CHAPTER 9. Implications for evolutionary models of the Himalaya.

9.1. Outcome

Most models proposed for the evolution of Himalaya assume the zone of plate convergence shifted progressively and temporally towards the foreland during the mountain building process. An intracontinental thrust, the Main Central Thrust (MCT), is thought to be active during the Miocene (e.g., Hodges et al., 1996). South of the MCT, Late Miocene movement slip occurred along the Main Boundary Thrust (MBT) (e.g., Meigs et al., 1995), and presently, the Main Frontal Thrust (MFT) is active (e.g., Yeats et al., 1992). Convergence is primarily accommodated by the youngest structures, ones closest to the Indian foreland.

This evolutionary model (Seeber and Gornitz, 1983) has its roots in traditional rules of thrusting developed as means of understanding thrust-belt geometries (Boyer, 1992; Wells, 1997). On its foundation, two classes of models arose seeking to explain the evolution of Himalayan inverted metamorphism. The first proposed a significant inverted geotherm developed during slip on the thrust (e.g., Le Fort, 1975; England et al., 1992), whereas the second suggested that recrystallization of the footwall units occurred prior to their juxtaposition with the hanging wall (e.g., Hubbard, 1996; Searle and Rex, 1989). These hypotheses are unique and unrelated, but rely on the assumption that MCT slip was a single episode. The geochronologic data reported here indicates the evolutionary model is wrong and forces the consideration of alternatives.

The steady-state model of Seeber and Gornitz (1983) suggests the Himalaya is a wedge of topography between the underthrust Indian plate and overriding Tibet. The process is similar to oceanic subduction, and large amounts of convergence can occur without drastic changes to the tectonic regime. At the time of initiation, contractional deformation progresses at the regional scale towards the foreland, but the hinterland of orogenic belts thicken internally continue (e.g., Burbank et al., 1992; Attoh et al., 1997; Gray and Mitra, 1999). In this scenario, the Main Himalayan Thrust (MHT) and MCT are active structures. Synchronous thrusting and out-of-sequence imbrication are mechanisms in which the wedge of topography maintains a critical taper (e.g., Davis et al., 1983; Boyer, 1992). Erosion and accretion of frontal imbricate thrust sheets decrease the thrust-belt taper, which in turn drives internal deformation.

The geochronologic and thermobarometric information from rocks collected along four MCT transects (Figs. 9.1-9.3; Table 9.1) suggest MCT-related activity during the Miocene, Late Miocene, and Pliocene. The data are consistent with a thermal-kinematic model in which the footwall inverted metamorphic sequences formed by the transposition of right-way-up metamorphic sequences during the Late Miocene and Pliocene (Harrison et al. 1988).

The Harrison et al. (1998) model is outlined in Figure 9.4. Several aspects are supported by petrologic and thermochronologic constraints. The MCT juxtaposes the Greater Himalayan Crystallines against the Lesser Himalaya at ~25 Ma (Figure 9.4a). In this scenario, the Greater Himalayan Crystallines has already sustained Eohimalayan metamorphism and thickening. The Harrison et al. (1998) model maintains that monazite grains from Greater Himalayan Crystalline rocks cooling from different depths should reveal age gradients due to variable diffusive Pb loss. In addition, the model requires a hanging wall lithostatic pressure gradient, with the highest pressures and temperatures recorded in rocks collected near the MCT.

In central and eastern Nepal, monazite grains collected near the MCT record ages from 23-18 Ma. A sample from the Marysandi drainage collected near the boundary with the Tethys Formation metasediments has 30-50 Ma monazite. Samples collected near the Greater Himalayan Crystallines-Tethys Formation contact are from shallower levels, have traveled along a thrust flat, and preserve their Eocene-Oligocene origin, whereas samples near the MCT have been exhumed from the deep crust along the MCT ramp.

According the to Harrison et al. (1998) model, the MBT becomes active when slip on the MCT ceases, causing the MCT ramp to rotate. During a Late Miocene southward propagating locus of thrusting, MCT footwall rocks transfer to the hanging wall (e.g., Figure 9.4b-c). The model maintains that upper Lesser Himalaya monazite grains should record a polymetamorphic history, whereas lower Lesser Himalaya samples should contain monazite with Late Miocene ages, consistent with a reactivation of the shear zone during that time (Figs 9.1-9.3; Table 9.1). The allanite and monazite ages and garnet-zoning pattern from sample MA33, collected at the base of the upper Lesser Himalaya along the Marysandi River transect, are consistent with a polymetamorphic history.

Pressure-temperature (P-T) paths from samples Ma61a, DH17, and DH19 suggest the presence of a tectonic and metamorphic break within the MCT shear zone. This break does not correlate with the location of a lithological boundary suggested by

Colchen et al. (1980) or the tectonic boundary of Arita (1983). The observations suggest that thermobarometric and geochronologic information from samples collected within the upper Lesser Himalaya should be considered before placing boundaries within the shear zone that are difficult to discern because of poor exposure and access.

9.2. Conclusions and summary of contributions

Several themes emerge from the data reported in this dissertation. The following is an attempt to outline the summary of contributions and future research related to the research question stated in Chapter 4.

1. *Pliocene monazite ages from a sample collected near the garnet isograd along the Marysandi River transect indicates this portion of the MCT shear zone accommodated a minimum of ~30 km of slip in the last 3 Ma (i.e., a slip rate of >10 mm/yr) and thus may have accommodated nearly half of the convergence across the Himalaya.* If the monazite in MA86 formed at the maximum temperature recorded by the garnet (T ~535°C), this rock experienced ~43 km of slip in the last 3 Ma along a 30° MCT ramp. If the MCT ramp was as steep as 45° and the monazite formed at a temperature as low as ~435°C (~65° lower than estimates suggested by Smith and Barriero, 1980), this portion of the MCT shear zone slipped ~30 km of since ~3 Ma. The range of exhumation rates from these calculations is 10-14 mm/yr. This is 16-32% of the total convergence rate between the Indian and Eurasian plates (44-61 mm/yr; Minster and Jordan, 1978; Armijo et al., 1989; DeMets et al., 1990), and is similar to shortening rates estimated for the MFT (9-16 mm/yr; Lyon-Caen and

Molnar, 1985; Baker et al., 1988; Powers et al., 1998; Yeats et al., 1992). If the average Indo-Himalayan convergence rate is 14±4 mm/yr (Powers et al., 1998), in central Nepal, 50-70% of this rate appears to be localized along the MCT shear zone during the Pliocene.

2. *Geochronologic and thermobarometric data reported here support the lateral continuity of tectonic events within the Himalayan orogen*. Late Miocene monazite grains are not unique to central Nepal. Sample GM74, collected ~800 km west of central Nepal along the Bhagirathi River, Garhwal region in NW India, contains ~6 Ma monazite. Further evidence of the timing uniformity comes from a High Himalayan leucogranite collected from an injection complex along the Dudh Kosi-Everest transect (ET7), which contains ~20 Ma monazite grains, resembling ages of these bodies elsewhere along the range front (e.g., Noble and Searle, 1995; Searle et al., 1997; Harrison et al., 1999b; Simpson et al., 2000).
3. *Garnets from the Greater Himalayan Crystallines, upper Lesser Himalaya, and lower Lesser Himalaya show striking differences in compositional zoning.* The location of the MCT is difficult to discern in the field (e.g., Upreti, 1999) and geochemical techniques reported here are useful for aiding in its identification. Garnets from the Greater Himalaya are characterized by diffusion, whereas lower Lesser Himalaya appear to preserve their growth-related compositions. P-T paths calculated for Lesser Himalaya samples from eastern and central Nepal suggest the presence of a previously unseen structural break.

4. *Thermobarometry for MCT footwall rocks show an inverted thermal gradient of ~18°C/km and apparent pressure gradient of ~6 km/kbar.* As illustrated in Chapter 2, the thermobarometric data set previously reported for rocks collected along the Himalayan range mainly concern the MCT hanging wall. The lack of P-T constraints for the MCT footwall leads those seeking to decipher the origin of Himalayan inverted metamorphism to relocate hanging wall P-T data to the footwall (e.g., England and Molnar, 1993). This dissertation reports information required for developing models for the evolution of the Himalaya.
5. *Th-Pb ion-microprobe analyses of monazite inclusion in garnets immediately beneath the Greater Himalayan Crystallines suggest Miocene MCT activity.* Th-Pb ion microprobe analyses of monazite inclusion in garnets immediately beneath the Greater Himalayan Crystallines in central Nepal indicate monazite growth was occurring at 18±1 Ma (P ~9 kbar, T ~640°C). Monazite grains from the rocks of the Greater Himalayan Crystallines collected along the Dudh Kosi-Everest transect are ~23 Ma, consistent with estimates of MCT slip reported elsewhere (e.g., Hodges et al., 1996).
6. *Pliocene ^{40}Ar/^{39}Ar muscovite ages from Darondi Khola rocks suggest rapid exhumation of the MCT shear zone.* Pliocene mica ages from MCT shear zone have been rationalized as late-stage brittle thrusting (Macfarlane, 1993) or products of fluid flow (Copeland et al. 1991). Late Miocene/Pliocene monazite grains reported for rocks along the MCT transects in central and eastern Nepal suggest these hypotheses

are unsupported, and indicate the muscovite ages represent cooling through their ~350°C closure temperature.

7. *Along the Dudh Kosi-Everest transect, upper Lesser Himalayan monazite grains from three rocks record a clear signal at 14.1±0.1 Ma (MSWD= 8.4), and the ~23 Ma age that characterizes the hanging wall is absent.* The ~14 Ma age requires consideration when evaluating episodes of MCT shear zone activity in eastern Nepal. The youngest monazite grain analyzed along the Dudh Kosi-Everest transect is 10.3±0.8 Ma. The absence of 7-3 Ma monazite in this region may reflect a different nappe structure, which obscures the reactivated ramp equivalent exposed in the NW India and central Nepal.
8. *The idea of simultaneous slip along the MCT and South Tibetan Detachment (STDS) is unsupported by the data reported here.* 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 (Fig. 9.3). X-ray element maps of garnets from the unit suggest structurally higher garnets preserve their prograde compositions better than those collected near the MCT, consistent with exhumation from shallower levels. The thermobarometric constraints indicate rocks from the Greater Himalayan Crystallines record a lithospheric gradient, consistent with a flat-ramp geometry.
9. *Monazite collected within a large-scale Greater Himalayan Crystallines fold yield ~14 Ma, suggesting the structures formed due to MCT-related compression.* Prior to this study, time constraints for the origin of Himalayan folds were absent. Godin et

al. (1999) predict the north-east verging folds of the Tethys Formation in central Nepal record the earliest contraction of this part of the orogen. Their existence has also been attributed to activity along the STDS (e.g., Burchfiel et al., 1992; Hodges et al., 1996; Vannay and Hodges, 1996). The presence of ~23 Ma and ~14 Ma monazite grains in sample ET12, collected with one of the large-scale structures along the Dudh Kosi-Everest transect, requires an alternative hypothesis. Upper Lesser Himalaya garnets in this region contain ~14 Ma monazite grains, similar to the age of the inclusion in sample ET12. The data are consistent with the hypothesis that the fold formed via progressive shortening within the MCT shear zone combined with a steepening MCT ramp.

10. *Monazite grains analyzed here are unaffected by significant fluid alteration.* Late Miocene and Pliocene monazite grains are typically found in garnet-bearing assemblages that have experienced temperatures below 600°C. These grains appear both as inclusions in garnet and in the matrix. The MCT is as a locus of hot springs, but the rocks sampled for this study show no evidence of hydrothermal alteration. To force Pb loss, fluids would have to supply enough thermal energy to maintain monazite above its closure temperature so that ~23 Ma, 50-100 μm-sized grains would lose enough Pb to yield 7-3 Ma ages. This process is unseen in any rocks collected along the four MCT transects. Instead, the hot springs may imply that the MCT is presently active (e.g., Chamberlain et al., 1995; Curewitz and Karson, 1997).
11. *In situ Th-Pb ion-microprobe dating of allanite helps to elucidate geologic problems that can be addressed with an age accuracy of ±10%.* This method permits *in situ*

dating of small (~15 μm) grains and grains included in phases such as garnet, with the spatial selectivity to analyze areas unaffected by alteration. Although the extreme compositional variability of allanite poses a challenge for ion-microprobe analysis, a 3-D calibration plot ($^{208}Pb^*/Th^+$ vs. ThO_2^+/Th^+ vs. FeO^+/SiO^+) overcomes the problem at a level of accuracy of about ±10%.

9.3. Future research

Geochronologic and thermobarometric information reported here directly impacts our understanding of the stages of mountain building and origin of inverted metamorphism in orogenic regimes. Monazite ages from MCT footwall rocks strongly support the idea that the shear zone was active during the Late Miocene and Pliocene. Establishing the event along MCT strike is of primary interest for those seeking to understand the evolution of the Himalaya, and has implications for estimating the amount of Indo-Asian convergence accommodated by structures within the range and to the north.

Models that attempt to describe the Himalayan evolution are exported as paradigms for similar phenomenon in other orogenic belts, suggesting the range is an ideal natural laboratory for the study of continental convergence (e.g., Guillot, 1999; Macfarlane, 1999; Hodges, 2000). Thus, exploration of the Morely (1988) hypothesis, that out-of-sequence thrusts are normal and typical of a contractional deformation sequence, requires consideration.

Integration of *in situ* dating of allanite and monazite grains with thermobarometric constraints has a Himalayan application, but is also a means to decipher the history of metamorphic terrains elsewhere. Allanite is found in a variety of rocks types, thus the Th-Pb dating method has broad application. Methods previously employed to obtain the chronology of deformation events within the range destroyed textural relationships of the phase being dated, making the results ambiguous (e.g., Simpson et al., 2000). The ages presented here are fundamentally unique because *in situ* analysis preserves a connection between the thermobarometry and geochronology. If the thermal history of the sample is unknown, observations of the grain being dated in the context of the rock thin section allow clarification.