

CHAPTER 2. Geologic overview of the Himalaya: emphasis on previous work.

2.1. Introduction

The Himalayan arc extends ~2400 km from Nanga Parbat (8138 m) in the west to Namche Barwa (7756 m) in the east (e.g., Le Fort, 1996). This region includes the independent kingdoms of Nepal and Bhutan as well as parts of Pakistan, India, and China. The orogen forms a sharp transition between the average ~5 km-high, arid Tibetan plateau and the warmer, wetter Indian lowlands (Fig. 2.1), and is comprised of roughly parallel, crustal-scale fault systems that bound distinctive lithologic units along strike (Fig. 2.2).

This chapter describes geology of the Himalaya, emphasizing the Garhwal region of northern India, the Annapurna-Manaslu-Ganesh territory of central Nepal, and the Dudh Kosi-Everest transect in eastern Nepal (Fig. 2.2). It also reviews thermobarometric and geochronologic information reported for rocks adjacent to the Main Central Thrust (MCT), located at the base of the Himalaya's sharp change in slope.

The MCT hanging wall has been the primary focus of Himalayan geologists thus far (e.g., Hodges et al., 1996; Coleman, 1998, Guillot, 1999). Careful examination of previous studies suggests quantitative constraints of the metamorphic conditions recorded by rocks of the Greater Himalayan Crystallines and the methods used to generate the data are of limited use (Kohn and Spear, 2000). MCT footwall samples contain information fundamental to our understanding of Himalayan evolution, and the lack of data from this location is problematic.

2.2. Orogen-scale description of the Himalaya

Figure 2.2 is a general geologic map of the Himalaya and Figure 2.3 shows a cross-section through the range in eastern Nepal. The MCT is one of five fault systems that formed due to the collision that telescoped the Indian margin (Gansser, 1981; Pêcher, 1989; Schelling, 1992; Le Fort, 1996; Yin and Harrison, 2000). The Indus Tsangpo Suture Zone juxtaposes low-grade Cambrian to mid-Eocene Indian shelf sediments (Tethys Formation) with Asian metasedimentary and igneous rocks (Yin et al., 1994; Quidelleur et al., 1997). The north-dipping South Tibetan Detachment System (STDS) separates the Tethys Formation in its hanging wall from a 5- to 20- km thick Late Proterozoic unit of footwall gneisses called the Greater Himalayan Crystallines (Burg et al., 1984; Valdiya, 1988; Burchfiel et al., 1992). North Himalayan granites intrude the Indian shelf sediments, whereas High Himalayan leucogranites form a linear chain in close proximity to the STDS (e.g., Harrison et al., 1997a).

At their base, the Greater Himalayan Crystallines are thrust over Middle Proterozoic phyllites, metaquartzites, and mylonitic augen gneisses of the Lesser Himalaya along the MCT (Arita, 1983; Brunel and Kienast, 1986; Pêcher, 1989). Further south, the Main Boundary Thrust (MBT) separates the Lesser Himalaya from Neogene molasse, the Siwalik Formation (Valdiya, 1992; Meigs et al., 1995). South of the MBT, the Main Frontal Thrust (MFT) typically defines the boundary between the Siwalik Formation and the northern Indo-Gangetic Plains (e.g., Mugnier et al., 1999). The MFT cuts Siwalik strata in places and is often manifested as growing anticlines (Yeats et al., 1992; Powers et al., 1998). These crustal-scale faults appear to sole into a common

decollement termed the Main Himalayan Thrust (MHT) (Zhao et al., 1993; Nelson et al., 1996).

At present, the Indian craton moves north-northeast at a rate of 44-61 mm/yr relative to Eurasia/Siberia (Minster and Jordan, 1978; DeMets et al., 1990; Bilham et al., 1997). Recent global positioning studies suggest this rate may be significantly slower at 37-42 mm/yr (Chen et al., 2000; Shen et al., 2000). The active faults within the Himalaya are the MBT (Ni and Barazangi, 1984; Valdiya, 1992; Joshi and Patel, 1997) and MFT (Lyon-Caen and Molnar, 1983; Baker et al., 1988; Powers et al., 1998; Yeats et al., 1992; Lavé and Avouac, 2000). A clearly identifiable ~50-km wide zone of predominately moderate earthquakes ($5 \leq m_b \leq 6$), termed the Main Himalayan Seismic Zone, is located between the MCT and the MBT (Seeber et al., 1981; Khattri and Tyagi, 1983; Valdiya, 1992; Pandey et al., 1995; Kayal, 1996). Seismic activity in this region may be linked to the underthrusting of the Lesser Himalaya beneath the Greater Himalayan Crystallines (Seeber et al., 1981; Valdiya, 1994; Sarkar et al., 2001a, 2001b), or the low-angle thrust that separates the underthrusting Indian Plate from the Lesser Himalayan crustal block (Ni and Barazangi, 1984). In general, the middle of the Himalaya (from ~80°E to ~86°E) displays lower levels of seismicity compared to adjacent sections (Khattri and Tyagi, 1983; Pandey et al., 1999; Raval, 2000).

2.3. Rocks and structures associated with the Main Central Thrust (MCT)

The MCT closely parallels the topographic front of the Himalaya along approximately the 4-km contour (see Fig. 2 in Ni and Barazangi, 1984 or compare Figs.

2.1 and 2.2 in this chapter). Balanced cross-sections of transects across the Himalaya suggest that the MCT is the dominant crustal structure of the orogen, accommodating a minimum of 140 km to >500 km of displacement (Schelling and Arita, 1991; Srivastava and Mitra, 1994). These estimates are significant fractions of the ~1400 km of north-south shortening absorbed by the Himalayan-Tibet orogen (see Yin and Harrison, 2000).

The fault separates similar lithologies along its entire ~2400 km strike. Thus, in eastern Nepal (Fig. 2.4), central Nepal (Fig. 2.5), and northern India (Fig. 2.6), many of the same tectonic elements of the Himalaya are exposed. These include the Greater Himalayan Crystallines, High Himalayan leucogranites, the Lesser Himalaya, and inverted metamorphic isograds (e.g., Pêcher and Le Fort, 1986; Hubbard, 1989; Pêcher, 1991; Hodges et al., 1996).

2.3.1. The Greater Himalayan Crystallines

The Greater Himalayan Crystallines are mainly comprised kyanite- to sillimanite-grade gneisses intruded by High Himalayan leucogranites in structurally higher levels (e.g., Upreti, 1999). Throughout much of the range, the unit is divided into three formations (Colchen et al., 1980; Pêcher and Le Fort, 1986; Swapp and Hollister, 1991; Lombardo et al., 1993). In central Nepal (see Guillot, 1999 for a review), the upper Formation III consists of augen orthogneisses, whereas the middle Formation II are calc-silicate gneisses and marbles, and the basal Formation I are kyanite- and sillimanite-bearing metapelites, gneisses, and metagreywackes with abundant quartzite (Fig. 2.5).

The division of the package into three units mirrors the nomenclature proposed for a locale ~250 km east (Lombardo et al., 1993; Pognante and Benna, 1993; Carosi et

al., 1999a), although the assemblages differ from that of central Nepal. In eastern Nepal (Fig. 2.4), the upper unit, termed the Black Gneiss, is comprised of biotite-sillimanite paragneisses with metaconglomerates and quartzite layers. The middle unit, the Namche Migmatite Orthogneiss, contains granite-granodiorite sillimanite-bearing orthogneisses. The base, Barun Gneiss, is a complex of migmatized paragneiss with minor metabasites, calc-silicate rocks and marbles. In the Garhwal Himalaya, ~800 km west of central Nepal (Fig. 2.6), the Vaikrita Group is the analogue to the Greater Himalayan Crystallines (e.g., Ahmad et al., 2000) and consists of formations speculated to extend throughout the entire length of the Himalaya as well (Pêcher and Scaillet, 1989; Pêcher, 1991; Bhargava and Bassi, 1994; Vannay and Grasemann, 1998).

The upper and lower bounds of the Greater Himalayan Crystallines are unclear in many of regions throughout the Himalaya. A sharp break in structure and metamorphic grade is absent across the MCT (e.g., Pêcher, 1989), whereas in some localities, no discontinuity exists at the top of the slab (e.g., Stöcklin, 1980; Fuchs et al., 1988; Vannay and Steck, 1995). This observation, the unit's complex metamorphic history, and possibility of out-of-sequence thrusting at higher levels led Stöcklin (1980) to doubt the assumption of a three-tiered, laterally-continuous, tectonostratigraphic framework.

The protolith of the Greater Himalayan Crystallines is thought to be a sedimentary sequence intruded by Cambro-Ordovician granitoids (e.g., Trivedi et al., 1984; Bhargava and Bassi, 1994; Upreti and Le Fort, 1999). The depositional age is bracketed between the age of the youngest detrital zircons (~800 Ma) and granite intrusions (~500Ma) (Ahmad et al., 2000; DeCelles et al., 2000). Some workers suggest the unit was

unconformably deposited on the Lesser Himalaya (Parrish and Hodges, 1996), whereas others support a purely tectonic juxtaposition (Upreti and Le Fort, 1999; DeCelles et al., 2000).

A Tertiary history involving two metamorphic episodes has been proposed for the Greater Himalayan Crystallines in central Nepal (see Pêcher and Le Fort, 1986), and has been echoed by geologists working in the eastern Nepal (Pognante and Benna, 1993; Carosi et al., 1999b; Lombardo and Rolfo, 2000) and NW India (Metcalf, 1993). The first stage (Eocene-Oligocene) of Barrovian-type metamorphism, termed the Eohimalayan event, corresponds to the burial of the nappe beneath Asia (e.g., Pêcher, 1989). During this stage, the base of the unit reached 550-700°C and at least 8 kbar (e.g., Pognante and Benna, 1993). During the second stage (Miocene), the Neohimalayan event, the base of the formation experienced 550-600°C, whereas the top records lower pressures and/or temperatures. The Neohimalayan event has been associated with MCT slip and with the development of the High Himalayan leucogranites (Pêcher, 1989; Metcalf, 1993).

2.3.2. The South Tibetan Detachment System (STDS)

The STDS has been reported at many localities in the Himalaya, separating rocks of the Greater Himalayan Crystallines in the footwall from metasediments of the Tethys sequence in the hanging wall (e.g., Burg and Chen, 1984; Burg et al., 1984; Burchfiel et al., 1992). In eastern Nepal, the fault consists of a lower ductile shear zone and an upper low-angle brittle fault, with the basal structure considered the principal extensional feature (Carosi et al., 1996, 1998, 1999a, 1999b; Searle, 1999). The analogue to the

STDS in the Garhwal Himalaya is the Jhala Normal Fault (Pêcher and Scaillet, 1989; Metcalfe, 1993; Searle et al., 1993).

The presence of the STDS in central Nepal is debated. Along the Marysandi River transect, augen gneisses of the Greater Himalayan Crystallines show a tectonically transitional relationship with limestone of the Tethys sediments (e.g., Bordet et al., 1975; Schneider and Masch, 1993) and metamorphic grade remains unchanged across the fault (see Fig. 2.5). Temperature continuously decreases across the Greater Himalayan Crystallines to the Tethys Formation (Schneider and Masch, 1993), and stratigraphy and lithology exclude a distinct fault boundary (Fuchs et al., 1988). Formation III may be the core of a huge recumbent anticline between the similar carbonate lithologies of Formation II and the lower structural levels of the Tethys Formation (Bordet et al., 1975; Fuchs et al., 1988, 1999). This is in contrast to the views of several workers who place a detachment fault between the open folding of the Tethys and the homoclinal structure of the Greater Himalayan Crystallines (Brown and Nazarchuk, 1993; Schneider and Mash, 1993; Coleman, 1996a; Coleman and Hodges, 1998; Le Fort and Guillot, 1998). In central Nepal (Fig. 2.5), the Manaslu Intrusive Complex records extensional structures (Le Fort, 1975; Guillot et al., 1993). Whether these structures are associated with significant slip along the STDS remains unknown.

In other localities across the range front, including near Kathmandu (Stöcklin, 1980) and NW India (Fuchs, 1986, 1987; Fuchs and Linner, 1995; Vannay and Steck, 1995), the Greater Himalayan Crystallines show no evidence of a tectonic juxtaposition with the Tethys metasediments. Fuchs (1986) suggests a stratigraphic passage from the

crystallines to the Tethyan strata is the rule for the Himalayan range. The STDS may be a local phenomenon, occurring when the Tethys dissociated from the Greater Himalayan Crystallines and slid along N-dipping planes due to gravity following uplift (e.g., Pêcher and Le Fort, 1986; Fuchs, 1987). Alternatively, the STDS has been proposed to exist in some locations as a reactivated thrust, primarily based on field observations show extensional structures overprinted by mylonitic compressional fabrics. These areas include, Himachal Pradesh, NW India (Vannay and Grasemann, 1998), Zaskar, NW India (Patel et al., 1993), and the Kali Gandaki, central Nepal (Vannay and Hodges, 1996).

Along the Kali Gandaki drainage (see Fig. 2.1), Godin et al. (1999a, 1999b) suggest the north-east verging folds of the Tethys Formation developed prior to ductile extension along a shearing system, and record some of the earliest contraction of this part of the orogen. Others interpret these folds, reported also in the Greater Himalayan Crystallines in the Garhwal (Bhargava and Bassi, 1994) and eastern Nepal (Carosi et al., 1999b), to result from gravity sliding along the STDS (e.g., Burchfiel et al., 1992; Hodges et al., 1996; Vannay and Hodges, 1996).

2.3.3. The Lesser Himalaya Formations and the MCT

The Lesser Himalaya is mainly comprised of Gondwana sediments (e.g., Tripathi and Singh, 1987) that experienced granite intrusion at ~1800 Ma (e.g., Trivedi et al., 1984). In many locations along the range front, the metamorphic grade within the Lesser Himalaya increases towards the MCT and higher structural levels (i.e., inverted metamorphism, (Ray, 1947; Pêcher, 1989). For example, in central Nepal, the

metamorphic grade increases from low (chlorite + biotite) to medium (biotite + garnet + kyanite \pm staurolite) towards the MCT over a north-south distance of \sim 20 km (Fig. 2.5). The highest-grade rocks (kyanite and staurolite gneisses) are found within the MCT shear zone (=upper Lesser Himalaya). Understanding the origin this phenomenon has implications for establishing the role of various crustal heat sources and mechanisms of heat transfer within collisional belts (e.g., radiogenic, asthenospheric input, shear heating, addition of melts).

Lack of an obvious break in metamorphic grade between Greater Himalayan Crystallines and Lesser Himalaya makes the placement of the boundaries of the MCT shear zone difficult to discern. U-Pb and Sm-Nd studies of zircon grains show the sedimentary provenance of the Lesser Himalaya is \sim 1 Ga older than the Greater Himalayan Crystallines (Parrish and Hodges, 1996), and the two units are differentiated based on their Nd and Sr isotope systematics, thus Ahmad et al. (2000) suggest the use of geochemical aids for MCT placement.

Pêcher (1989) adopted three criteria to identify the MCT in the field: (1) the boundary between hanging wall gneisses and upper carbonate-rich formations of the Lesser Himalaya, (2) where Lesser Himalaya shear fabric (L-S) is replaced by the flattening fabric of the Greater Himalayan Crystallines, and (3) where the rotational deformation that increases progressively through the Lesser Himalaya reaches a maximum. In central Nepal, Arita (1983) places two thrusts (MCT-I and MCT-II) on each side of the MCT shear zone (Fig. 2.5). The MCT-II corresponds to that described by Pêcher (1989), whereas the MCT-I separates a mylonitic augen gneiss from other

Lesser Himalaya metasedimentary rocks. Some researchers do not recognize the MCT-I anywhere in the Nepal Himalaya (see Upreti, 1999).

Along the Dudh Kosi-Everest transect (see Fig. 2.4), the MCT corresponds to the contact between the Greater Himalayan Crystallines gneisses and the upper Lesser Himalaya pelitic schists, whereas the MCT-I separates the mylonitic Phaplu augen gneiss from low-grade Lesser Himalaya metasedimentary rocks. Along the Bhagirathi River, Garhwal region, the Vaikrita Thrust (=MCT) and Munsiri Thrust (=MCT-I) bound the MCT shear zone (Fig. 2.6), but no equivalent to the Phaplu augen gneiss is exposed (e.g., Valdiya, 1980; Pêcher, 1991; Metcalfe, 1993; Searle et al., 1993; Ahmad et al., 2000; Singh and Thakur, 2001). As in eastern Nepal, no obvious break in metamorphic grade exists across the fault, and an inverted metamorphic sequence characterizes the footwall (Metcalfe, 1993; Ahmad et al., 2000).

2.4. Previous Work

2.4.1. Geochronology

The Himalayan mountain range has been the recent target of several workers seeking to understand its evolution. From the NW India to eastern Nepal, numerous rock-collecting expeditions have been conducted across the MCT, and the samples analyzed using a variety geochemical techniques, including $^{40}\text{Ar}/^{39}\text{Ar}$, U-Th-Pb, U/(Th-He), and fission track. These studies suggest (1) the Greater Himalayan Crystallines experienced metamorphism from Eocene to Miocene and (2) the MCT shear zone

contains Pliocene $^{40}\text{Ar}/^{39}\text{Ar}$ mica and apatite fission track ages. See Fig 2.1 for approximate locations of the drainages mentioned below.

Studies of U- and Th- bearing accessory minerals and $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of mica and hornblende, primarily conducted for rocks from the Greater Himalayan Crystallines, suggest the MCT was active in the Early Miocene. For example, Hodges et al. (1996) report ~23 Ma zircons from a Greater Himalayan Crystallines Formation II pegmatite collected along the Modi Khola, central Nepal. Along the Kali Gandaki drainage in central Nepal, monazite grains separated from a pegmatite that crosscuts the Greater Himalayan Crystallines Formation I, and thorite grains from a folded Formation II leucogranite yield ~21 Ma ages (Nazarchuck, 1993). Coleman (1998) reports ^{235}U - ^{207}Pb monazite ages separated from a migmatitic pelitic schist from the MCT shear zone along the Marysandi River (central Nepal) that range from 20.5-30.5 Ma, whereas monazite from a foliated migmatitic Greater Himalayan Crystallines leucogranite crystallized ~22 Ma.

In eastern Nepal, Miocene (17-21 Ma) $^{40}\text{Ar}/^{39}\text{Ar}$ ages of Greater Himalayan Crystallines mica and hornblende grains are linked to MCT slip and uplift of the range (Kaneoka and Kono, 1981; Hubbard and Harrison, 1989). Similar Miocene $^{40}\text{Ar}/^{39}\text{Ar}$ ages of muscovite are reported for the Greater Himalayan Crystallines in NW India (16-11 Ma, Oliver et al., 1995; 14-22 Ma, Metcalfe, 1993), central Nepal (13-15 Ma, Vannay and Hodges, 1996), and Bhutan (14-11 Ma, Stüwe and Foster, 2001). Sakai et al. (1999) reports a $^{40}\text{Ar}/^{39}\text{Ar}$ biotite age of 25.7 ± 0.1 Ma for a gneiss from lower structural levels of the Greater Himalayan Crystallines from the western Nepal Himalaya. The last

deformation event along the MCT has been suggested to occur during this time (e.g., Schelling and Arita, 1991; England et al., 1992).

The emplacement of High Himalayan leucogranites along the range front occurred during the Miocene as well. For example, in eastern Nepal, monazite grains from these granites yield 23.0 ± 1.0 Ma (Makalu, Schärer, 1984) and 20.3 ± 0.3 Ma (Everest, Simpson et al., 2000), similar to ages reported in central Nepal (Nyalam, 17.2 ± 0.9 Ma, Schärer et al., 1986; Manaslu, 19.3 ± 0.3 Ma, Harrison et al., 1999b; Shishi-Pangma, 20.2 ± 0.2 Ma, Searle et al., 1997), and NW India (Zaskar, 20.0 ± 0.5 Ma, Noble and Searle, 1995).

Monazite grains from the Greater Himalayan Crystallines contain a significant inherited Oligocene-Eocene component (Hodges et al., 1996; Edwards and Harrison, 1997; Coleman, 1998; Coleman and Hodges, 1998). For example, Hodges et al. (1996) report normally and reversely discordant U-Pb ages of four multigrain monazite fractions from a kyanite-bearing Formation I leucosome ranging between 22.5 and 37.6 Ma, and suggest the monazite aliquot records a crystallization at ~ 22.5 Ma. The Oligocene ages of these grains may be associated with the Eohimalayan event, the metamorphic or magmatic episode that occurred prior to slip along the MCT (Hodges et al., 1996). U-Pb ages of monazite grains separated from samples collected in higher structural levels of the Greater Himalayan Crystallines in eastern Nepal are interpreted as evidence that ~ 20 -25 m.y. elapsed between the Eohimalayan event and subsequent exhumation and granite emplacement (e.g., Coleman, 1998; Walker et al., 1999; Foster, 2000; Simpson et al., 2000).

Along the Marysandi River, Coleman and Hodges (1998) report $^{40}\text{Ar}/^{39}\text{Ar}$ biotite ages from gneisses collected from the Greater Himalayan Crystallines Formation III of 17-14 Ma, whereas the Tethys Formation micas are older at 30-27 Ma. They view this age difference as clear evidence of a STDS-type structure in central Nepal, contradicting field observations that support no evidence of extension along the Marysandi River transect (e.g., Fuchs et al., 1999). Geochronologic analyses of deformed leucogranite plutons in the Zaskar Shear Zone of NW India suggest this strand of the STDS was active 22.2-19.8 Ma (Dèzes et al., 1999). Th-Pb monazite ages of the Manaslu Intrusive Complex, which cross-cuts extensional structures in central Nepal, was emplaced during two episodes at ca. 23 and 19 Ma (Harrison et al., 1999b). Movement on the STDS in northern Bhutan occurred at 12.5 ± 0.4 Ma (Edwards and Harrison, 1997).

In central Nepal, biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the Greater Himalayan Crystallines increase progressively to the north from 3.8 ± 0.1 Ma above the MCT to 14.9 ± 0.2 Ma at the Greater Himalayan Crystallines-Tethys Formation boundary (Copeland et al., 1991). The youngest mica ages include those collected from the MCT shear zone: 3.4 ± 0.4 Ma muscovite age along the Burhi Gandaki (Copeland et al., 1991) and 2.9 ± 0.1 Ma biotite age along the Marysandi transect (Edwards, 1995). Copeland et al. (1991) suggested the Pliocene mica ages in central Nepal were the result of thermal resetting from hot fluids that infiltrated the MCT shear zone, whereas Macfarlane (1993) proposed a late-stage brittle deformation event in the Langtang region.

Apatite U-Th/He ages from samples collected from upper structural levels of the MCT hanging wall and shear zone along the Dudh Kosi-Everest transect are Late

Miocene (6 ± 4 Ma) and Pliocene (4.6 ± 0.2 Ma), but a sample from lower levels of the Greater Himalayan Crystallines yields a Pleistocene (0.8 ± 0.1 Ma) age (Hubbard and House, 2000). Hubbard and House (2000) interpret the younger age to reflect post-MCT movement on a localized fault or the influence of late-stage hydrothermal fluids. In the Himachal Pradesh region, apatite fission track ages for the basal sections of the Greater Himalayan Crystallines are 4.9 ± 0.2 Ma, whereas a sample from the MCT shear zone is younger at 2.7 ± 0.4 Ma (sample specific closure temperature $130\pm 20^\circ\text{C}$; Jain et al., 2000). Sorkhabi et al. (1996) report ~ 2 Ma fission track ages for apatite collected from the Gangotri granite. Stüwe and Foster (2001) report a 3.1 ± 0.6 Ma apatite fission track age from a sample collected from the MCT hanging wall in Bhutan and suggest the result times low-temperature cooling and final exhumation of the thrust in this area.

Late Miocene Th-Pb monazite ages characterize samples collected within the inverted metamorphic sequence adjacent to the MCT along transects in central Nepal (Harrison et al., 1997b). The ages led Harrison et al. (1997b) to conclude the MCT shear zone was active at ~ 6 Ma, significantly later than the Early Miocene deformation suggested by timing constraints from the hanging wall.

2.4.2. Thermobarometry

Previous thermobarometric studies of the Greater Himalayan Crystallines (1) imply maximum temperatures of ~ 600 to 700°C at the MCT, (2) suggest the entire section is nearly isothermal, and (3) show a lithostatic pressure gradient (e.g., Hodges et al., 1988; Hubbard, 1989; Inger and Harris, 1992; Pognante and Benna, 1993; Macfarlane, 1995; Vannay and Hodges, 1996).

Figure 2.7 shows the remarkable lateral continuity of pressures and temperatures reported for 11 transects across the Himalaya. In general, the peak pressures recorded by the Greater Himalayan Crystallines decrease from 6-12 kbar at the MCT to 3-4 kbar closer to the STDS. For instance, along the Darondi Khola, Hodges et al. (1993) report 7 ± 1 kbar and $700\pm 50^\circ\text{C}$ from a sample collected at the MCT, and 4 ± 1 kbar and $590\pm 20^\circ\text{C}$ near the Greater Himalayan Crystallines-Tethys Formation contact. Along the Marysandi River, Coleman (1996b) reported estimates of 12 ± 1 kbar and $660\pm 50^\circ\text{C}$ at the MCT decreasing to 6 ± 1 kbar and $600\pm 60^\circ\text{C}$ at the top of the Greater Himalayan Crystallines. The pressure constraints resemble a lithostatic gradient (Hodges et al., 1988; Hubbard, 1989; Hodges et al., 1993) and is consistent with observations of metamorphic grade within the unit and a right-way-up metamorphic sequence.

Vannay and Grasemann (1998) report nearly isothermal temperatures of $580\pm 40^\circ\text{C}$ for 34 samples collected from the upper Lesser Himalaya and Greater Himalayan Crystallines in Himachal Pradesh region of NW India. Similar results characterize the entire section sampled at Langtang, central Nepal ($600\pm 40^\circ\text{C}$; Macfarlane, 1995). Irregular temperature profiles within the Greater Himalayan Crystallines at some localities (e.g., eastern Nepal, Fig. 2.7) has been proposed to reflect structural breaks or localized heating due to granitic intrusions (Brunel and Kienast, 1986).

Despite numerous previous studies of metamorphic assemblages in the hanging wall (see Guillot, 1999; Macfarlane, 1999 for detailed reviews), little work of this kind has been done on footwall rocks. Kaneko (1995) reported metamorphic temperatures

from rocks collected from the Greater Himalayan Crystallines and Lesser Himalaya along the Modi Khola, central Nepal. Peak footwall temperatures increase towards the fault from 400–450°C to 600–650°C over a distance of ~13 km. Here, garnet rims from the Lesser Himalaya record higher temperatures than the cores, whereas garnet rims from the Greater Himalayan Crystallines record lower temperatures than the cores. Vannay and Grasemann (1998) show pressures increasing from 6.0 ± 0.6 kbar at the MCT to 8.5 ± 0.9 kbar further south (see Fig. 2.7), suggesting a right-way-up sequence and contradicting field observations of metamorphic grade in this area.

2.5. Discussion

The primary focus of many workers has been on geochemical and petrological analyses of rocks collected from the MCT hanging wall. These studies support the uniformity of metamorphic events experienced by the Greater Himalayan Crystallines from NW India to Bhutan. The thrust is linked to the generation of many fundamental geologic elements of the Himalaya (i.e., High Himalayan leucogranites, inverted metamorphism), and to the generation of the high topography (Schelling and Arita, 1991; Srivastava and Mitra, 1994). Garnet-bearing assemblages of the Lesser Himalaya are part of an anomalous geothermal gradient that outcrops throughout the range, and contain valuable information about the chronology of deformation events related to MCT slip.

Unfortunately, the techniques previously used to obtain the geochronologic information employed mineral separation, destroying the textural relationships of the phase being dated with those used to calculate thermobarometric conditions. Himalayan

monazites typically yield highly uncertain U-Pb age results (see Nazarchuk, 1993; Coleman, 1996b; Hodges et al., 1996; Coleman, 1998). The large uncertainties may represent a significant inherited component, variable Pb loss, instrumental limitations in measuring small amounts of U and Pb, or excess ^{206}Pb due to enrichments in ^{230}Th during crystal growth (Schärer, 1984; Parrish, 1990; Coleman, 1998). These problems are minimized in the Th-Pb dating system, thus the ion-microprobe ages of monazite reported in this dissertation and elsewhere (e.g., Harrison et al., 1995, 1997b, 1999b) permit more accurate interpretations.

Some studies report thermobarometric conditions inconsistent with stability of the mineral assemblage. For example, Hubbard (1989) and Coleman (1996b) calculate pressures and temperatures of muscovite-bearing rocks that are incompatible with the presence of this mineral. Hodges and Silverberg (1988) suggest a sillimanite-bearing rock experienced maximum pressure and temperature conditions in the andalusite field. Similarly, Vannay and Grasemann (1998) and Brunel and Kienast (1986) have kyanite-bearing samples, but calculate conditions in the sillimanite field. Manickavasagam et al. (1999) report improbably precise P-T conditions (e.g., $546\pm 1^\circ\text{C}$). Recent reviews of the thermobarometric evidence provided for the Himalaya predict that a majority of samples experienced retrograde net transfer reactions, causing mineral growth and dissolution within these high-grade rocks. The pressures and temperatures reported for the garnet-bearing assemblages of the Greater Himalayan Crystallines may be erroneous by hundreds of degrees and several kilobars (Kohn and Spear, 2000).

Although the thermobarometric and geochronologic information from rocks within the inverted metamorphic sequence are important to evaluate the thermal and mechanical behavior of the orogen (e.g., England and Thompson, 1984; Ruppel and Hodges, 1994), this potential avenue into understanding the evolution of rocks affected by movement along the MCT has largely been ignored (see Fig. 2.7). The belief that additional thermobarometric analyses of rocks collected from Nepal are useless for answering any significant questions about the tectonic evolution of the Himalaya is beginning to emerge (Macfarlane, 1999; Hodges, 2000). The opinion is unacceptable in light of the present need for data to quantitatively constrain metamorphic conditions related to the MCT along strike.