CHAPTER 8. Geochronologic and thermobarometric constraints on the evolution of the MCT, eastern Nepal and NW India.

8.1. Introduction

Late Miocene and Pliocene monazite from rocks in central Nepal imply large-scale reactivation of the Main Central Thrust (MCT) during this time (Harrison et al., 1997b; Harrison et al., 1998; Catlos et al., 1999; see chapter 7). The generality of the conclusion awaits confirmation of the event elsewhere in the Himalayan orogen. Towards this goal, *in situ* Th-Pb ion microprobe ages of monazite grains found as inclusions in garnet porphyroblasts and within the deformed rock matrix were obtained from samples from the Dudh Kosi-Everest region, eastern Nepal (Figs. 2.4, 4.4, 4.5), and from a locale ~800 km west, the Bhagirathi River, Garhwal Himalaya, India (Fig. 2.6). Dudh Kosi-Everest transect samples are referred to as ET# and 85H20g (see Hubbard, 1989), whereas those obtained along the Bhagirathi River are GM74 and GM85 (see Metcalfe, 1993). As outlined in Chapter 7, the rocks are divided into three domains: the Greater Himalayan Crystallines (including the Barun Gneiss and Namche Migmatite Orthogneiss), upper Lesser Himalaya, and lower Lesser Himalaya. The uncertainty in all ages reported here is 1σ.

Previous work in these areas include ^{40}Ar/^{39}Ar mica and thermobarometric data from rocks of the Greater Himalayan Crystallines and upper structural levels of the Lesser Himalaya (e.g., Hubbard, 1989; Hubbard and Harrison, 1989; Metcalfe, 1993). The pressure-temperature (P-T) conditions previously reported for the high-grade garnet-bearing assemblages collected along the Dudh Kosi-Everest transect and the Garhwal Himalaya may be affected by substantial errors (see Kohn and Spear, 2000).

In this chapter, X-ray compositional garnet maps and P-T data are only reported for four Everest transect samples (ET19, ET52, ET33, and ET45), and thirteen rocks are the focus of *in situ* monazite dating techniques. The data reveal a protracted and complex metamorphic history of the lithologies separated by the MCT, and indicate a uniformity of tectonic episodes across the range.

8.2. Thermobarometric information from garnet-bearing assemblages

8.2.1. Observations of garnet X-ray element maps

X-ray element maps of garnets from the lower Lesser Himalaya differ from those collected from the upper Lesser Himalaya and Greater Himalayan Crystallines (Figs. 8.1-8.5). Sample ET45, collected <1 km beneath the MCT-I (Fig. 8.5), is an example of a lower Lesser Himalayan garnet. The garnet has a bell-shaped profile in spessartine, with a maximum mole fraction of ~14.5 in the cores and minima of ~0.04 at the rims (Fig. 8.6), consistent with prograde growth (e.g., Spear, 1993). The grossular content and Fe/(Fe+Mg) content of the garnet are flat, but slight decreases near the rim suggest it grew with increasing temperature during exhumation.

The zoning pattern of ET45 contrasts those seen in upper Lesser Himalayan samples ET33 and ET52, or in Greater Himalayan Crystallines sample ET19 (Fig. 8.6). These garnets contain mole fraction spessartine of <0.06 within the cores that increase slightly at the rim, consistent with diffusion or retrogression (e.g., Spear, 1993).

Grossular compositions in all the garnets analyzed are flat, although ET19 shows a slight decrease from core to rim (0.04 to 0.02), suggesting this sample may contain a remnant record of exhumation. The profiles reported here are similar to garnets from the Greater Himalayan Crystallines NW India, central Nepal, and Bhutan (e.g., Hodges et al., 1993; Metcalfe, 1993; Kaneko, 1995; Davidson et al., 1997; Vannay and Grasemann, 1998; chp 7 of this study).

8.2.2. Peak metamorphic P-T estimates

Table 8.1 lists the mineral compositions and P-T results from samples ET52, ET19, ET33, and ET45. Lower lesser Himalaya sample ET52 records 680±10°C and 6.9±0.4 kbar. Sample ET33 yields 720±40°C and 10±1 kbar, whereas sample ET19, collected at higher structural levels, records a similar pressure to ET33 but higher temperature conditions of 830±75°C. The abundance of muscovite and the absence of partial melting textures in sample ET19 are inconsistent with the P-T results. Retrograde net transfer reactions that cause mineral growth and dissolution within high-grade rocks may significantly affect these garnets and result in erroneous P-T estimates (Kohn and Spear, 2000). Matrix biotite grains near ET33 and ET19 garnets show lower Fe/(Fe+Mg) than those collected further away (0.68 to 0.62 for ET33; 0.50 to 0.48 for ET19), and the rims of these garnet increase in Fe/(Fe+Mg) (see Fig. 8.6). The observations suggest the samples are significantly affected by retrogression.

Sample ET45 yields a garnet-chlorite temperature of 550±20°C (at P= 3-8 kbar, see Table 8.1). Unfortunately, monazite is absent in sample ET45 and is not found in samples collected near this rock. Allanite appears as the only rare-earth bearing accessory mineral, and attempts to date grains using the Th-Pb ion microprobe methods outlined in Catlos et al. (2000) were unsuccessful due to high common Pb concentrations.

8.2.3. P-T paths

Sample ET33 and ET52 contain biotite inclusions (Fig. 8.7, 8.8), allowing core temperatures to be estimated using the flat garnet core composition and inclusions. ET33 has a long, thin, zoned plagioclase grain that extends from the garnet core to rim (Fig. 8.7). In an attempt to discern the P-T path this rock followed, core pressures were also calculated using this inclusion along with biotite inclusions (e.g., St. Ogne, 1987). For ET52, plagioclase inclusions are not found, but matrix plagioclase is compositionally zoned (Table 8.1, Fig. 8.4). For this rock, core pressure was calculated using the matrix plagioclase core composition and biotite inclusions.

Thermobarometric calculations using garnets that appear affected by diffusion can create misleading results (e.g., Florence and Spear, 1991), but the ET52 biotite inclusion is rimmed by quartz, so we assume diffusional exchange of Fe and Mg did not significantly affect the biotite composition. This assumption may be invalid, because the biotite inclusion compositions for both samples ET52 and ET33 are more Mg rich than those within the matrix, indicating the temperature reported here is erroneous and lower than actually experienced by the rock (e.g., Spear and Peacock, 1989). This idea is supported by detailed compositional traverses along the garnet for ET33 show the garnet increases in Fe/(Fe+Mg) from 0.880 to 0.898 nearing the biotite (Fig. 8.7). To estimate core temperatures, the lowest garnet Fe/(Fe+Mg) nearest to the biotite inclusion was taken along with the highest Fe/(Fe+Mg) biotite inclusion compositions (Table 8.1).

Figure 8.9 displays the P-T paths followed by samples ET52 and ET33. These rocks were collected ~2 km apart within the upper Lesser Himalaya (Fig. 4.4), but follow opposite directions within P-T space. ET52 increases in P-T, whereas ET33 follows a retrograde path. The numerical estimates fall within the sillimanite field for ET52, but not for ET33, consistent with the observed mineral assemblages.

8.3. Th-Pb ion microprobe analyses of monazite

Table 8.2 summarize geochronologic data, whereas Tables 8.3-8.5 provide details. BSE images of the monazite grains dated in this study are shown in Figures 8.7-8.22. Their ages reveal a protracted and complex metamorphic history of these lithologies, which extend from the Paleo-Mesoproterozoic to the Late Miocene. Attempts to link the geochronologic data to deformation events affecting these samples are described below. All Th-Pb ion microprobe monazite ages are quoted at the level of 1σ.

8.3.1. Paleo-Mesoproterozoic (2500-900 Ma): the Assembly of India

The Indian subcontinent is a complex of unique tectonic and stratigraphic terranes, which were juxtaposed along sutures during different periods of the Earth's history (e.g., Radhakrishana, 1989). In the Precambrian, components of the continent existed as the northern Bundelkhand Block, the southern South Indian Block, and the eastern Trans-Aravalli Block (e.g., Balasubramaniyam et al., 1978). Contrasting paleomagnetic and other geologic signatures from these blocks indicate they each record an isolated, unrelated evolution on different lithospheric plates during the Proterozoic (Qureshy and Iqbaluddin, 1992). For example, paleomagnetic data from the Cuddapah basin in the

South Indian Block and the Vindhyan Basin in the Bundelkhand Block suggest these coeval basins evolved in the southern and northern hemispheres, respectively (Reddy and Prasad, 1979).

The South Indian Block and the Bundelkhand Block collided ~900 Ma along the Satpura Suture Zone (SSZ; a.k.a the Narmada-Son lineament), a prominent tectonic feature of the Indian Shield trending from the west coast of India to the eastern side (Mishra, 1992; Qureshy and Iqbaluddin, 1992; Rao et al., 1992). The SSZ is active, characterized by heat flow and present-day seismicity comparable to that of the convergent Himalayan boundary (Bhatia et al., 1999).

The oldest ages reported for monazite in this study are from matrix grains analyzed in a rock collected within the Phaplu augen gneiss (sample ET38; Fig. 8.22). This augen gneiss unit outcrops in central Nepal as well (Colchen et al., 1980). Spots on monazite grains in ET38 yield ages of 901±13 Ma to 1566±49 Ma, similar to those reported for a Lesser Himalayan monazite grain from central Nepal (1672±30 Ma; see Fig. 7.52) and zircon ages from an equivalent augen gneiss (~1831 Ma; DeCelles et al., 2000). Paleoproterozoic whole-rock Rb-Sr ages are also reported for Lesser Himalayan rocks from the Garhwal region (1907±91 Ma; Ahmad et al., 1999). These ages reflect tectonic events related to, or older, than the assembly of India.

8.3.2. Cambro-Ordovician (440-544 Ma): Suturing of India to Gondwana

Another episode that influenced the tectonic design and sedimentation history of the Himalaya was the Pan-African event, which has been well-described in Africa and western Europe (Duppert et al., 1990; Rabi et al., 1990). The Indian Pan-African event is characterized by an abrupt cessation of a long, almost unbroken cycle of Proterozoic sedimentation towards the end of the Lower Cambrian (Fuchs, 1968; Garzanti et al., 1986), and extensive emplacement of 500±25 Ma granite bodies (Le Fort et al., 1986).

Gondwana sediments are present in two domains within the Himalaya: the Lesser Himalaya and the Tethys Formation (Tripathi and Singh, 1987). During the Cambrian, the Lesser Himalaya and Peninsular India were characterized by a wholesale suspension of sedimentation, whereas the Tethys Formation experienced an interruption in basin-filling (Valdiya, 1993). The sedimentary evidence suggests the presence of the Pan-African orogenic event in the northwestern Himalaya during which time the Indian shield gradually rose from the ocean. The Lesser Himalaya emerged towards the close of the Lower Cambrian, whereas the Tethys marginal basin surfaced in the late Upper Permian (Valdiya, 1995). Due to the gap in deposition, the position of Gondwana during the Cambrian to Triassic is uncertain (e.g., Smith, 1999).

Cambro-Ordovician granite bodies are present throughout the Himalayan realm (Le Fort et al., 1986; Valdiya, 1993), and monazite grains of this age range are reside in rocks of the Greater Himalayan Crystallines. For example, a 548±17 Ma monazite inclusion in garnet is found in Namche Migmatite Orthogneiss sample ET19 (Fig. 8.13), whereas a monazite inclusion from Barun Gneiss sample ET26 yields 436±8 Ma (Fig. 8.17). The 141-246 Ma matrix monazite grains within ET19 may reflect a 500 Ma grain that lost Pb, or overlapping analyses on grains that experienced subsequent growth or dissolution. These grains may be source materials for monazite precipitation during subsequent metamorphism.

Cambro-Ordovician mineral ages appear within the Greater Himalayan Crystallines elsewhere in the range. For example, in the Himachal Himalaya, Rb-Sr whole rock ages are 545±12 Ma and 311±6 Ma (see Bhargava and Bassi, 1994). Sm-Nd isotopic analyses on garnets and whole rocks from the Garhwal region yield 534±24 Ma (Argles et al., 1999) and monazite grains collected in the northwest Himalaya have an average U-Pb age of 467±3 Ma (Foster, 2000). An allanite inclusion in garnet from the MCT shear zone in central Nepal gave a Th-Pb age of 445±16 Ma (Catlos et al., 2000).

8.3.3. Eocene-Oligocene (54-24 Ma): Indo-Asia collision to the Eohimalayan phase

During the Cretaceous to the Eocene, India separated from Gondwana and drifted ~4000 km northward at rates of 15-20 cm/yr (Klootwijik et al., 1985; Royer and Sandwell, 1989). Paleomagnetic data suggest suturing was complete by 55-50 Ma (e.g., Patzelt et al., 1996). Remnants of the metamorphic history of the Greater Himalayan Crystallines since Eocene are reported as Oligocene garnet ages (33-28, Vance and Harris, 1999; ~42 Ma, Foster, 2000), and U-Pb ages of monazite grains (33-29, Walker et al., 1999; 36-25 Ma, Foster, 2000; ~32 Ma, Simpson et al., 2000). These ages may record the Eohimalayan event, in which the protolith of the Greater Himalayan Crystallines buried beneath the southern edge of Asia (e.g., Le Fort, 1996).

The Th-Pb monazite ages reported here support the idea that metamorphism within the Greater Himalayan Crystallines in eastern Nepal began soon (~5-10 m.y.) after the final suturing of India to Asia. A monazite inclusion in garnet from Greater Himalayan Crystallines sample ET26 is 45.8±2.8 Ma, and a matrix monazite in this rock is a more precise 44.5±0.9 Ma (Fig. 8.17). In sample ET18b matrix monazites are

39.5±0.8 and 33.5±1.2 Ma (Fig. 8.12). These ages indicate the Greater Himalayan Crystallines were rapidly metamorphosed to temperatures that allowed monazite crystallization (i.e., 4-8 mm/yr assuming a 30° ramp and monazite formation at ~500°C).

Monazite inclusions in garnet with ages close to the Oligocene-Miocene boundary (~23 Ma) are also found in several Greater Himalayan Crystallines rocks. For example, sample ET22 contains monazite inclusions that are 28.1±0.5 to 23.0±0.7 Ma (Fig. 8.14). The textural relationship between monazite and allanite coexisting the crack of the ET22 garnet implies that monazite formation in this sample relates to allanite breakdown. Matrix monazite grains from ET12 fall in this age range at 25.3±0.5 to 23.3±0.8 Ma (Fig. 8.11), whereas ET18b average 23.4±0.9 Ma (Fig. 8.12). Samples ET23b and ET25 also contain 23-29 Ma monazite grains (Figs. 8.15, 8.16), and sample ET26 (Fig. 8.17) contains a 23.9±0.4 Ma monazite inclusion in garnet. These ages are consistent with geochronologic studies suggesting the MCT was active at that time (e.g., Hodges et al., 1996).

8.3.4. Miocene (24-5 Ma): Neohimalaya and MCT shear zone activity

Miocene monazite grains appear within the Greater Himalayan Crystallines as well. For example, ET18b contains monazites that range in age from 21.2±1.1 Ma to 17.3±0.9 Ma (Fig. 8.12), ET22 has a 19.4±0.5 Ma inclusion in garnet (Fig. 8.14), and sample ET25 contains a 17.9±0.4 Ma matrix grain (Fig. 8.16). These ages could reflect ~10-20% Pb loss from a 23 Ma grain, which could be achieved if a 100 μm monazite experienced a temperature of ~650°C for ≤5 m.y. (Smith and Gilletti, 1997).

Oligocene monazite grains are noticeably absent from rocks collected within the upper Lesser Himalaya in eastern Nepal. These samples contain several monazite grains that average ages of 13.0±1.2 Ma (85H20g; Fig. 8.20), 14.5±0.4 Ma (ET52; Fig. 8.18), and 15.5±1.5 Ma (ET33; Fig. 8.19). Monazite grains in 85H20g are 30-50 μm in size, and thermometric calculations indicate the rock experienced a maximum temperature of 530±50°C (Hubbard, 1989). A 23 Ma monazite grain would have to lose ~40% of its radiogenic Pb to yield a 14 Ma age. Pb diffusion in monazite studies require a 50 μm grain to be held at 600°C for ~10 m.y. to experience this amount of Pb loss (Smith and Gilletti, 1997). Therefore, the ~14 Ma monazite grains in sample 85H20g (Fig. 8.20) likely date their occlusion by the garnet.

Further support for this suggestion comes from the monazite inclusions in garnet for samples ET52 and ET33, collected within the Lesser Himalaya along the Dudh Kosi-Everest transect. These garnets experienced P-T paths that show opposite trajectories (Fig. 8.9). Garnet ET52 has a P-T consistent with burial and has a rim monazite that yields a Th-Pb age of 13.9±0.5 Ma. Garnet ET33 shows an exhumation path and the core monazite is 16.4±2.2 Ma. These ages reflect the time the monazite grain incorporated into the growing garnet. The weighted mean age of all the monazite grains in samples ET33, ET52, and 85H20g (n= 24 ion microprobe spots) is 14.1±0.1 Ma (MSWD= 8.4), indicating the MCT shear zone was active in eastern Nepal at this time.

The ~14 Ma monazite grains appear within the Greater Himalayan Crystallines as well. For example, sample ET12 contains a 14.5±0.7 Ma inclusion in garnet and two ~14 Ma matrix monazite grains (Fig. 8.11). This rock was collected within large-scale

Greater Himalayan Crystallines fold and support the hypothesis that these features formed due to compression related to MCT shear zone activation (e.g., Godin et al., 1999a, 1999b). Sample ET23b collected near the town of Ghat contains a 15.0±0.2 Ma matrix monazite grain (Fig. 8.15). Rocks collected near ET23b yield anomalously young $^{40}Ar/^{39}Ar$ muscovite age (7.7±0.4 Ma) and U-Th/He apatite age (0.8±0.1 Ma) compared to other samples along this transect, leading Hubbard and House (2000) to propose the existence of a small-scale shear zone at this locality. The nearest structure is a normal fault within the Greater Himalayan Crystallines reported ~4 km north of ET23b (Carosi et al., 1999b).

To explore the link between MCT fault slip and leucogranite generation, we also dated monazite within a tourmaline-bearing High Himalayan leucogranite. Eight matrix monazites in this sample (ET7) yield an average age of 20.2±0.6 Ma (Fig. 8.10). This ~20 Ma age is similar to those reported for the High Himalayan leucogranite from Everest (20.3±0.3 Ma; Simpson et al., 2000), and elsewhere along the range front (Zanskar, India, 20.0±0.5 Ma, Noble and Searle, 1995; Shishi-Pangma, eastern Nepal, 20.2±0.2 Ma, Searle et al., 1997; Manaslu, central Nepal, 19.3±0.3 Ma, Harrison et al., 1999b), and attest to the remarkable continuity of granite emplacement along the range front.

The youngest monazite ages reported in this study are from sample GM74 collected within the MCT shear zone in the Garhwal Himalaya (Fig. 8.21). This rock contains six matrix monazite grains that yield a weighted mean age of 5.9±0.2 Ma (MSWD= 0.4). The grains were large (~100 μm), and at least two ion microprobe spots could be placed on each (Table 8.2; Fig. 8.21). P-T calculations suggest this rock experienced conditions below the closure temperature of Pb in monazite (Metcalfe, 1993; Smith and Gilletti, 1997). The ~6 Ma age is similar to those found in rocks collected at the same structural location in central Nepal (e.g., Harrison et al., 1997b), and indicate that post-Early Miocene activity within the MCT shear zone occurred along two transects separated by a distance of ~800 km.

8.4. Discussion

8.4.1. Thermobarometry

Rocks from the Greater Himalayan Crystallines and lower Lesser Himalaya are differentiated based on compositional traverses along their garnets. Although the P-T paths for samples reported here (Fig. 8.9) are subject to uncertainty because of the difficulty in evaluating the thermobarometric conditions of garnets affected by diffusion (e.g., Florence and Spear, 1991; Kohn and Spear, 2000), their shapes suggest two different modes of tectonic activity occurred within the MCT shear zone. The ET52 garnet, collected immediately beneath the MCT, records a path consistent with burial, whereas the ET33 garnet, collected <1 km south, reveals the opposite trajectory. The monazite inclusion in the garnet core of ET33 is 16.2±2.2 Ma, and is within 1σ of the monazite inclusion in the rim of ET52 (13.9±0.5 Ma). The precise age of a monazite inclusion in the ET52 garnet provides a P-T-time constraint, and suggests an average exhumation rate of ~2 mm/yr.

8.4.2. Geochronology

In situ analysis of monazite grains collected along the two drainages lead to the conclusion that post-early Miocene activity within MCT has occurred along two transects separated by ~800 km. The discovery that ~7 Ma MCT footwall monazite grains (Harrison et al., 1997b) are not unique to central Nepal has implications for those seeking to model Himalayan evolution and partition the amount of convergence accommodated by structures created by the Indo-Asian collision.

Monazite inclusions in garnet seen in Figure 8.17 clearly illustrate the utility of an *in situ* technique. This garnet is so fragmented that the P-T history appears unrecoverable, but the three monazite inclusions of different age (436±8 Ma, 45.8±2.8 Ma, and 23.9±0.4 Ma) provide a glimpse into its polyphase evolution. This could only be elucidated by directly dating each monazite grain, and attaching significance to the ion microprobe spot age. The benefit of the approach increases if the thermobarometric conditions of the rock can be extracted (Fig. 8.9), because the timing of metamorphism can then be either directly dated or constrained.

Rocks exposed along the Dudh Kosi-Everest transect in eastern Nepal experienced several deformation events. The Phaplu augen gneiss contains Paleo-Mesoproterozoic monazite grains that represent episodes related to or preceding the assembly of the Indian subcontinent. Cambro-Ordovician monazite grains are located within the Greater Himalayan Crystallines, supporting the field observations that the unit's protolith may be clastic sediments intruded by granitic bodies during Pan African orogeny (Pognante and Benna, 1993; Carosi et al., 1999a).

An alternative hypothesis based on detrital zircon ages elsewhere in Nepal implies that these grains are related to Paleozoic movement along the MCT (DeCelles et al., 2000). This explanation reduces the amount of post-Eocene slip accommodated by the fault, and weakens its role in the total Indo-Asian convergence budget. However, the ~500 Ma monazite grains were absent in the footwall lithologies, and only found within hanging wall units: the Barun Gneiss and Namche Migmatitic Orthogneiss. Petrologic observations of these units strongly support the former, simpler explanation. The ~500 Ma grains may be the remnants of an intruded Pan-African granite and acted as source material for subsequent monazite growth within the Greater Himalayan Crystallines.

The presence of ~45 Ma monazite grains within rocks of the Barun Gneiss suggests subduction under Asia to conditions conducive to monazite crystallization relatively soon (~5-10 Ma) after final suture (50-55 Ma; Patzelt et al., 1996). The duration of the Eohimalayan event remains speculative, but the extensive presence of ~23 Ma monazite grains, consistent with estimates of MCT slip reported elsewhere (e.g., Hodges et al., 1996), support a 27-32 m.y. time span.

The structurally highest sample dated in this study, a High Himalayan leucogranite from an injection complex, yields a ~20 Ma age that corresponds well with those reported along the range front, and attests to the continuity of orogenic events within the range. The youngest monazite grain analyzed along the Dudh Kosi-Everest transect yields a Th-Pb age of 10.3±0.8 Ma (n= 2 spots; ~74% radiogenic ^{208}Pb). The presence of Oligocene ages from the upper Lesser Himalaya is notably absent, and 24 monazite grains from three samples from this unit yield a weighted mean age of 14.1±0.1

Ma, suggesting this age should be considered when evaluating episodes of MCT shear zone activity in eastern Nepal.

The presence of folds within the Greater Himalayan Crystallines has been thought to be due to gravity sliding along the South Tibetan Detachment (STDS) (e.g., Burchfiel et al., 1992), but the presence of ~23 Ma and ~14 Ma monazite grains in sample ET12 (Fig. 8.11), collected with one of these large-scale structures along the Dudh Kosi-Everest transect requires an alternative hypothesis. Analogue models intended to simulate continental convergence as seen in profile suggest the shape of an orogeny is strongly influenced by the geometry of the indenter (Bonini et al., 1999). The experiments support the idea that progressive shortening within the MCT shear zone combined with the steepening MCT ramp, as proposed by Harrison et al. (1998) model, could account for fold formation in the Greater Himalayan Crystallines. In central Nepal, fold growth within the Tethys Formation has been linked to compression (Brown and Nazarchuk, 1993; Godin et al., 1999a, 1999b), but time constraints for their origin were absent. The monazite ages reported here from eastern Nepal are consistent with the concept that folds within the Greater Himalayan Crystallines relate to post-early Miocene activation of the MCT.

8.5. Conclusions

This study attempts to decipher aspects of the deformation chronology of the Himalaya by using *in situ* Th-Pb ion microprobe dating of monazite grains collected from samples roughly perpendicular to the MCT along two river drainages: the Bhagirathi

River, Garhwal Himalaya, India, and the Dudh Kosi, south of Mt. Everest, Nepal. Paleo-Mesoproterozoic monazite grains are found in an augen gneiss unit collected within MCT shear zone, whereas high-grade hanging wall garnets retain Cambro-Ordovician monazite inclusions. The extensive presence of the ~23 Ma monazite grains in hanging wall rocks indicate the unit was subsequently exhumed by MCT slip after ~30 m.y. of Eohimalayan crustal thickening. Upper Lesser Himalayan monazite inclusions in garnet record a clear signature at 14.1±0.1 Ma, whereas the ~23 Ma signal that characterizes hanging wall rocks is notably absent. The ~14 Ma age is found in rocks collected within a large scale Greater Himalayan Crystallines fold, consistent with the hypothesis that these structures formed due to slip along a steepened MCT ramp.

Garnets from the MCT hanging wall (the Greater Himalayan Crystallines) and footwall (lower Lesser Himalaya) show fundamental differences in compositional zoning of Mn, Ca, Mg, and Fe. P-T paths calculated for two upper Lesser Himalaya samples collected <1 km apart show a sharp transition from burial to exhumation, consistent with a model in which the inverted metamorphic sequence underlying the MCT formed by the transposition of right-way-up metamorphic sequences during Late Miocene-Pliocene shearing (e.g., Harrison et al., 1998). The youngest monazite ages (5.9±0.2 Ma) are matrix grains located within the MCT shear zone along the Bhagirathi River, Garhwal region, India, and are similar to those reported for monazite at similar structural levels in central Nepal (e.g., Harrison et al., 1997b). The striking continuity of orogenic events within the range is further manifested by the ~20 Ma age of a High Himalayan leucogranite collected from an injection complex along the Dudh Kosi-Everest transect, resembling ages of these bodies elsewhere. The geochronologic and thermobarometric information documented here provides clear quantitative constraints to those seeking to decipher the evolution of the Himalayan orogen, and suggests that *in situ* methods are the ideal means of evaluating the history of an orogen that has experienced a lengthy and complex sequence of tectonic events.