CHAPTER-1

INTRODUCTION

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The Himalayan orogen, apart from being a classic example of the products of continental collisional zone, also shows the development of a complete sequence of Barrovian metamorphic zones. The isograds in the Barrovian zones exposed all along 2000 km of the Himalayan mountain chain from Nanga Parbat in the west to Arunachal in the east are inverted, such that progressively higher grade rocks are exposed towards higher structural levels. This unique phenomenon is known as the Inverted Metamorphic Sequence (IMS). Although significant progress has been made over the years to understand the tectono-metamorphic processes leading to the development of inverted metamorphic zonation (for reviews, see Hodges, 2000; Dasgupta et al., 2004, 2009 and the references cited therein), there is still considerable debate on the origin of the inverted thermal gradient in the IMS, the status and the location of the Main Central Thrust (MCT) in the IMS (see Searle et al., 2008 for a review), the nature of metamorphic P-T-t paths and the metamorphic field gradient across the Lesser and Greater Himalayan sequences.

Contrasting signatures of metamorphic field gradient have been noted by various workers in the different segments of the IMS. Kohn et al. (2001) documented a discontinuity of metamorphic P-T-t paths near the base of the Main Central Thrust Zone (MCTZ) in central Nepal based on contrasting garnet growth history. More in detail, the structurally lowest garnets grew with increasing P and T, while the structurally higher garnets grew with increasing T, but decreasing P. This implies a metamorphic field gradient (MFG) with negative slope in the P-T space. In the Sutlej section of the western Himalaya, the metamorphic field gradient across the High Himalayan crystallines is nearly flat, with nearly isobaric (at P~8 kbar) increase in metamorphic temperature from 600 to 750 °C higher up in the metamorphic sequence (Vannay and Grasemann, 2001). Lack of inverted metamorphic pressure gradient across the MCT has also been observed in the Bhutan Himalaya (Daniel et al., 2003) and in Langtang and Darondi regions, central Nepal (Kohn, 2008). On the other hand, Dasgupta et al. (2004, 2009) established a nearly continuous metamorphic field gradient across the IMS from the Sikkim Himalaya. The positive slope of the MFG is indicated by progressive increase of both pressures and temperatures at progressively higher structural levels.

Numerous thermo-tectonic models have been proposed during the last three decades to explain the origin of the IMS (reviewed in Hubbard, 1996; Hodges, 2000;

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Yin et al., 2006). In recent years, significant new information on the origin of the IMS and the exhumation of the deep crustal rocks has emerged from two segments of the eastern Himalaya, namely the Sikkim-Darjeeling Himalaya and the Bhutan Himalaya. Daniel et al. (2003) presented a ductile extrusion model by channel flow for the origin of the IMS in the Bhutan Himalaya. Faccenda et al. (2008) attributed this ductile extrusion to the formation of a mid-crustal, partially melted channel due to an anomalous concentration of radiogenic heat-producing elements in the protolith. According to these latter authors, the melting-triggered pro-foreland propagation of the channel was responsible for exhumation of metamorphic rocks (cf. Greater Himalayan Sequence) from different depths (15–23 kbar, ~700 °C) on top of a coherent Lesser Himalayan sequence, thereby producing a coherent and continuous IMS in the Sikkim Himalaya. A two stage exhumation of the rocks of the Greater Himalayan Sequence has been previously modelled by Ganguly et al. (2000) with an initial rapid decompression (exhumation rate, 15 mm/yr) being followed by slow cooling and exhumation (~2 mm/yr).

1.1 GEOLOGICAL BACKGROUND

1.1.1 Geotectonic subdivisions of the Himalayan Metamorphic Front

The Himalayan mountain belt is divisible into four east-west trending, continuous lithologic units, corresponding to four geo-tectonic domains (Fig. 1.1; Heim and Gansser, 1939; Gansser, 1964; LeFort, 1975a) namely,

(1) The Sub-Himalayan Sequence (SHS, molasse type Siwalik deposits of Neogene age)

(2) The Lesser Himalayan Sequence (LHS, non-fossiliferous, low-grade metamorphic rocks of Proterozoic age)

(3) The Greater Himalayan Sequence (GHS, Crystalline complex consisting of gneisses, migmatites and granites of Proterozoic to Ordovician age)

(4) The Tethyan Himalayan Sequence (THS, marine, fossiliferous strata of possible Proterozoic to Eocene age)

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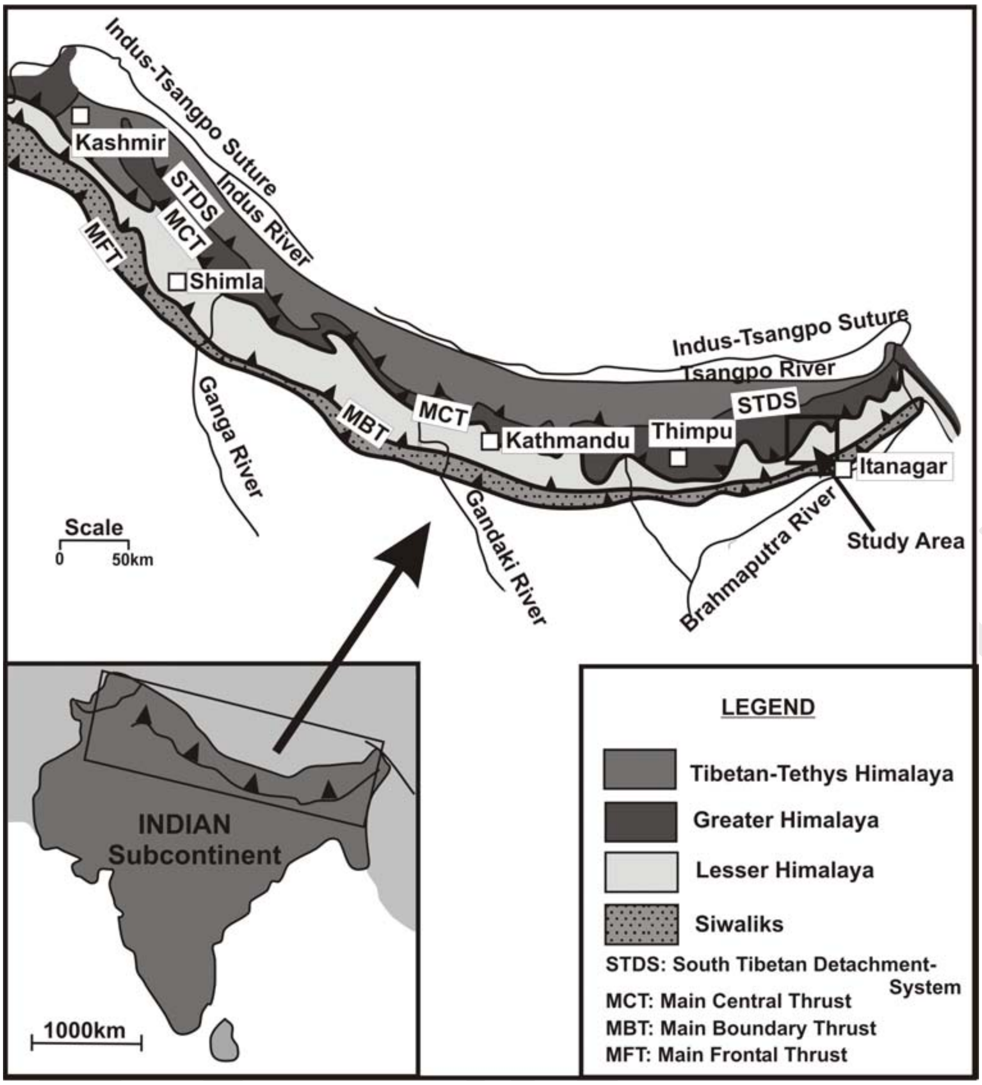

Fig. 1.1: Different lithotectonic units along the east-west trending Himalayan Metamorphic Front. The location of the present study is shown in a box.

The structural discontinuity surfaces, which separate these domains are termed as: (1) The Main Frontal Thrust (MFT), which differentiates Gangetic alluvium from the Sub-Himalaya, (2) The Main Boundary Thrust (MBT) that separates the Sub-Himalayas from the Lesser Himalayas, (3) The Main Central Thrust (MCT), which separates the Lesser Himalayas from the Greater Himalayas and finally (4) the South Tibetan Detachment System (STDS), which separates the Greater Himalayas from the Tethyan Himalayas. Amongst these units, the definition and lateral correlation of the GHS is debatable. Heim & Gansser (1939) originally defined the sequence as one of high-grade metamorphic rocks structurally underlying the THS. LeFort (1975a) considered the unit as a highly metamorphic and tectonised basement of the Tethyan sediments of Palaeozoic and Mesozoic age. He designated the GHS as the Tibetan slab. From northern Nepal and south-central Tibet, Schenider & Masch (1993) noted metamorphism up to amphibolite in the basal parts of the THS. This observation tends to negate the definition proposed by Heim & Gansser (1939) for the GHS. According to Yin (2006), the GHS and the THS units are chronostratigraphic units regardless of their metamorphic grades. Key features of the different subdivisions are briefly summarised below.

1.1.1a Sub-Himalayan Sequence (SHS)

The Tertiary strata below the MBT were traditionally assigned as the sub-Himalayan geographic and stratigraphic zone (Gansser, 1964). This sequence consists of the Neogene Siwalik strata in the MBT footwall and Paleogene-Early Miocene strata in both the MBT hanging wall and footwall (e.g., Schelling and Arita, 1991; Burbank et al., 1996; DeCelles et al., 1998a,b). The Paleocene–Eocene strata of the Himalayan foreland were deposited in a marine setting while the Miocene–Pliocene strata were deposited in a continental setting. A prominent unconformity exists between upper Eocene–? Lower Oligocene strata below and lower Miocene strata above. This unconformity is present in the MFT and MBT hanging walls (Burbank et al., 1996; DeCelles et al., 1998a), and in the Indo-Gangetic depression (Raiverman, 2000).

1.1.1b Lesser Himalayan Sequence (LHS)

The main lithology of the LHS includes metasedimentary rocks, metavolcanic rocks, and augen gneiss (e.g., Frank et al., 1995; DeCelles et al., 1998a; Upreti, 1999). Radiometric dating of gneisses, detrital zircons and metavolcanic rocks yielded an age range of 1870–850 Ma (Trevidi et al., 1984; Miller et al., 2000; DeCelles et al., 2000; Singh et al., 2002). Upper Proterozoic strata are in conformable contact with overlying Cambrian strata in NW India and possibly in Nepal (Valdiya, 1980; Brunel et al., 1984, 1985). But in Pakistan, Mesoproterozoic strata of the LHS are overlain by either Cambrian or Carboniferous sequences of the THS (DiPietro and Pogue, 2004).

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1.1.1c Greater Himalayan Sequence (GHS)

In general, the GHC consists of high-grade rocks, the protolith ages of which range from Paleoproterozoic to Ordovician (?1800-480 Ma). These high-grade GHS rocks generally form a continuous belt along the east-west trending axis of the Himalayan range, but they also occur as isolated patches surrounded by low-grade Tethyan Himalayan strata such as in the Zanskar and Tso Morari regions of NW India, along the North Himalayan Antiform (NHA), and in the Nanga Parbat massif of northern Pakistan (Honegger et al., 1982; Steck et al., 1998; DiPietro and Pogue, 2004). In Nepal, the GHC of Neoproterozoic to Ordovician age (Parrish and Hodges, 1996; DeCelles et al., 2000) is bounded by the MCT below and the STDS above. The metamorphic grade in the GHC first increases upward in its lower part and then decreases from the middle to the upper part towards the STDS (e.g., Hubbard, 1989; LeFort, 1996). In Himachal Pradesh along the Sutlej River in NW India, the inverted metamorphism appears to span the whole GHC from MCT zone to the STDS (Vannay and Grasemann, 1998). Deformed and undeformed Early to Middle Miocene leucogranites are widespread in the GHC, but they are mostly concentrated in the very top part of the GHC (e.g., Gansser, 1964, 1983; LeFort, 1975a, 1996; Scaillet et al., 1990, 1995; Guillot et al., 1993, 1995; Parrish and Hodges, 1996; Searle et al., 1997, 1999a, b; Murphy and Harrison, 1999; De`zes et al., 1999; Grujic et al., 2002).

In Zanskar of NW India, the GHC is surrounded by low-grade THS of Carboniferous and Triassic age. The rocks of the THS are also metamorphosed to amphibolites facies (Honegger et al., 1982) and lie together with the GHC below the north-dipping Zanskar shear zone (e.g., Herren, 1987). Based on this observation, Yin (2006) suggested that the metamorphic grade should not be taken as the sole criterion to distinguish between the THS and the GHC. Thus in northern Pakistan, the high-grade equivalent of the GHC similar to that observed in the central Himalaya is lacking (e.g., Yeats and Lawrence, 1984). In contrast, several workers have demonstrated the presence of high-grade Lesser Himalayan rocks within and adjacent to the Nanga Parbat syntaxis (Whittington et al., 1999; DiPietro and Isachsen, 2001; Zeitler et al., 2001). These rocks have experienced Pre-Himalayan ductile deformation, intrusion, and metamorphism at ~500, 1850, and 2174 Ma, respectively

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(DiPietro and Isachsen, 2001; Zeitler et al., 2001). The intrusive age of ~1850 Ma matches with the ~1800 Ma Ulleri gneiss and ~1914 Ma Bomdila gneiss of the LHS in Nepal and Arunachal Himalayas respectively (e.g., DeCelles et al., 2001; Dikshitulu et al., 1995).

1.1.1d Tethyan Himalayan Sequence (THS)

The Tethyan Himalayan Sequence consists of Proterozoic to Eocene siliciclastic and carbonate sedimentary rocks interbedded with Paleozoic and Mesozoic volcanic rocks (Baud et al., 1984; Garzanti et al., 1986, 1987; Gaetani and Garzanti, 1991; Garzanti, 1993, 1999; Brookfield, 1993; Steck et al., 1993; Critelli and Garzanti, 1994; Liu and Einsele, 1994, 1999). Yin (2006) subdivided the THS into four subsequences:

(1) Proterozoic to Devonian pre-rift sequence characterized by laterally persistent lithologic units deposited in an epicratonal setting.

(2) Carboniferous–Lower Jurassic rift and post-rift sequence that show dramatic northward changes in thickness and lithofacies.

(3) Jurassic–Cretaceous passive continental margin sequence.

(4) Uppermost Cretaceous–Eocene syn-collision sequence (Liu and Einsele, 1994; Garzanti, 1999).

1.1.2 Definition and the status of the MCT in the Himalayan Metamorphic Front

Based on the observations along the Kali and the Alakananda rivers in the Garhwal and the Kumaun regions of NW India, Heim and Gansser (1939) first defined the MCT as a thrust fault that juxtaposed high-grade gneisses and schists (Greater Himalayan Sequence, GHS) over limestone and quartzite (Lesser Himalayan Sequence, LHS). Since this first definition, the MCT, over the years, has been variously defined as a discontinuity surface, (a) akin to a Himalayan unconformity that separates the structurally underlying Palaeo- to Mesoproterozoic Lesser Himalayan

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Sequence from the overlying Greater Himalayan Sequence of Neoproterozoic to Cambrian age (Searle and Rex, 1989; Hubbard, 1996; Kohn et al., 2001), although this has been contradicted by Goscombe et al. (2006), (b) which is coincident with the kyanite-isograd in the IMS (Bordet, 1961; LeFort, 1975a; Colchen et al., 1986), (c) marking a contrast in lithological (e.g., Gansser, 1983; Daniel et al., 2003) and Nd isotope composition (e.g., Parrish and Hodges, 1996; Ahmad et al., 2000; Robinson et al., 2001; Martin et al., 2005; Richards et al., 2005, 2006) and, (d) which locates young U–Pb and Th–Pb monazite metamorphic ages down the structural sequence (e.g., Harrison et al., 1997a; Catlos et al., 2001, 2002a). Because of these differential interpretations, the structural position of the MCT is found to be ambiguous, varying both along and across the orogen, often occupying multiple structural heights in the IMS (e.g., MCT I and MCT II, Arita, 1983). In the Nepal Himalayas, the MCT is exposed in 2-10 km broad zone. Here the location of the MCT is variably defined. LeFort (1975a), Pecher (1989) and Ahmad et al., (2000) placed MCT at the top of the shear zone, while Arita (1983) found the abrupt change in the structure, lithology and metamorphic grade far below the earlier defined location of the MCT. Arita (1983) mentioned the lower boundary of the shear zone as MCT-I and the upper boundary as MCT-II, which is equivalent to the MCT defined by LeFort (1975a). In Kathmandu Nappe area, the MCT is named as the Mahabharat thrust (Upreti and LeFort, 1999; Johnson et al., 2001), equivalent to the MCT-II. In the Kumaun and the Garhwal regions (Western Himalaya) the root zone of the MCT is named as the Munsiari thrust (equivalent to the MCT-I in Nepal) and the thrust at higher structural position is known as the Vaikrita thrust (Valdiya, 1980) (equivalent to the MCT of LeFort, 1975a). The Munsiari thrust is divided into two parts, The Ramgarh thrust below and the Almora thrust above. The latter is named as the Dadeldhura thrust in Western Nepal. In the eastern Himalaya, the MCT is placed in between the LHS and the GHS, in locations, more or less similar to the MCT of LeFort (1975a). Emphasizing the structural criteria, Searle et al. (2008) recently defined the MCT as the base of a domain of high ductile strain, along which Tertiary metamorphic rocks of the GHS are thrusted over unmetamorphosed and low-grade rocks of the LHS. According to this definition, the MCT coincides with the base of the zone of inverted metamorphic isograds. This definition is equivalent to the MCT defined by Stephenson et al., (2000, 2001) in Kishtwar window and the Ramgarh thrust in the Garhwal Himalayas.

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1.1.3 Chronology of the Metamorphic Events in the Himalayan Orogen

Two metamorphic events have been broadly recognised in the Himalayan orogen: The Eohimalayan event that occurred during the time period, 55-30 Ma and the Neohimalayan event that occurred since the early Miocene (e.g., LeFort, 1996; Hodges, 2000). The Eohimalayan event is related to the subduction of the Indian lithosphere beneath the Tibetan slab, producing ultra high-pressure (UHP) metamorphic rocks, including eclogites. Eclogites are reported from two locations, near the western syntaxis (Kaghan and Tso Morari). Pognante and Spencer (1991) first reported eclogite from the Kaghan Valley in Pakistan. Sachan et al. (2004) reported coesite and micro-diamond in the Tso Morari Crystalline Complex, Ladakh. Carbonate-bearing eclogite, which occurs as lenses in kyanite-sillimanite-grade rocks in Tso Morari area, contains microdiamond inclusion within zircon (Mukherjee et al., 2003). Metamorphic pressures in excess of 3.9 GPa has been inferred by the authors for this UHP event. Using multiple Lu-Hf, Sm-Nd, Rb-Sr and Ar-Ar chronometers, de Sigoyer et al. (2000) dated the eclogitisation and exhumation of the Tso Morari UHP rocks. These authors have obtained Lu-Hf garnet, omphacite and mafic eclogite mineral-whole rock isochron and Sm-Nd garnet, glaucophane and high-pressure metapelite mineral-whole rock isochron age of 55±12 Ma to 55±7 Ma for the eclogitisation event. This age is indistinguishable from that of Kaghan eclogites. The age data provide precise time constraints on the timing of the onset of Indian continental subduction, producing the first contact of India with the Asian continent. Sm-Nd mineral (garnet, calcic amphibole)-whole rock (metabasalt) isochron, Rb-Sr mineral (phengite, apatite)-whole rock (metapelite) isochron and Ar-Ar ages on phengites suggest that by 47 Ma, the eclogites underwent rapid exhumation and thermal relaxation to 9±3 kbar, which led to partial recrystallisation under amphibolite facies conditions (de Sigoyer et al., 2000). By ~30 Ma, the eclogites were exhumed to upper crustal levels. The time coincides with crustal thickening associated with the Himalayan collision.

The Neohimalayan event is associated with the continent-continent collision event that produced the Barrovian metamorphic sequence. Neohimalayan structures are found throughout all the tectonostratigraphic zones of the Himalaya. The most

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significant one is the thrust systems that separate Greater Himalayan, Lesser Himalayan and Sub-Himalayan zones from one another and also the north dipping normal faults and related fold structures. The Greater Himalayan Sequence and the metamorphic cores of the North Himalayan gneiss domes contain a signature of Neohimalayan metamorphism. Over the entire length the Himalayan metamorphic sequences display inverted Barrovian sequence of metamorphic isograds (Heim and Gansser, 1939; LeFort, 1975a; Pêcher and LeFort, 1986). In general the peak metamorphic temperature ranges from 500-550 °C near Main Central Thrust zone to >700 °C in the Greater Himalayan Sequences (Brunel and Kienast, 1986; Pognante and Lombardo, 1989; Metcalfe, 1993; Davidson et al., 1997; Vannay and Grasemann, 1998). As the Neohimalayan slip on MCT structures have shuffled with the Lesser and Greater Himalayan lower and middle Miocene metamorphic rocks which are having different metamorphic histories, metamorphic studies on the MCT zone are complicated (Brunel and Kienast, 1986; Hubbard and Harrison, 1989). LHS metapelites show the assemblage of biotite + muscovite ± chlorite + quartz + garnet ± staurolite ± kyanite through chlorite, biotite, garnet, staurolite, kyanite grade, while garnet + biotite + muscovite + quartz + kyanite ± sillimanite ± K-feldspar- bearing migmatites are reported from GHS area. Voluminous thermo-chronological data has been generated over the years from the different sectors of the Himalayan orogen to constrain the timing of the collision orogeny. This has been briefly summarised below and presented in Table 1.1.

In central Himalaya, the peak metamorphism in the GHS has been constrained at 6-10 kbars/600-700 °C (Brunel and Kienast, 1986; LeFort, 1996; Vannay and Hodges, 1996; Davidson et al., 1997; Lombardo and Rolfo, 2000). A protracted thermal history in the MCT root zone has been established from this segment of the Himalayan orogen. From the upper bounding surface of the MCT zone (MCT-II of Arita, 1983), $^{40}Ar/^{39}Ar$ hornblende ages from amphibolite facies rocks and U-Pb zircon ages of a leucogranite that cuts the MCT zone yielded ages in the range, 23-20 Ma (Hubbard and Harrison, 1989; Hodges et al., 1992, 1996; Parrish and Hodges, 1996; Coleman, 1998; Godin et al., 2001).This suggests that amphibolite-grade metamorphism associated with motion on the MCT occurred at 23–20 Ma. The age of deformation in the MCT root zone becomes progressively younger southward, from ~20 Ma at the top to about 5–3 Ma at the base of the MCT shear zone as indicated by

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Th–Pb ages of monazite inclusions in syn-kinematic garnets (Harrison et al., 1997a, 1998b; Catlos et al., 2001, 2002a, b) and $^{40}Ar/^{39}Ar$ muscovite ages (Macfarlane, 1993). The younger 5-3 Ma cooling and metamorphic ages in the MCT root zone (Wadia, 1931) are in strong contrast to the older muscovite cooling ages of 22-14 Ma in the Kathmandu Nappe along the thrust flat portion of the MCT (Copeland et al., 1996; Arita et al., 1997). The age progression within the MCT zone and the age difference between the internal (northern) and external (southern) segments of the MCT zone was interpreted to originate from discontinuous downward migration of simple-shear deformation (Harrison et al., 1998b), southward propagation of discrete thrusts in a duplex system (Robinson et al., 2003) or out-of sequence thrusting (Rai et al., 1998; Johnson et al., 2001).

The age of motion along the southern part of the MCT in the geographically defined Lower Himalaya is best constrained in the Kathmandu area of south-central Nepal. Johnson and Rogers (1997) and Johnson et al. (2001) showed that the basal thrust zone of the Kathmandu Nappe was active between 22 and 17 Ma based on U–Pb ages of deformed pegmatites and Rb–Sr cooling ages of muscovite and biotite. Arita et al. (1997) also investigated the emplacement history of the Kathmandu Nappe by dating muscovites from the MCT hanging wall and footwall. Their results suggest that the MCT shear zone was cooled below 350 °C between 21 and 14 Ma and that the southernmost portion of the MCT shear zone ceased motion since 14 Ma.

In the western Himalaya, the peak metamorphism (M_1 at ~9.5-10.5 kbars/550-680 °C) in the GHS has been dated at ~35-25 Ma from the Zanskar area (Vance and Harris, 1999) and at ~40 Ma from the Garhwal area (Prince et al., 1997). A second metamorphism (M_2 at ~4.5–7 kbars/650–770 °C) has been dated at 22–16 Ma (Walker et al. 1999; Searle et al., 1999b; Stephenson et al., 2000). The age of the MCT in the Garhwal Himalaya is constrained to be at 22-14 Ma by K-Ar cooling ages of muscovite in the GHC (Metcalfe, 1993). Within the MCT zone below the Vaikrita thrust (=MCT), thrusting was active between 6 and 2 Ma as determined by Th–Pb ion-microprobe dating of monazites (Catlos et al., 2002a). This age is broadly consistent with the youngest K-Ar muscovite cooling ages (5.7-5.9 Ma) from the same localities (Metcalfe, 1993). The age of the MCT around the Kishtwar window was constrained to be active between 22 and 16 Ma (Walker et al., 1999; Searle et al., 1999a;

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Table: 1.1: Geochronology of the metamorphic event in the Himalayan orogen

Locality	Area	Method	Analysed material	Age	Comment	Reference
Western Himalaya						
Nanga Parbat massif	MCT shear zone	$^{40}Ar/^{39}Ar$	Hornblend	56.1±1.5 Ma		Hubbard et al., 1995
Kaghan section	Kaghan eclogite	Sm-Nd, U-Pb	Quartz bearing eclogite facies, zircon	(a) 50±1 Ma (b) ~(46-47) Ma	Prograde meta^{sm} UHP condition	Kaneko et al., 2003 Kaneko et al., 2003; Parish et al., 2006
			Zircon, rutile from coesite free eclogite	(c) ~44 Ma	HP condition; fast exhumation (3-8cm/yr)	Spencer & Gebaur, 1996; Treloar et al., 2003; Parrish et al., 2006
		Rb-Sr	Phengite	(d) ~43-40 Ma	Slow cooling rate (0.3cm/yr)	Tonarini et al., 1993
		$^{40}Ar/^{39}Ar$	Hornblend from adjacent amphibolite	(e) ~39-43 Ma	Do	Chamberlain et al., 1991; Smith et al., 1994; Hubbard et al., 1995
Tso Morari massif	(i) Puga Fmn, Qtz-Fsp gneiss	U-Pb SHRIMP	Zircon	53.3±0.7 Ma, 50±0.6 Ma	UHP condition	Leech et al., 2005
	(ii) Amphibolite facies	$^{40}Ar/^{39}Ar$	Phengite	47±0.5 Ma		
	(iii) Green schist facies	(a) Fission track	Zircon	(a) 34±2 Ma, 45±2 Ma	Final cooling	Schlup et al., 2003
		(b) U-Pb SHRIMP	Zircon	(b) 60.1±0.9 Ma		
	(iv) Eclogite facies	Lu-Hf, Sm-Nd, Rb-Sr, Ar-Ar	garnet, omphacite, whole rock	~55 Ma		Sigoyer et al., 2000
Ladakh Batholith	(i) Grano-diorite (N of Shyok Suture Zone (SSZ)) (ii) Diorite (S of SSZ)	U-Pb SHRIMP	Zircon	~58.4±1 Ma		Singh et al., 2007

Mineral abbreviations after Kretz (1983) except meta^{sm}=metamorphism; Fmn=Formation

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Table: 1.1. Continued

Locality	Area	Method	Analysed material	Age	Comment	Reference
Sutlej Valley	HHCS	$^{40}Ar/^{39}Ar$: Fission track	Muscovite	(16-1) Ma	Exhumation & cooling of HHCS	Jain et al., 2000; Grasemann, Vannay & Rahn, unpublished data
Adjacent N.W India	HHCS	Do	Do	23 Ma	Peak meta^{sm}, Partial melting	Dèzes et al., 1999; Searle et al., 1999a; Vance & Harris, 1999; Jain et al., 2000
70 km S.E. of Sutlej	HHCS	(i) Sm-Nd	(i) Garnet whole rock	(a) (35-25) Ma	Prograde meta^{sm} upto upper Amphibolite facies	Metcalfe, 1993; Prince et al., 1994; Sorkhabi et al., 1996; Catlos et al., 1999; Searle et al., 1999a
		(ii) U-Th-Pb	(ii) Monazite	(b) 23 Ma	Peak meta^{sm}, Partial melting	
		(iii) K-Ar, $^{40}Ar/^{39}Ar$	(iii) Biotite, Muscovite, Hornblende	(c) (23-20) Ma	Rapid cooling, ductile thrusting	
		(iv) Fission track	(iv) Zircon, Apatite	(d) (15-2) Ma	Slow cooling, controlled by erosion & thrusting	
Central Himalaya						
Eastern Nepal	MCT shear zone	$^{40}Ar/^{39}Ar$	Mica	Pliocene		Copeland et al., 1991; Macfarlane, 1993; Edwards, 1995
	LHS	$^{40}Ar/^{39}Ar$	Mica	2.9±0.1 Ma		Edwards, 1995
Marysandi transect	(i) GHS	(i) Th-Pb ion microprobe	(i) Monazite, inclusion within Grt to matrix	(i) (37.5±0.3 - 11.0±0.4) Ma	monazite growth during Eohimalayan meta^{sm}	(i) Catlos et al., 2001
	(ii)upper LHS	(ii) Th-Pb ion microprobe	(ii) Monazite	(ii) (6.3-18.7) Ma		(ii) Catlos et al., 2001
	(iii) towards south from MCT	(iii) Th-Pb ion microprobe	(iii) Monazite	(iii) 10-15 Ma to 7-8 Ma		(iii) Catlos et al., 2001
	(iv) lower LHS	(iv) Th-Pb ion microprobe	(iv)matrix Monazite	(iv) (20±1 - 9.5±0.4) Ma		(iv) Catlos et al., 2001
Darondi Khola transect	(i) GHS	(i) $^{40}Ar/^{39}Ar$	(i) Muscovite	(i) (4.37-13.9) Ma		
	(ii) upper LHS	(ii) (a) Th-Pb ion microprobe	(ii) (a) Monazite	(ii) (a) (366-8.2) Ma		
		(b) $^{40}Ar/^{39}Ar$	(b) Muscovite	(b) (2.8-15.9) Ma		
	(iii) lower LHS	(iii) $^{40}Ar/^{39}Ar$	(iii) Muscovite	(iii) (4.8-257) Ma		

Mineral abbreviations after Kretz (1983) except meta^{sm}=metamorphism; Fmn=Formation

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Table: 1.1. Continued

Locality	Area	Method	Analysed material	Age	Comment	Reference
Dudh Kosi-Everest transect	(i) Greater Himalayan Crystallines (GHC)	i) $^{40}Ar/^{39}Ar$	(i) Mica, Hornblende	(i) (17-21) Ma	linked to MCT slip & uplift of the range	(i) Kaneoka & Kono, 1981; Hubbard & Harrison, 1989
	(ii) Upper GHC	(ii) U-Th/He	(ii) Apatite	(ii) 6±4 Ma		ii) Hubbard & House, 2000
	(iii) Upper LHS	(iii) U-Th/He	(iii) Apatite	(iii) 4.6±0.2 Ma		(iii) Hubbard & House, 2000
	(iv) Phaplu augen gneiss	(iv) (a) Th-Pb ion microprobe	(iv) (a) matrix Monazite	(iv)(a) (901±13 - 1566±49) Ma	(iv) time of the assembly of Indian subcontinent	(iv) Catlos et al., 2002a
		(b) U-Pb	(b) Zircon	(b) ~1831Ma		(b) DeCelles et al., 2000
	(v) GHC- Namche migmatite orthogneiss	(v) Th-Pb	(v)(a) Monazite, inclusion within Grt	(v)(a) 548±17 Ma	(v) time of the suturing of India to Gondwana	(v) Catlos et al., 2002a
			(b) matrix Monazite	(b)(141-246) Ma		
	(vi)Barun Gneiss	(vi) Th-Pb	(vi)Monazite, inclusion within Gneiss	(vi) 436±8 Ma	young for the Pan African orogenic episode	(vi) Catlos et al., 2002a
Garhwal	(i) High Himalayan Leucogranite-					
	(a) Gangotri,	(i)(a) Th-Pb	(i)(a) Monazite	(i)(a) 22.4±0.5 Ma		Harrison et al., 1997b
	(b) Shivling	(b) Th-Pb	(b) Monazite	(b) 21.9±0.5 Ma		Harrison et al., 1997b
		(b) U-Pb	(b) Monazite	(b) 23.0±0.2 Ma		Searle et al., 1999b
	(ii)(a) upper LHS, GHC	(ii)(a) $^{40}Ar/^{39}Ar$	(ii) Mica	(ii) (a) 17-22 Ma		Metcalfe, 1993
	(b) GHC, adjacent to the Bhagirathi river	(b) Th-Pb	(ii)(b) Monazite, inclusion within Grt	(b) (43.4±2.5 - 36.3±2.0) Ma		Foster et al., 2000
			Matrix Monazite	(40-26) Ma		Foster et al., 2000
		(c) Sm-Nd	(c.) Garnet, whole rock	(c) 534±24 Ma		Argles et al, 1999
	(iii) LHS	(iii) Rb-Sr	(iii) Whole rock	(iii) 1907±91 Ma		Ahmed et al., 1999
Eastern Himalaya						
Eastern Bhutan	LHS (below MCT)-					
	(i) Qtz-Fsp gneisse	U-Pb	Monazite	(22-18) Ma		Daniel et al., 2003
	(ii) St-Ky schist					
	GHS (above MCT)-					
	(i) Bt schist	U-Pb	Monazite	22±1 Ma		Daniel et al., 2003
	(ii)Ky migmatite & leucosome	U-Pb	Monazite & Xenotime	(18-14.5) Ma		Daniel et al., 2003

Mineral abbreviations after Kretz (1983).

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Table: 1.1. Continued

Locality	Area	Method	Analysed material	Age	Comment	Reference
Sikkim	(i) LHS	Th-Pb ion microprobe	Monazite	(10.5-18.3) Ma		Catlos et al., 2004
	(ii) MCT shear zone	Th-Pb ion microprobe	Monazite	(10.3-20.5) Ma		Catlos et al., 2004
	(iii) GHS	Th-Pb ion microprobe	Monazite	(18.5-25.6) Ma		Catlos et al., 2004
	(iv) Pauhunri leucogranite	Th-Pb ion microprobe	Monazite	(17±0.8) Ma		Catlos et al., 2004
Arunachal	i) Bomdila gneiss	i) whole rock Rb/Sr isochron	Bomdila gneiss	(i) 1644±40 Ma, 1676±122 Ma		Bhalla & Bishui, 1989
	ii)Bomdila augen gneiss	ii)Rb-Sr with six point isochron	Bomdila gneiss	(ii) 1914±23 Ma		Dikshitulu et al., 1995
	iii) metasedimentary Rupa Group	(iv) U-Pb	Detrital zircon	(iii)(a) youngest age at ~950 Ma		Yin et al., 2006
	iv) Lumla and Dirang	(v) U-Pb	Detrital zircon	(iv) 2 dominant age clusters at ~1400 & ~1700 Ma		Yin et al., 2006
	v) above MCT near	(vi) U-Th ion microprobe	Monazite, inclusion within Grt	v) 10±1.4 Ma	v) Records crystallisation ages and suggests MCT was active in the late Miocene	Yin et al., 2006

Mineral abbreviations after Kretz (1983).

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Stephenson et al., 2001). The youngest $^{40}Ar/^{39}Ar$ muscovite ages reported from the Zanskar region is about 16 Ma (Stephenson et al., 2001). In the absence of 7–3 Ma young ages of the MCT obtained from Nepal and Garhwal Himalaya (Harrison et al., 1997a; Catlos et al., 2001; 2002a, b), it has been suggested that Zanskar Himalaya did not experience late Miocene-Pliocene reactivation of the MCT.

In the Eastern Himalaya, peak metamorphism in the GHS from Sikkim has been variously estimated at 750-800 °C, 10-12 kbar (Neogi et al., 1998; Ganguly et al., 2000; Harris et al. 2004). These authors also recorded a steep decompression of the granulite facies GHS rocks to mid-crustal levels. Harris et al. (2004) dated the metapelites granulites of the GHS from Yuksam section. Sm–Nd ages of garnet cores and rims yielded 23 Ma and 16 Ma respectively. The older age is correlated with a phase of pre-decompression garnet growth along the prograde segment of the clockwise P-T path, while the younger age constrains the timing of near-peak temperatures at mid-crustal levels. The age data was taken as evidence that the MCT was active at ~23 Ma during prograde metamorphism. The MCT in Bhutan cuts 16-Ma-old leucogranite, whereas the north-dipping Kakhtang thrust in the MCT hanging wall cuts a leucogranite of 14-15 Ma (Grujic et al., 2002). U-Pb dating of monazite and xenotime indicates that the MCT in Bhutan was already active at 22 Ma and continued its motion during and after ~14 Ma (Daniel et al., 2003). Similar Th-Pb monazite ages between 22 and 14 Ma were also obtained for the MCT zone in Sikkim (Catlos et al., 2002b). In the Arunachal Himalaya, Yin et al. (2006) show that the MCT was active at and after ~10 Ma based on ion-microprobe dating of monazite inclusions in garnets from the MCT zone.

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1.2 ARUNACHAL HIMALAYA: GEOLOGICAL SETTING

Arunachal Himalayas represent the easternmost part of the Eastern Himalaya. The present study area in the western Arunachal Himalaya (WAH) is located in between the Bhutan Himalaya to the west and the eastern Himalayan syntaxis to the east (Fig. 1.2). This area has been geologically mapped by Das et al. (1975), Thakur (1986), Singh and Chowdhary (1990), Acharya (1987), Kumar (1997) and Bhattacharjee and Nandy (2008). A plethora of stratigraphic names have been

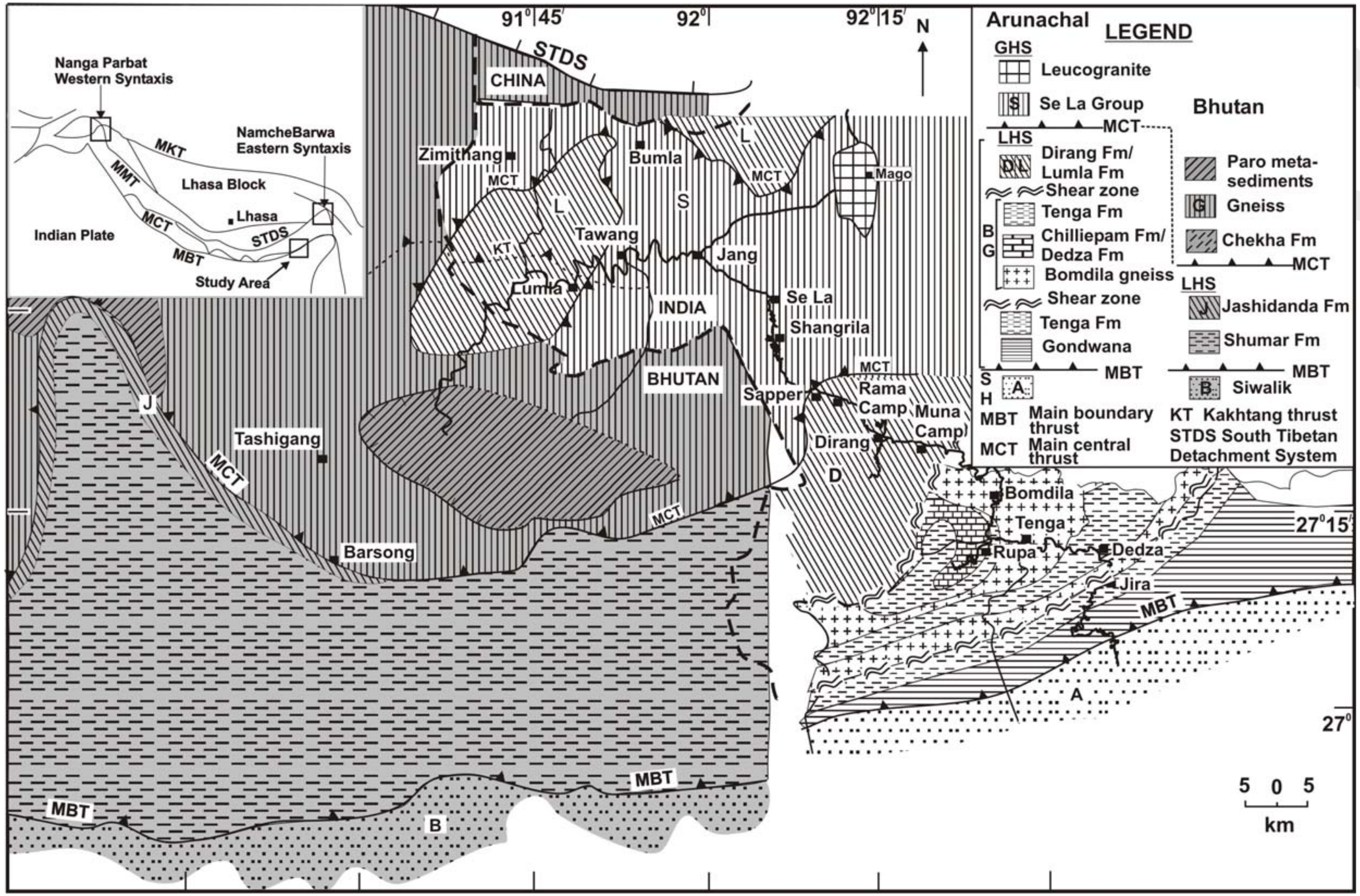

Fig. 1.2: Geological map of the western Arunachal and adjoining Bhutan Himalayas (modified after Kumar (1997) and Daniel et al. (2003)), showing the distribution of different tectono-stratigraphic units and the location of the Main Central Thrust (MCT). Other abbreviations used: SH, Sub Himalaya; LHS: Lesser Himalayan Sequence; GHS: Greater Himalayan Sequence; BG: Bomdila Group. Inset shows the location of the present study in the eastern Himalayan syntaxis.

proposed by these workers, resulting in considerable confusion on the litho-tectonic framework of the WAH. Three major, thrust bounded tectonic units, namely the sub-Himalaya (Siwaliks), the Lesser Himalaya (including the Gondwana Group) and the Greater Himalaya were recognized in these studies, which are described below.

1.2.1 Sub-Himalaya (SH)

The southern Sub-Himalayan domain of molasse-type Siwalik deposits of Lower Miocene to Lower Pleistocene age is separated from the structurally overlying Lesser Himalayan Sequence (LHS) by the Main Boundary Thrust (MBT) (Kumar, 1997).

1.2.2 Lesser Himalayan Sequence (LHS)

1.2.2a Gondwana rocks and Bomdila Group

Das et al., 1975 recorded dirty green sandstone and carbonaceous shale with occasional coal bands in the basal part of LHS and defined these as Gondwana rocks. Grey micaceous sandstone with slaty partings, white gritty quartzitic sandstone with some plant fossils are also present. These are overlain by quartzite, chlorite-sericitic schist and thin intercalations of para gneisses of the Bomdila Group, locally referred to as the Tenga Formation (or Group) (Das et al., 1975; Kumar, 1997). Tripathi et al. (1982) considered the Bomdila Group to be of Early Palaeozoic to Precambrian in age, whereas Tenga Group is to be of lower Palaeozoic age. They divided Tenga Group into two formations. Namely Lower Rupa/Jhameru Formation and Upper Chillipam/Dedza Formation.

1.2.2b Bomdila gneiss and Bomdila Group

These low-grade metamorphites of the basal LHS are structurally overlain by a thick unit of megacrystic granite gneiss (Bomdila gneiss). These orthogneisses, which have yielded Palaeo- to Early Mesoproterozoic Rb-Sr whole rock isochron ages (Dikshitulu et al., 1995) resemble the megacrystic Lingtse gneiss of the Sikkim

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Himalayas (Sinha-Roy, 1982), the Ulleri augen gneiss in the Annapurna region (LeFort, 1975a, b; Pecher and LeFort, 1977), the Num orthogneiss of Arun valley (Brunel, 1983; Lombardo et al., 1993) and the Phaplu augen gneiss in the Everest region of central Nepal (Maruo and Kizaki, 1983). Preliminary kinematic analysis of the Bomdila gneiss led Yin et al. (2006) to correlate the deformation to regional top-south movement during the Cenozoic thrusting. These workers also documented Late Mesoproterozoic (~950 Ma) depositional ages in the metasediments of the Bomdila Group and the Dirang Formation (see later). This raises the possibility that the Bomdila gneiss could represent tectonic slivers of Palaeo- to Mesoproterozoic basement rocks. The occurrence of tectonic slivers of basement granitic rocks within the overlying Shumar Formation has also been reported from the LHS of the adjoining Sikkim Himalayas (Sinha-Roy, 1982) and Bhutan (Ray et al., 1989; Ray, 1995; Dasgupta, 1995) (Fig. 1.2).

1.2.2c Dirang Formation

The Dirang Formation constituting the upper part of the LHS is represented by a thick metasedimentary sequence of garnetiferous muscovite-biotite schist (Fig. 1), often calcareous, phyllite, sericite quartzite, calc-silicate and tremolite-actinolite marble, with pods and lenses of amphibolites. There is progressive increase in the size of the garnet with structural height. The pelitic schist in the upper part of the Dirang Formation contains sporadic occurrence of kyanite and staurolite, along with garnet and mica (Bhattacharjee and Nandy, 2008). These low-medium grade schists are exposed in the adjoining Bhutan Himalaya as the Jaishidanda Formation (Daniel et al., 2003), immediately below the Greater Himalayan Sequence (GHS) (Fig. 1.2). In the Lumla, Thimbu and Womingla areas in the north western extremity of the transect, an identical low-medium grade metamorphites of quartz-chlorite-biotite-garnet schist, quartzite, marble and calc-silicate rocks, belonging to the Lumla Formation is exposed as tectonic window within higher-grade rocks of the GHS (Fig. 1.2). Although previously correlated with the Tethyan metasediments, recent studies infer that the Lumla Formation has Late Mesoproterozoic depositional age (Yin et al. 2006) and is equivalent to the Dirang Formation (Bhattacharjee and Nandy, 2008). Yin et al. (2006) dated monazite inclusions within syn-deformational garnet from Dirang area by U-Th

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ion-microprobe dating technique, which yielded an age of 10±1.4 Ma (1σ). This was taken as evidence that movement along the MCT was as young as 10 Ma.

1.2.3 Greater Himalayan Sequence (GHS)

1.2.3a Se La Group

Rocks of the Se La Group, which represents the exposed GHS in the WAH lies north of the MCT. The predominance of migmatites, high grade schists and intrusions of tourmaline granites characteristically differentiates this sequence from the Bomdila metamorphites (Das et al., 1975). The stratigraphic unit derives its name from the Se La pass in the West Kameng district (Bakliwal and Das, 1971). Dhoundial et al. (1989) classified the Se La Group into Lower Taliha Formation and Upper Galensiniak Formation on the basis of differences in lithological association and metamorphic grade. The former, metamorphosed at relatively lower grade consists of graphitic schist, calc-silicate gneiss, marble, amphibolite and quartzite. The higher grade Galensiniak Formation comprises of schists and gneisses with intrusive tourmaline granite and pegmatite. In the Se La-Tawang-Bumla section, the rocks are a complex association of migmatite, garnetiferous biotite-plagioclase gneiss, calc-gneiss/marble (diopside and scapolite bearing), staurolite schist, tourmaline-bearing leucogranite, quartzite and pegmatite (Bhattacharjee and Nandy, 2008). They noted the presence of kyanite+biotite+staurolite-bearing assemblages at the lower part of the Se La Group at Lish and north of Changla while sillimanite-bearing assemblage with garnet and biotite is present in the migmatitic upper part. Scapolite-bearing calc silicate rocks are present as enclaves within migmatite near YJN on the Tawang-Bumla road. Previous workers noted increase in the proportions of leucogranite with structural height, becoming extremely abundant in places like Senge, Se La Pass, Jaswantgarh, Mago and Pangila. In agreement with mineralogy from other sectors of GHS, the leucogranites in the Se La Group are characteristically two mica-bearing (muscovite-biotite) with accessory tourmaline and garnet.

The different litho-tectonic domains that are encountered in the studied transect Sessa-Tenga-Rupa-Bomdila-Dirang-Se La Pass, and its correlations with the adjoining Bhutan Himalaya are summarised in Table 1.2. It becomes evident from the literature

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Table 1.2: Tectono-stratigraphic subdivisions of the western Arunachal Himalaya (modified after Das et al., 1975)

Tectonic domains	Stratigraphic units	Rock units
Greater Himalayan Sequence	Se La Group	Grt-Sil gneiss/migmatites, Bt–Hbl-Pl gneiss/migmatite, often garnetiferous, garnetiferous calc silicate gneiss, Tur-(Grt)-bearing two mica granites
------------	------------ MCT---------	---------------------------- MCT-----------------------
Lesser Himalayan Sequence	Dirang Formation	Garnetiferous mica schist, often St- and Ky-bearing, quartzite, calc schist and marble, amphibolites
	--------Shear Zone-------	---------------------------- Shear Zone ----------------
	Bomdila gneiss	Megacrystic granite with mafic microgranular enclaves, augen gneisses and amphibolites
	Bomdila Group Tenga Formation	 Quartzite, quartz schist etc.
	Chilliepam Formation/ Dedza Formation	Dolomites (white and dark grey) and carbonaceous phyllite
	Bomdila gneiss	
	--------Shear Zone-----	---------------------------- Shear Zone ----------------
	Bomdila Group Tenga Formation	Quartzite, Qtz-Chl-sericite schist, talcose schist, thin intercalation of quartzite bands
	Gondwana rocks	Dirty green sandstone and carbonaceous shale with occasional coal bands, grey micaceous sandstone with slaty partings, white gritty quartzitic sandstone. Plant fossils recorded
-------------	-----------MBT----------	-----------------------------MBT-----------------------
Sub-Himalaya	Siwalik	Grey to green sandstone ------------Fault--------------- Siltstone -------------Fault--------------- Pebble to boulder bed

Abbreviations used: MCT=Main Central Thrust; MBT=Main Boundary Thrust

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survey that there is no information from the Arunachal Himalaya, in relation to (a) the zonal distribution of the index metamorphic minerals and the disposition of the metamorphic isograds, (b) the metamorphic reaction history that was responsible for the formation of the different mineral zones, (c) the exact location of the MCT separating the Lesser (LHS) and the Greater Himalayan Sequences (GHS), (d) the peak P-T conditions of metamorphism recorded in these metamorphic zones and the attendant MFG and finally (e) the metamorphic P-T paths that characterise the different metamorphic zones.

1.3 OBJECTIVES

In the absence of information on points (a) to (e), it is neither possible to reconstruct the basic framework of the IMS in Arunachal Himalaya nor to make a correlation with other segments of the Himalayan Metamorphic front. It is in this context, the present dissertation topic has been chosen to address these issues, using rocks from the western Arunachal Himalaya (WAH), which lies at the northwestern extremity of the state of Arunachal Pradesh, India, bordering Bhutan to the west and China to the north (Fig. 1.2). For this purpose, a transect along Sessa-Rupa-Bomdila-Dirang-Se La Pass has been chosen (Fig. 1.2). The prime objectives of the current dissertation are set as – (1) To understand the lithological and the structural framework of the different metamorphic zones, exposed along the studied transect. (2) To determine the disposition of the metamorphic isograds and also the location of the MCT. (3) To deduce the metamorphic reaction history using textural criteria and mineral compositional data. (4) To constrain the thermal and baric conditions of metamorphism of the different metamorphic zones using geothermobarometry and P-T pseudosection modelling techniques. (5) To reconstruct the MFG and the metamorphic P-T path of evolution of the different metamorphic zones. (6) To integrate the results obtained in (1) to (5) to formulate a coherent model of inverted metamorphic gradient in the eastern Himalaya.

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