CHAPTER 7. Geochronologic and thermobarometric constraints on the evolution of the MCT, central Nepal Himalaya.

7.1. Introduction

This chapter presents new thermobarometric and geochronologic data from rocks collected adjacent to the Main Central Thrust (MCT) in central Nepal. This area (Fig. 2.5) was the site of earlier studies, and ^{40}Ar/^{39}Ar mica and hornblende ages (Copeland et al., 1991; Edwards, 1995; Coleman and Hodges, 1998), U-Pb zircon, monazite and xenotime ages (Hodges et al., 1996; Coleman, 1998), and pressure-temperature (P-T) information (Hodges et al., 1988, 1993; Coleman, 1996b) are reported for rocks of the Greater Himalayan Crystallines and upper structural levels of the Lesser Himalaya. The results suggested (1) the Greater Himalayan Crystallines is a right-way-up metamorphic sequence, (2) a single episode of MCT slip, and (3) simultaneous movement along the MCT and South Tibetan Detachment (STDS).

The goal of this study is also to ascertain metamorphic P-T-t histories, but focuses on rocks from the MCT footwall inverted metamorphic sequence as well. Thermobarometric analyses were combined with *in situ* ion microprobe Th-Pb ages of monazite inclusions in garnet and within the rock matrix, and ^{40}Ar/^{39}Ar ages of muscovite grains. The additional information suggests (1) the MCT footwall records an inverted metamorphic P-T gradient, (2) MCT activity continued until at least the Pliocene, and (3) rocks collected beneath the MCT and Tethys metasediments experienced temporally distinct metamorphic episodes.

Samples were collected along two cross-strike transects in central Nepal along the Marysandi River (Figs. 4.1, 4.3) and Darondi Khola (Figs. 4.2, 4.3). See Figure 2.5 for an overview of the regional geology of central Nepal. Marysandi River transect samples are referred to as MA#, whereas those obtained along the Darondi Khola are DH#. To evaluate the possible MCT-I structural break described by Arita (1983), the rocks are divided into three domains: the Greater Himalayan Crystallines, upper Lesser Himalaya, and lower Lesser Himalaya. The uncertainty in all ages reported here is 1σ.

Upper Lesser Himalaya (= MCT shear zone) rocks were collected between the MCT and MCT-I. Based on field observations along the Marysandi River transect, Colchen et al. (1980) mapped the MCT near the town of Bahundunda (Fig. 4.1). Along the Darondi Khola, the MCT is placed at the base of the Greater Himalayan Crystalline gneisses (Fig. 4.2). The Ulleri augen gneiss that defines Arita's (1983) MCT-I appears along the Darondi Khola transect, but is absent along the Marysandi River (Fig. 4.1). The presence of the MCT-I in the Marysandi area is debated because the boundary separating upper and lower Lesser Himalayan metasediments is unclear (see Upreti, 1999). In this chapter, the MCT-I is arbitrarily assigned here as the contact between aluminous and carbonate schists of the upper Lesser Himalaya and similar rocks of the Kunchha Formation. Lower Lesser Himalaya rocks were collected below the MCT-I. Note that the presence of the STDS is debated in central Nepal (e.g., Fuchs et al., 1988).

7.2. Thermobarometry

7.2.1. Garnet X-ray element maps

Garnet is a physically refractory mineral, stable over a wide range of pressures, temperatures and bulk compositions. The mineral can retain compositional zoning that reflects its growth and reaction histories (e.g., Chakraborty and Ganguly, 1991; Spear, 1993). X-ray element maps of garnets from the Greater Himalayan Crystallines (Figs. 7.1-7.9), upper Lesser Himalaya (Figs. 7.10-7.21) and lower Lesser Himalaya (Figs. 7.22-7.27) show differences in zoning of Mn, Ca, Fe, and Mg. Compositional traverses across these garnets (Figs. 7.28-7.33) indicate the units experienced unique thermal histories, and suggest the maps and profiles are useful for delineating tectonic domains across the MCT (see also Kohn et al., 1999). For descriptions of the Darondi Khola samples, see Kohn et al. (2000).

7.2.1.1. The Greater Himalayan Crystallines. Lack of noticeable zoning within the interior of most garnets from the Greater Himalayan Crystallines (Figs. 7.1-7.9) is typical of high-grade metamorphic rocks (e.g., Tracy et al., 1976; Chakraborty and Ganguly, 1991; Florence and Spear, 1991; Spear, 1993) and is consistent with those reported from the unit elsewhere in the range (e.g., Hodges et al., 1993; Metcalfe, 1993; Kaneko, 1995; Davidson et al., 1997). Figure 7.28 and 7.33a shows compositional profiles of three garnets from the Greater Himalayan Crystallines. Almandine and spessartine within the cores are flat until the rim, where they increase slightly. This behavior of spessartine is typical of garnets from the Greater Himalayan Crystallines (see Figs. 7.1-7.9). The grossular profile of the MA45 garnet is flat, but decreases near the rims of the MA24 and MA49 garnets. MA45 and MA49 garnets decrease in pyrope and increase in Fe/(Fe+Mg) near the rim, whereas MA24 shows the opposite behavior.

High-grade garnets commonly show zoning characterized by diffusion, evidenced by an increase in almandine, spessartine, Fe/(Fe+Mg) and a decrease in pyrope from core to rim (e.g., Tracy et al., 1976; Chakraborty and Ganguly, 1991; Florence and Spear, 1991). The increase in pyrope and decrease in Fe/(Fe+Mg) seen in the MA24 garnet suggests the retention of original composition. This sample is a larger grain (~2 mm), collected further away from the MCT than the smaller garnets in MA45 and MA49 (~1 mm). The MA24 garnet may be exhumed from shallower depths compared to those closer to the MCT, and affected less by diffusion because of its larger size (e.g., Florence and Spear, 1991). The MA45 and MA49 garnet compositions are homogenized, probably due to prolonged experience at high temperature (e.g., Davidson et al., 1997).

The decrease in grossular at the rim of garnets MA24 and MA49, coupled with albite-rich plagioclase grains in these samples, suggests the garnets grew during decompression (Spear et al., 1990). X-ray element maps of garnets from MA45 show a ring of lower grossular within some of the grains (Figs. 7.7. and 7.8). The ring may result from a polymetamorphic or complicated reaction history, involving the breakdown of plagioclase or other Ca-bearing minerals in the rock (e.g., Matsumoto and Hirajima, 2000).

P-T path calculations are unwarranted for samples with garnets that yield X-ray element maps suggesting their original compositional distributions were disturbed or erased (e.g., Florence and Spear, 1991). To estimate P-T conditions experienced by these rocks, retrograde garnet rims were avoided, and data collected from areas with the lowest Mn and Fe/(Fe+Mg) values.

7.2.1.2. Upper Lesser Himalaya samples. Along the Marysandi River transect, upper Lesser Himalaya garnets show zoning patterns reflecting prograde growth, diffusional modification, or a complex reaction history. Samples MA27, MA43, MA79, and MA81 were collected near the MCT, whereas MA83 and MA33 were collected near the MCT-I. These garnets show element distributions that vary significantly, despite their classification within a single lithology (see Colchen et al., 1980).

MA27 garnets yield X-ray element maps that suggest the influence of diffusion (Figs. 7.11-7.13), similar to the Greater Himalayan Crystallines MA49 garnet. Spessartine, almandine, and pyrope increase from core to rim, whereas Fe/(Fe+Mg) decreases with a slight increase at the rim. Several garnets from MA27 show lower grossular abundance within their cores (Figs. 7.11-13), suggesting the grains grew during burial. Similar behavior is observed in garnets obtained at equivalent structural locations (MA81, Fig. 7.17), but is contrary to the higher Ca cores seen in the Greater Himalayan Crystallines (Fig. 7.28) and structurally lower samples (MA43, Figs. 7.14-7.16; MA33, Fig. 7.20; MA83, Fig. 7.21). The MA27 grossular profile plotted in Fig. 7.29 may be an artifact due to the transect location along a broken edge. Garnets in sample MA79 have flat grossular zoning (Figs. 7.18, 7.19, 7.29)

Garnet MA43 slightly increases in spessartine at the rim, suggesting the grain was influenced by retrogression (Fig. 7.29). This garnet decreases from 0.24 to 0.04 mole fraction spessartine from core to rim, and differs from the flat, <0.5 mole fraction spessartine seen in the MA27 and the Greater Himalayan Crystalline garnets. Similarly, garnet MA79 decreases from 0.20 to 0.04 mole fraction spessartine. Sample MA81 preserves a higher Mn core, with no evidence of rim retrogression (Fig. 7.17). The MA79 and MA43 garnets increase in pyrope and almandine, whereas Fe/(Fe+Mg) decreases from core to rim (Figs. 7.14-7.16, 7.18, 7.19), suggesting they grew with increasing temperature (e.g., Spear, 1993).

Samples MA83 and MA33 were collected near the MCT-I and contain <0.07 mole fraction spessartine (Fig. 7.30). The MA83 garnet increases in spessartine and Fe/(Fe+Mg) at the rim, indicating the grain retrogressed (Fig. 7.21, 7.30). The MA33 garnet has a distinct profile that spikes in spessartine, almandine, and pyrope and decreases sharply in grossular within 0.02 mm of the rim (Fig. 7.30). Garnet is the only phase that incorporates MnO to any significant degree within these pelitic bulk compositions (e.g., Spear, 1993). As the mineral grows, MnO is consumed, and the grain records a bell-shaped spessartine profile (e.g., garnet MA79, Fig. 7.29). An increase of spessartine at the rims suggests the garnet may be affected by diffusion (e.g., MA27, MA83, MA43, and the Greater Himalayan Crystalline garnets). The spike in spessartine seen in the MA33 zoning profile strongly indicates the garnet experienced a polymetamorphic history.

Upper Lesser Himalayan garnets with zoning controlled by significant retrogression, diffusional homogenization, and/or a complicated reaction history may lead to erroneous P-T paths (e.g., Florence and Spear, 1991; Frost and Tracy, 1991). Some upper Lesser Himalaya garnets preserve prograde compositions (see also Kohn et al., 1999, 2000) and P-T paths were estimated for these samples. To estimate the metamorphic conditions experienced by upper Lesser Himalaya rocks, quantitative analyses were obtained on the portion of their garnets that exhibit the lowest Mn and Fe/(Fe+Mg) values. In the case of MA33, this area is just inside the rim, outside of the Mn spike and Ca discontinuity.

7.2.1.3. Lower Lesser Himalaya samples. Lower Lesser Himalayan garnets preserve prograde zoning and signal an abrupt shift from those characterized by retrogression (e.g., Greater Himalayan Crystallines garnet MA49) or complicated reaction histories (e.g., upper Lesser Himalaya garnet MA33). Figure 7.31 shows the profiles of three lower Lesser Himalayan garnets (MA61, MA64, and MA58) collected <2 km south of the MCT-I along the Marysandi River transect, whereas those found >2 km south of the MCT-I are seen in Figure 7.32 (MA65, MA68, MA86). These garnets, and those from MA74 (Figs. 7.25, 7.26), show similar growth patterns.

Lower Lesser Himalaya garnets decrease in spessartine, grossular, and Fe/(Fe+Mg) from core to rim, expected if they formed with increasing temperature during decompression and preserved growth-related compositions (e.g., Spear et al., 1990). The zoning profiles are similar to those of the Lesser Himalaya from central Nepal reported by Kaneko (1995). Most garnets from the lower Lesser Himalaya probably underwent a simple reaction and thermal history, and their P-T paths are readily decipherable. To estimate the peak metamorphic conditions, the portion of the garnet rim that showed the lowest Mn and Fe/(Fe+Mg) values was analyzed.

7.2.2. Quantitative thermobarometric results

Figures 7.34 summarizes the maximum P-T conditions recorded by samples collected along the Marysandi River and Darondi Khola transects. The temperature of those without pressure constraints (MA79, MA83, MA64, MA68, MA58) is plotted within a range of 0-10 kbar on Figure 7.35. Figure 7.36 displays P-T paths recorded by garnets that display prograde compositional zoning patterns. Tables 7.1-7.6 report the compositional data used to estimate these conditions. For details of the Darondi Khola samples, see Kohn et al. (2000).

7.2.2.1. Peak metamorphic P-T estimates. Rocks from the Greater Himalayan Crystallines record the highest P-T conditions of 600-800°C and 8-13 kbar (Fig. 7.34, 7.35). Due to the extent of retrogression and homogenization experienced by these samples, the P-T results are a lower bound (e.g., Florence and Spear, 1991). The estimates are similar to data reported from the unit from NW India, central Nepal, and Bhutan (Hodges et al., 1993; Metcalfe, 1993; Kaneko, 1995; Davidson et al., 1997). The high-grade metamorphic conditions may reflect the Eohimalayan event, when unit was buried beneath the southern edge of Tibet.

Upper Lesser Himalaya samples collected near the MCT have higher or similar peak P-T results as those from Greater Himalayan Crystallines, whereas samples collected further away yield lower estimates (Fig. 7.35). Typically, rocks from lower Lesser Himalaya experienced the lowest P-T conditions (~525°C and ~6-7 kbar). Footwall P-T estimates increase towards the fault, and Figure 7.35 shows the apparent thermal and pressure gradients (~18°C/km; ~6 km/kbar) are inverted and significantly differ from lithospheric conditions (25°C/km; 3.7 km/kbar).

7.2.2.2. P-T paths. Figure 3.4 outlines the P-T paths predicted for two scenarios of MCT movement. All central Nepal garnets analyzed here grew with increasing temperature

(Fig. 7.36). The path estimated for the Greater Himalayan Crystallines sample MA24 increases in temperature with little change in pressure. Some Lesser Himalaya garnets record little change in pressure (DH75a/b) or decrease in pressure with increasing temperature (MA65, MA86, DH26, DH23, DH22), consistent with heating during exhumation (Fig. 3.4). Structurally lower garnets analyzed in the transects (MA61a, DH17, DH19) grew during an increase in both P-T. The change in path is consistent with a multi-slip model, in which successive footwall slivers accrete to the MCT hanging wall (see Fig. 3.4).

Samples MA61a, DH17, and DH19 reveal a structural and metamorphic discontinuity near the base of the MCT shear zone, and are far south of a suggested lithologic (~2 km; Colchen et al., 1980) and structural break (~5 km; Arita, 1983). The thermobarometric data indicates the MCT shear zone extends further south of the boundaries suggested by Arita (1983) and Colchen et al. (1980). To explore this suggestion and link the P-T results with the temporal history of these samples, *in situ* monazite Th-Pb ages and $^{40}Ar/^{39}Ar$ muscovite ages were obtained.

7.3. Th-Pb ion microprobe analyses of monazite from central Nepal

Monazite grains were analyzed from samples collected from the Greater Himalayan Crystallines (Figs. 7.37-7.43), upper Lesser Himalaya (Figs. 7.44-7.51) and lower Lesser Himalaya (Figs. 7.52-7.56) along the Marysandi River and Darondi Khola. Tables 7.7 and 7.8 summarize the age data along both transects, whereas Tables 7.9-7.11 provide analytical details.

7.3.1. The Greater Himalayan Crystallines

The structurally highest sample analyzed in this study is a garnet- and tourmaline-bearing Greater Himalayan Crystallines Formation II gneiss, collected near the base of the Tethys Formation (MA11; Fig. 4.1). This sample contains matrix monazite grains that average 41±4 Ma. The analyses lie outside the range defined by the calibration, creating a larger uncertainty (Table 7.9). The age suggests the Greater Himalayan Crystallines experienced monazite growth in structurally higher levels during the Eocene.

Monazite grains from Greater Himalayan Crystallines Formation I yield age ranges consistent with Oligocene formation followed by Pb loss. For example, Figure 7.42 shows BSE images from sample MA45 (P ~10 kbar; T ~735°C) collected <0.2 km north of the MCT. In this sample, seven spots on two matrix monazites and two spots on an inclusion in garnet were analyzed. The ages range from 37.5±0.3 Ma for the inclusion to 11.0±0.4 Ma for the matrix grain. The younger monazite grains probably experienced diffusional Pb loss, whereas the Oligocene-age inclusion was shielded from the process, maintaining a record consistent with the timing of Eohimalayan metamorphism. Evidence for suggestion comes from the higher temperatures experienced by the hanging wall (>650°C), lower radiogenic ^{208}Pb contents of the younger matrix grains (^{208}Pb*= 73-86% compared to 97-98% for the inclusion), and depth profiling measurements. Several analyses of monazite grains from sample DH68, a pegmatite located <0.2 km above the MCT along the Darondi Khola, showed Pb* diffusion profiles within ~2 μm of their surfaces (Grove and Harrison, 1999).

The youngest spot on a monazite dated from the Greater Himalayan Crystallines is 6.3±0.3 Ma from structurally lower sample MA48 (Fig. 7.43). The grain is located near a chlorite vein in the garnet, and an additional spot is older at 18.5±0.5 Ma. Monazite inclusions in the core of this garnet are Oligocene (average 27.7±0.4 Ma). The Late Miocene age may reflect Pb loss, suggested by the ~85% radiogenic ^{208}Pb content of this grain. Alternatively, the grain may have crystallized during the Late Miocene from a deforming Oligocene monazite, and the garnet captured the process.

7.3.2. Upper Lesser Himalaya samples

Early Miocene ages characterize monazite found immediately below the MCT along both drainages. For example, sample MA27 yields an average of 18±1 Ma (Fig. 7.44), and two samples along the Darondi Khola traverse (DH58 and DH71) contain ~22 Ma monazite (Figs. 7.47, 7.48). Geochronologic evidence suggest MCT activity during this time (e.g., Hodges et al., 1992; Coleman, 1998). Sample DH58a contains a 366±21 Ma core, suggesting detrital grains may provide source materials for subsequent monazite growth but have not been completely reworked.

South of the MCT, ages decrease from 9-15 Ma at higher structural levels of the upper Lesser Himalaya (DH73, DH51, DH39), to 7–8 Ma for lower samples (MA33, MA83). Monazite grains from MA83 (T ~545°C) average 8.3±0.5 Ma. In this sample, inclusions in garnet are older than grains in the matrix (Fig. 7.46), whereas monazite in sample MA33 shows the opposite behavior (Fig. 7.45). The MA33 matrix grain appears in an area where garnet resorbed, and may represent a former inclusion.

Late Miocene MA33 monazite grains are only found in the matrix or as inclusions within 0.2 mm of the garnet rim, near the area used for composition and thermobarometric analyses. An allanite grain in the core of the MA33 garnet yields a significantly older age (~270 Ma; Catlos et al., 2000) than the monazite (6.7±0.3 Ma). This fact, coupled with the garnet zoning pattern (Fig. 7.20), indicate this rock experienced a polymetamorphic history. Matrix allanite may be the source material used to precipitate monazite during the Late Miocene, and the garnet isolated allanite inclusions from participation in the process.

7.3.3. Lower Lesser Himalaya samples

Figure 7.52 is a BSE image of lower Lesser Himalaya sample MA84, collected beneath the MCT-I along the Marysandi River transect. This rock records multiple stages of monazite growth, and contains a 1.6 Ga monazite grain located <0.5 mm from a ~7 Ma monazite. The oldest grain is ~70 μm and the youngest is located in a strongly foliated region of the sample. The Proterozoic age is consistent with the assembly of the Indian continent (e.g., Balasubramaniyam et al., 1978), whereas the Late Miocene age records footwall crystallization associated with slip within the MCT shear zone. The Proterozoic grain suggests the sample experienced conditions below the monazite closure temperature. The hypothesis is supported by temperature estimates from sample MA83, collected <0.2 km above MA84 (T ~550°C), which yields ~100°C below the closure temperature of Pb in ~0.1 mm-sized monazite (Smith and Giletti, 1997).

Smaller (<40μm) MA84 monazite grains are Carboniferous and Cretaceous, suggesting they contain zones that record multiple growth stages or experienced Pb loss. The Carboniferous age may represent Pb loss from a grain that formed during the ~500 Ma Pan African event (e.g., Le Fort et al., 1986), but the Cretaceous age has no known corollary. The material needed to form the Late Miocene monazite may originate from the dissolution of these grains.

Sample MA65, collected ~2 km west of the Marysandi River, contains matrix monazite grains that range from 20±1 Ma to 9.5±0.4 Ma (Fig. 7.53). The weighted mean age is 12.1±0.2 Ma. Older ages may represent artifacts of higher amounts of common Pb (the grains are 94±5 %^{208}Pb*), or monazite growth due to Miocene MCT slip. These grains probably failed to fully reset Late Miocene MCT-related activity due to the lower P-T conditions experienced by the rock (P ~7.5 kbar; T ~510°C). Alternatively, MA65, collected ~2 km west of the main Marysandi River transect, may belong to the upper Lesser Himalaya. Unfortunately, attempts to date other lower Lesser Himalaya samples were unsuccessful (MA64a, MA74, MA71, DH16, DH19) because their monazite exhibited high ^{204}Pb^{+}/^{208}Pb^{+} ratios.

Figure 7.54 shows BSE images of monazite grains from sample MA86, located near the garnet isograd (P ~7.2 kbar; T ~535°C). Eleven spots on 7 grains yield a weighted mean age of 3.3±0.1 Ma, and are some of the youngest dated in this study. The 0.1 mm-sized monazite are found near or within biotite grains that cross-cut the fabric of the rock. High-contrast BSE images show they are unzoned. The ~3-4 Ma ages from sample MA86 indicate this portion of the MCT shear zone continued activity until at least the Pliocene. Sample MA71 (1.9±0.9 Ma) contains smaller (~20 μm), younger monazite than those in MA86. The higher uncertainty reflects a contribution of unsupported ^{208}Pb that contaminated the small amount of ^{208}Pb* in these grains.

7.4. ^{40}Ar/^{39}Ar muscovite ages from rocks along the Darondi Khola

7.4.1. Methods

High-purity concentrates of muscovite grains were separated from 20 rocks collected along the Darondi Khola MCT transect, and analyzed using the ^{40}Ar/^{39}Ar method with a VG 3600 automated mass spectrometer. These samples were irradiated in the Ford Reactor at the University of Michigan. The J factor, determined from Fish Canyon sanidine (27.8 Ma) flux monitors, is ~0.007 for all samples. About 10 mg of muscovite from each rock was step heated within a double vacuum furnace. Table 7.12 summarizes the K-Ar ages, and Tables 7.13-7.15 provides details.

7.4.2. Results

Himalayan micas typically yield ages affected by extraneous argon (see Vannay and Hodges, 1996; Coleman and Hodges, 1998; Vance et al., 1998; Stüwe and Foster, 2001), and less than half of the samples analyzed here show well-correlated arrays of ^{39}Ar/^{40}Ar vs. ^{36}Ar/^{40}Ar (see Figs. 7.57-7.59). Grains that contain uniformly distributed ^{40}Ar* produced *in situ* and a trapped atmospheric component of ^{40}Ar/^{36}Ar of ~295.5 are unaffected by radiogenic Ar introduced by physical contamination of older material. Their ages represent the cooling through the muscovite ~350°C closure temperature (Purdy and Jäger, 1976; Jäger, 1979). Unfortunately, muscovite grains with poor correlation between $^{39}Ar/^{40}Ar$ vs. $^{36}Ar/^{40}Ar$ contain unknown quantities of extraneous argon and their ages are uninterpretable.

Pliocene total gas ages from the Darondi Khola samples (Table 7.12) are similar to the youngest mica ages reported by Edwards (1995) from the Marysandi transect in central Nepal. These ages extend from ~8 km north of the MCT along the Marysandi River transect (4.6±0.1 Ma; Edwards, 1995) to the base of the Ulleri augen gneiss along the Darondi Khola (4.85±0.04 Ma). Figure 7.60 is a contour map comprised of mica ages reported for samples collected throughout central Nepal (after Copeland et al., 2000). Ages decrease northward from the Main Boundary Thrust (MBT), with the youngest (Late Miocene and Pliocene) appearing to trace the MCT. The oldest micas in this study are the structurally lowest samples collected: DH2 (116.8±0.2 Ma) and DH76 (257±1 Ma), similar to those reported for the lower Lesser Himalaya elsewhere (e.g., Copeland et al., 1991). Their post-Eocene ages indicate they represent a cooling prior to Indo-Asia collision.

7.5. Discussion

7.5.1. Thermobarometry

Garnets from the Greater Himalayan Crystallines lost their original compositions via diffusion and experienced significantly different P-T histories than those of lower Lesser Himalaya, which preserve their original element distributions. Upper Lesser Himalaya garnets show complex zoning patterns, which range from those characterized by diffusion (e.g., MA25, MA49, MA27), polymetamorphic histories (e.g., MA33) or prograde growth (e.g., MA74, MA86).

Most available thermobarometric data regarding the evolution of the MCT report hanging wall conditions (e.g., Hubbard, 1989; Inger and Harris, 1992; Pognante and Benna, 1993; Macfarlane, 1995), and the P-T results reported here are largely consistent with those estimates. New thermobarometric data in this dissertation indicates the Lesser Himalaya records an apparent inverted thermal gradient of ~18°C/km and pressure gradient of ~6 km/kbar (Fig. 7.35).

All footwall garnets grew with increasing temperature, and most record P-T paths consistent with heating during exhumation (Fig. 7.36; Fig. 3.4). Garnets in samples MA61a, DH19, and DH17 grew with increasing P-T and suggest the presence of a metamorphic and tectonic break north of the garnet isograd along the Darondi Khola and Marysandi River transects. These samples are located far south of breaks suggested by lithology (Colchen et al., 1980; Arita, 1983) and their paths are consistent with a distributed simple shear model (Fig. 3.4).

7.5.2. Geochronology

Rocks from the Greater Himalayan Crystallines typically contain monazite with a range of ages, consistent with either Miocene deformation associated with MCT slip or Pb loss from Eocene-Oligocene grains that formed during Eohimalayan metamorphism. This latter case is illustrated by the monazite inclusion in garnet from sample MA45 that yields older ages than matrix grains (Fig. 7.42). In the upper and lower Lesser Himalaya, monazite inclusions in garnet have ages similar to those in the matrix (e.g., MA33, Fig. 45), and suggest their link to garnet growth.

Samples from the lower Lesser Himalaya and those from upper Lesser Himalaya collected >5 km south of the MCT (MA33, MA83, DH38) experienced temperatures below 600°C (Fig. 7.35). A 200 μm monazite grain held at 600°C for 10 m.y. experiences less than 15% Pb loss due to diffusion (Smith and Gilletti, 1997). A ~22 Ma monazite grain would have to lose at least 60% of ^{208}Pb* to yield an apparent age of 8 Ma. To sustain this quantity of Pb loss, a 50 μm monazite grain requires 600°C for >10 m.y. (Smith and Gilletti, 1997). These calculations indicate that monazite from Himalayan samples with garnets that experienced <600°C have a strong potential to record their crystallization age.

An alternative means of Pb loss is via a dissolution/reprecipitation process, which may explain the range of monazite ages in lower Lesser Himalaya sample MA84. The striking age differences of grains in this rock (Fig. 7.52) demonstrates the advantage of an *in situ* technique for obtaining information from rocks that experienced multiple episodes of deformation and monazite growth.

The late cooling of the MCT shear zone has long been indirectly observed as Pliocene mica ages, and rationalized as late-stage brittle thrusting (Macfarlane, 1993) or products of fluid flow (Copeland et al., 1991), but the youngest monazite grains reported for rocks collected along the Marysandi River MCT transect (3.3±0.1 Ma; sample MA86) require an alternative explanation. The area affected by slip within the MCT shear zone extends from the base of the hanging wall gneisses at least to the outcrop that contains sample MA86. The garnet from this sample records temperature conditions insufficient to allow Pb loss from ~0.1 mm-sized monazite (Fig. 7.34; P ~7.2 kbar; T ~535°C). A hydrothermal origin seems unlikely because textural evidence of fluid or related alteration is absent. This sample contains coexisting allanite near the monazite grains, suggesting a reaction between the two minerals without influence from an improbable Th- or REE-bearing fluid (Fig. 7.54). The garnet from this sample preserves prograde compositional zoning (Fig. 7.27), shows no evidence of fluid inclusions or alteration, and has a bell-shaped growth profile in Mn, similar to other rocks collected from the lower Lesser Himalaya.

The oldest monazite ages from the Greater Himalayan Crystallines are from rocks collected near the base of the Tethys Formation, whereas the youngest grains are found at lower structural levels of the Lesser Himalaya Formations (Table 7.7). X-ray element garnet maps suggest that rocks found in structurally higher levels of the MCT hanging wall preserve their prograde compositions, whereas those collected near the thrust show zoning consistent with diffusional modification. The observation is consistent with thermobarometric constraints that indicate rocks from the Greater Himalayan Crystallines record a lithospheric gradient reflecting a flat-ramp thrust geometry (e.g., Hubbard, 1989).

7.6. Conclusions

Garnet-bearing assemblages were sampled adjacent to the MCT along the Marysandi River and Darondi Khola in the Annapurna region of central Nepal. Garnets from the Greater Himalayan Crystallines, upper Lesser Himalaya, and lower Lesser Himalaya differ in compositional zoning of Mn, Ca, Mg, and Fe. Thermobarometry for MCT footwall rocks record an inverted thermal gradient of ~18°C/km and apparent pressure gradient of ~6 km/kbar. P-T paths calculated for Lesser Himalaya samples that preserve prograde compositions show evidence of decompression during heating. However, structurally lower garnets grew during a P-T increase.

Th-Pb ion microprobe analyses of monazite inclusions in garnets immediately beneath the Greater Himalayan Crystallines indicate monazite growth occurred at 18±1 Ma (P ~9 kbar, T ~640°C). Pliocene ^{40}Ar/^{39}Ar muscovite ages suggest rapid exhumation of the MCT shear zone. Late Miocene and Pliocene monazite ages characterize rocks collected within the apparent inverted metamorphic strata. The youngest, more precise monazite age determined (sample MA86, 3.3±0.1 Ma; P ~7.2 kbar, T ~535°C) was obtained for a rock located near the garnet isograd (Fig. 4.1). Monazite collected near the base of the Tethys Formation record an Eocene age (41±4 Ma), dissimilar to the Miocene and Late Miocene ages yielded by monazite collected near the MCT, suggesting the rocks experienced temporally unrelated metamorphic episodes.