterozoic to Ordovician (Parrish and Hodges, 1996; DeCelles et al., 2000), crystalline rocks. 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. Since the collision at about 50-55 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 (~23-17 Ma) (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 Manickvasagam, 1993; Jain et al. 2000).

Heim and Gansser (1939) described the geology of the HHC 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 THS 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 HHC 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 Kumaon Himalaya to the lower part of the HHC exhibiting low-grade metamorphism in greenschist to amphibolite facies rocks. All workers except Valdiya (1977; 1979; 1980) include the 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. It has been sandwiched between the Munsiari and the Vaikrita Thrusts. The Munsiari thrust slab is a severely tectonised and drastically condensed lithotectonic sheet representing the root zone of the Lesser Himalayan crystalline nappes/klippen. Lithologically and petrologically, the Munsiari formation is related with the Almora, Askot-Baijnath klippen and Chiplakot Crystalline Belt (CCB) (Valdiya, 1980; Patel and Kumar, 2006; Patel et al., 2007; Patel et al. 2011a). Therefore, Valdiya (1980) regarded them as one and the same lithostratigraphic unit as originally described by Heim and Gansser (1939). The name Vaikrita was first time introduced by Griesbach (1891) to a pile of higher grade metamorphics intruded by young Tertiary granites. In Kumaon, these crystallines were included as integral part of the HHC by Heim and Gansser (1939). This group of rocks is separated from the Munsiari formation along NE-dipping Vaikrita Thrust (VT). At the top of the Vaikrita group is the THS. Different workers describe the contact between the Vaikrita group and the THS 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) and Arita et al. (1984) described no apparent break between the Vaikrita group and the THS. 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 THS). Virdi (1980) described the contact as a thrust contact.

The HHC is recently described to be evolved due to ductile extrusion during 23 to 17 Ma along a broad northeast dipping intracontinental ductile shear zone between coeval MCT in the south and STDS in the north (Frank et al., 1977; Pecher, 1977; Bouchez and Pecher, 1981; Brunel, 1986; Coward et al., 1986; Pecher and Le Fort, 1986; Searle, 1986; Thakur, 1987; Jain and Anand, 1988; Hubbard and Harrison, 1989; Burchfiel et al., 1992; Hodges et al., 1992; Jain and Manickvasagam, 1993; Patel et al., 1993; Coleman, 1998; Dezes et al., 1999; Robyr et al., 2006).

The HHC is characterized by high grade metamorphic rocks intruded by ~500 Ma granites. Inverted metamorphism has been described within the HHC between the MCT and STDS (Gansser, 1964; Le Fort, 1975; Caby et al., 1983; Arita, 1983; Sinha-Roy, 1982; Hodges et al., 1988; Vannay and Grasemann, 1998; Pecher, 1989). Metamorphic evolution of the HHC has been studied in details by Vannay and
Grasemann, (1998, 2001) and Vannay et al., (1999). This inverted metamorphism is revealed by a gradual superposition of staurolite, kyanite, sillimanite, and migmatite mineral zones, from the base to the top of the HHC unit (Fig. 1.5). Thermobarometry and thermometry study of HHC rocks show that peak temperatures increases from ~600 to 750°C from the base to the top of the HHC and these peak condition of temperature were reached at an almost constant pressure around 8kbar. For lithostatic gradient of 0.27 kbar/km, this pressure was at a burial depth of around 30 km (Vannay et al., 2004). The structural, metamorphic and geochronological data from the HHC show that the HHC has gone high temperature metamorphism during sillimanite grade event lasting at least ~39 Ma upto ~15 Ma with final leucogranite dykes injected as young as 11.6 Ma (Dietrich and Gansser, 1981; Streule et al., 2012). Study of this leucogranite with in the HHC allow to understand that crustal melting occurred along the upper part of the middle crust (4 to 6 kbar, 15-20km depth), but not in the lower crust. A vast in situ migmatite terrane generated melts from the melting of a heterogeneous variety of protolith rocks. Interconnected leucosome melts aggregated to force magma into layer-parallel sills and a few cross-cutting dykes. Early Mocene leucogranites (24-17 Ma) are largely concordant with the foliation, whereas later ones (16 to 12 Ma) may cross-cut the ductile fabrics. All leucogranites are cut by the uppermost brittle-low-angle normal fault (Searle et al., 2008).

The HHC reveals a complex polyphase deformed metamorphic succession where four episodes of deformation (D1 to D4) (Jain and Anand, 1988, Patel et al., 1993; Jain and Patel, 1999) and two metamorphic phases M1 –M2 (Jhingran et al., 1976; Thakur, 1980) have been identified. The predominant stretching lineation/mineral lineations have been developed during D2 ductile deformation and plunge due NE i.e. orogen perpendicular (Jain and Anand, 1988; Jain and Patel, 1999; Patel and Kumar, 2009). It attributes to the southward extrusion of the HHC. The folds are having flattening strain ranging from 15% to about 95% (Bhattacharya and

Fig. 1.5. Diagram is showing different metamorphic zone in Himalaya.
Siawal, 1985; Bhattacharya, 1999). Overall structure of HHC looks homoclinal monotonously north dipping sequence (Bhattacharya, 2008).

1.3. Lesser Himalayan Sequence (LHS)

The LHS rocks lie structurally below the HHC rocks and are dominantly composed of un-fossiliferous, meta-sedimentary rocks overlain crystalline nappes/klippen (Heim and Gansser, 1939 and Lefort, 1975). LHS has an age range of 870-850 Ma based on radiometric dating of interlayer gneisses, detrital zircons and metavolcanic rocks (Trivedi et al., 1984; Miller et al., 2000; De Celles et al., 2000; Singh et al., 2002). The LHS domain is bounded between MCT in the north and MBT in the south (Heim and Gansser, 1939 and Valdiya, 1980, Srivastava and Mitra, 1994). In the Kumaon-Garhwal Himalaya, the LHS is composed of Lesser Himalayan meta-sedimentary zone (LHMS) and Lesser Himalayan Crystalline (LHC) belt.

1.3.1. Lesser Himalayan meta-sedimentary (LHMS) zone: Valdiya (1980) has studied the the LHMS and divided it into two major units: the autochthonous unit and Krol Nappe. The autochthonous unit is comprised of the Precambrian sediments exposed in the vast windows. Valdiya (1980) has described it as the inner (northern) LHMS zone. The Krol nappe is made up of Palaeozoic sediments. He says it as outer (southern) LHMS zone. Srivastava and Mitra (1994) have described that the LHMS is largely Precambrian sedimentary units with few outcrops of the Cambrian Tal Formation, the lower Tertiary Subathu Formation, and rare upper Palaeozoic and upper Mesozoic strata. Based on lithological variation between the northern and southern parts of the LHMS, they have divided the LHMS into a northern and southern sedimentary zone. The Damta group is the lowest exposed lithologic unit in both the northern and southern zones. In the northern zone, the Damta is followed upward successively by the Deoban Group, the Berinag Formation and the Kophara Formation. In the southern sedimentary zone, the Damta Group is succeeded by the Chandpur, Nagthat, Blaini, Infra-Krol, Krol and Tal Formations.
Ahmad et al. (2000) and Célérier et al., (2009) have divided the LHMS in the Garhwal-Kumaon Himalaya into the Inner (older) and outer (younger) LHMS units. The inner LHMS is comprised of 1800 Ma Berinag quartzite at the base and is overlain above a regional unconformity by the Chakrata and Rautgara Formation. These are succeeded by Neoproterozoic Deoban dolomites and Mandhali carbonaceous slates and carbonates. The outer LHMS comprises of 850 Ma Chandpur Formation, Nagthat quartzite and Blaini conglomerate. Above these, the Neoproterozoic Krol and Tal (Early Cambrian) Formations are present.

Studies based on illite crystallinity, the LHMS older than the Subathu Formation have undergone a Pre-Tertiary metamorphism in the temperature range 200 to 300$^\circ$C (upto greenschist grade) while the Subathu Formation has undergone metamorphism below 200$^\circ$C in the Tertiary (Johnson and Oliver, 1990). Recently, peak metamorphic temperature close to the Munsiari thrust and steep (20-50$^\circ$C/km) inverted thermal gradients in the south of the Munsiari thrust have been documented in the Nepal Himalaya based on the structural state of carbonaceous material (Beyssac et al., 2004, Bollinger et al., 2004, 2006). The thermal structures of the LHS in the Kumaon-Garhwal region has been investigated using Raman spectroscopy of carbonaceous material (RSCM) and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology (Célérier et al., 2009). This study shows that the LHS in the Kumaon-Garhwal region has experienced locally variable thermal metamorphism. South of Tons thrust, peak metamorphism occurred at ~330$^\circ$C. In the north of the Tons thrust, a transition to higher temperature adjacent to the MT is documented with peak temperatures up to ~570$^\circ$C. An inverted thermal field gradient of ~20$^\circ$C/km is documented beneath crystalline klippe and a peak footwall temperature of 530$^\circ$C is recorded close to the shear zone at the base of the klippe. Thermal modelling of these data shows two stages of thermal evolution for the LHMS: an early Miocene phase of overthrusting of a hot hanging wall over the cold LHMS followed by the initiation of a duplex within the LHMS (Célérier et al., 2009).

Structural studies from the LHMS in the Kumaon-Garhwal region shows systematic change in deformation style from lower to higher structural levels. In the south and lower structural levels, the LHMS is characterised by parallel folding and rare development of axial cleavage. Quartz microstructures indicate that deformation
occurred at temperatures below 350°C. In contrast, in the north and higher structural levels close to the MCT, deformation is characterised by replacement of original bedding plane, development of penetrative cleavage, and schistosity. Folds are tight. At some places it is isoclinal and overturned. The microstructures of quartz indicate that deformation occurred above 350°C (Célérier et al., 2009).

1.3.2. Lesser Himalayan Crystalline Zone (LHC): Several klippen consisting of largely amphibolites grade rocks and intrusive and basement granites belonging to Precambrian age, tectonically overlie the LHMS (Fig. 1.1). These klippen may be remnants of a once more extensive thrust sheet, the Munsiari thrust sheet which lies structurally below the VT (Valdiya, 1980). Those have been found to occupy the cores of the major synformal structures of the LHMS (Fig. 1.1) (Gansser, 1964; Stocklin, 1980; Schelling, 1992; Webb et al., 2007; Webb et al., 2011). These crystalline thrust sheet and klippen over the LHMS are known as the LHC zone. The LHC zone broadly occurs in three belts in Kumaon-Garhwal region and fourth belt in Himachal Himalaya (Thakur, 1992).

(a) Lansdowne, Banali and Satengal klippen
(b) Almora and Ramgarh klippen
(c) Askot, Baijnath and Purola klippen
(d) Jutogh nappe

Heim and Gansser (1939), Gansser (1964) and Valdiya (1980) have identified these crystalline rocks overlying the LHMS and called them as nappes. Heim and Gansser (1939), Gansser (1964) described these nappes as tectonically transported units from the HHC and also interpreted that the disposition of these crystalline units had taken place due to recumbent anticline of the crystalline axis of the HHC. The lower inverted limb is represented by the present day synformal structure over the LHMS. Valdiya (1980) described the Munsiari thrust sheet of the HHC which lies below the VT, as the root zone of the nappes. Later, the nappes which have no more visible/direct connection with the root zone as shown on figure 1.6 have been described as klippen (Srivastava and Mitra, 1994, 1996; Célérier et al., 2009; Antolin et al., 2013; Patel et al., 2015).
Fig.1.6 Block diagram illustrating klippe, window (or fenster), allochthon (grey), and autochthon in a thrust faulted region.

The intrusive and basement granites within the klippen have been dated 560±20 Ma and 1865±60 Ma respectively (Rb/Sr whole rocks) (Trivedi et al., 1984). At some places, the amphibolites grade klippen are underlain by lower klippen consisting of mainly greenschist grade metasedimentary rocks of Precambrian age. This greenschist grade thrust sheet is known as Ramgarh klippe (Thakur, 1992; Srivastava and Mitra, 1994).

LHC belt is composed of porphyritic peraluminous quartz-rich granite and augen gneisses from Proterozoic to early Paleozoic age (Le Fort et al., 1981; Scharer and Allegre, 1983; Trivedi et al., 1984). These granitic augen gneisses are mapped as rootless plutons that intruded the metamorphic country rocks in the erosional outliers of the LHC (Chatterji and Swami Nath, 1977; Valdiya, 1980; Thakur, 1983). The LHC shows the inverted metamorphic sequence (Heim and Gansser, 1939 and Gansser, 1964; Oliver et al., 1995; Sakai et al., 1999; Thapliya and Paudal, 2011).

1.4. Relationship of the Lesser Himalayan Crystalline with the Higher Himalayan Crystalline and Lesser Himalayan meta-sedimentary zone

All models of the HHC describe the tectonic transport of thrust sheets of the HHC/THS over LHMS along the MCT/Munsiari Thrust during early Miocene, followed by the initiation of duplex within the LHMS and folding of thrust sheet into structurally complex synform and antiform during Himalayan orogeny (Heim and Gansser, 1939; Gansser, 1964; Valdiya, 1980, Srivastava and Mitra, 1994, 1996, and Céléri et al., 2009). Number of klippe/nappe between the HHC and MBT are widely regarded as erosional outliers of the
thrust sheet located in the synform which lies structurally below the VT (Gansser, 1964; Stocklin, 1980; Valdiya, 1980; Schelling, 1992; Webb et al., 2007; Webb et al., 2011). The THS thrust sheet in Jammu and Kashmir and Himachal Pradesh have connection with the root zone in the north and extends continuously to the south leaving a narrow zone of the LHMS between MCT and MBT while in the Kumaon, Garhwal and Nepal regions, thrust sheet (klippe) have no connection with roots and thus represent exotic slices on the LHMS (Fig. 1.1). Root zone of these klippen has not been well established and still debate is going on regarding their emplacement.

Improper identification of the hanging wall and footwall rocks in the klippen throughout the Himalaya, the bounding faults and the emplacement mechanism has led to controversy in emplacement of the klippen/nappes. The klippen are widely described as erosional remnant of the Munsiari Thrust sheet (Gansser 1964; Sto¨cklin 1980; Schelling 1992), which suggests that the MT/MCT continues to the south. However, Hodges (2000) argues that there is no correlation between the klippen with the HHC rocks, because there is a difference in metamorphic grade and the absence of cordierite-bearing monzogranite within the HHC, which is common within the klippen. Another idea is that the klippen are composed of the HHC rocks but are not from the same thrust sheet (Rai et al. 1998; Upreti and LeFort, 1999; Khanal et al. 2015). Valdiya (1980) suggests that the HHC (Munsiari thrust sheet) rocks are bound by two major thrusts at the base, the VT and the structurally lower MT. The thrust sheet between these thrusts is known as the Munsiari thrust sheet and it is described as the root of the klippen. Srivastava & Mitra (1994) and Ce´le´rier et al. (2009) drew their cross-sections following the geological and structural map of Valdiya (1980) and described the Munsiari thrust sheet as the root of the LHC. The MT is described to continue to the south and is renamed the Almora thrust/ Dadeldhura thrust bounding the Almora/Dadeldhura klippe at its base (DeCelles et al. 2001; Robinson et al. 2003).

Srivastava and Mitra (1996) have observed that the Palaeocene–Eocene Subathu Formation lies unconformably over the Mussoorie Group and tectononically under the klippen. It constraints the age of emplacement of the klippen (Munsiari thrust sheet) as upper Eocene (~40 Ma) or younger. Based on metamorphism, granitic plutonism and cooling ages of Vaikrita Group of rocks, it is suggested that the VT was associated with the emplacement of Vaikrita thrust sheet during Oligocene –Middle Miocene
Based on these observations they suggested that MT is older than the VT and VT formed as a break-back thrust emplacing the Vaikrita thrust sheet sometimes after the emplacement of Munsiari thrust sheet. Similar break-back thrusting/ back breaking thrusting has also been described in central Nepal Himalaya (Macfarlane et al., 1992). Later Vanny et al., (2004) described the emplacement of the HHC over the LHMS in Himachal Himalaya along the MCT/VT during early Miocene. It was then followed by emplacement of Munsiari thrust sheet along the MT during the late Miocene-Pliocene time. Based on this study, it is described that the MCT/VT is older than MT.

1.5. Aims:

From previous study it is understood that the crystalline klippen over the LHMS have mainly two episodes of evolution history: (1) Emplacement along the MT over the LHMS and (2) post emplacement tectonic and exhumation of the crystalline klippen. Keeping this, aims of this research are

- To document the deformation and strain patterns of the Almora and Ramgarh thrust sheets and to understand the kinematic of the Almora and Ramgarh thrusts.
- To document the thermal history of the Almora and Ramgarh thrust sheets using apatite and zircon fission-track analysis.
- To understand the role of Almora and Ramgarh thrusts in exhumation of the Almora and Ramgarh thrust sheets after their emplacement over the LHMS.

1.6. Selection of the area:

In order to achieve the aims set out at section 1.2, a traverse across the Almora and Ramgarh klippen in the eastern Kumaon, NW-Himalaya has been undertaken. (see Fig. 1.1). Study area is delineated by 29°11’27.24’’ to 29°29’53’’N Latitudes and 80°05’31’’ to 80°07’32’’E Longitudes. The study area falls under the following Survey of India Toposheets No. 62C/2, 62C/3 and 62C/4 and is drained by Kali, Ladhiya, Panar and Saryu rivers.
1.7. Physiography, Climate and Precipitation of the Kumaon-Garhwal Region:

The Kumaon-Garhwal region lies in the central part of the NW-Himalaya. This region is comprised into four physiographic distinct domains between the Indo-Gangetic plains in the south and the Tethys domain in the north. The four physiographic domains are the Siwalik Himalaya, the Lesser Himalaya, the Higher Himalaya and the Tethyan Himalaya. The Indo-Gangetic plains are separated by the Main Frontal Thrust (MFT) from the ruggedly youngful Outer Himalaya of elevation range 900-1500 m high (Fig 1.7a). It is characterised by steep hill- slopes and deep valleys with crumbling walls scarred with landslides. Separated from the Siwalik by the Main Boundary Thrust (MBT) (also known as Krol Thrust in Kumaon-Garhwal Region) is the Lesser Himalaya terrain. Elevation of these Siwalik Hills ranges between 1500- 2500 m. It has a comparatively mild and mature topography with gentle slopes and deeply dissected valleys which suggest that the rivers and streams are still active. The Lesser Himalayan terrain is divided into two ranges, one is in south part extending from Nainital (2591 m) through Lansdowne (1837 m) to Mussoorie (2510 m) rises abruptly to the great height over the Siwalik ranges and northern range extends through Kranteshwar (2196 m) near Champawat, Ranikhet (1849 m), Dudhatoli (3114 m) east of Pauri and Nag – Tibba (3022 m). The north of the Lesser Himalayan terrane, the Main Central Thrust (MCT) demarcates the lower boundary from the extremely rugged and youngful Great Himalaya (or Himadri). Its elevation is highest in the region ranging between 3000 – 6500 m high (see Fig 1.7a). This region is characterised by precipitous scarps and vertical-walled gorgeous valleys and violently flowing rivers. This region is topographically active. To the north of the formidable Great Himalaya lies the vast expanse of Tethys (or Tibetan Himalaya) which is separated by the Trans-Himadri Fault (T-HF). This part is extremely vegetation less and sparsely populated zone of frigid climate conditions. It appears that this region is comparatively milder tectonic instability. The Tethyan terrane ends against the Indus-Tsangpo Suture (ITS) zone which is marked as the junction of the Indian and Eurasian continental masses.

The Kumaon-Garhwal region is influenced by a tropical weather system that comprises three seasons loosely described as hot, wet and cool. The hot season runs from April to June, when midday temperatures reach 30-35°C, dropping to a nighttime minimum of 10-20°C. July marks the arrival of the rainy season, with
precipitation reaching a maximum in the months of August and September. This region receives precipitation between 80 to 160 cm/yr (Fig. 1.7b). Modern precipitation pattern of Kumaon-Garhwal region shows average rain fall range between 10 to 12 meter during last ten years (Bookhagen and Burbank, 2006). Regions around Munsiari-Dharchula-Pithoragarh-Baijnath are prone to heavy precipitation during this time. The best time to conduct fieldwork is during March to June and October to November months.

1.8. Access:

The Kumaon-Garhwal region stretches from the Kali River which defines the India-Nepal border in the east, to the Tons-Pabar valleys demarcating the eastern border of Himachal Pradesh. It comprises of districts Nainital, Almora, Pithoragarh, Pauri, Chamoli, Uttarkashi, Tehri, Dehradun, Champawat and Udham Singh Nagar. The three districts of Kumaon constitute the administration division of Kumaon and other five are of Garhwal region. Tanakpur, Kathgodam, Ramnagar, Kotdwar, Rishikesh and Dehradun are the six railway stations by which the area is very well connected to other part of India.

Similarly by road the area is very well connected and each and every part of the study area is accessible by Govt. Bus (Uttarakhand Bus Parivahan), Private Bus Service and by hiring the Private Taxi Service. The Kumaon-Garhwal region is also connected with airways. In these region two domestic airports one is in Udham Singh Nagar and another is in Dehradun which are very well connected with whole world via Delhi. The present study area can be accessed from Tanakpur.
Figure 1.7. (a) The Topographic map with major tectonic contacts of the Kumaon-Garhwal region, (b) TRMM derived rainfall variations for the study area and adjacent regions (precipitation data: GTOPO30, U.S. Geological Survey). The TRMM-based monsoon rainfall amounts are averaged from January 1998 to August 2008 (after Bookhagen and Burbank, 2006).