

## **CHAPTER 1: The Himalayan orogenesis in perspective.**

### **1.1. Introduction to the Himalaya**

Nineteenth century geologists studying the Himalaya perceived an anomalous geologic relationship that appeared to contradict two commonly accepted principles: the oldest rocks in a sedimentary succession are found at the base of the pile, and metamorphosed strata are older than unmetamorphosed. The Main Central Thrust (MCT), located at the base of the Himalayan break in slope, places lower-grade Lesser Himalayan Formation metasediments beneath high-grade gneisses of the Greater Himalayan Crystallines. Exploration of the Himal Pradesh region, northern India, surprised pioneering geologists (Medicott, 1864; Oldham, 1883; Middlemiss, 1887) who saw the highest-grade, and thus supposedly oldest rocks, form the tallest peaks.

"Now the belief which is at present so rapidly gaining ground that metamorphic strata are presumably older than unmetamorphosed strata makes one at first glance assume the strong probability in favor of the inner schistose series [Greater Himalayan Crystallines] being of much greater age than the outer zone of formations [Lesser Himalaya]. But no sooner has this *a priori* probability obtained a firm hold of the mind than a rude shock is given to it by the discovery that at every point round the schistose area the Outer formations appear to dip towards and under the schistose series at steep angles (50°-60°), whilst the schistose series itself is disposed apparently...upon the top of the Outer Formations, and culminating in a capping of gneissose rock on the summit of Kalogarhi mountain, the highest point in the neighborhood (Middlemiss, 1887)."

The recognition of widespread thrusting within the Himalaya was largely based on the observations (Pilgrim and West, 1928; Auden, 1937) and the orogen's "inverted metamorphism," an increase in metamorphic intensity towards higher structural levels, appeared resolved by invoking tectonic activity.

However, more recent detailed studies indicated that mineral isograds remain unbroken across the MCT, and its footwall is characterized by an inverted geotherm (Ray, 1947; Gansser, 1964; Pêcher, 1989; England et al., 1992). The idea of Himalayan inverted metamorphism reemerged, but was relocated to the MCT footwall. Inverted metamorphic gradients suggest the presence of wholly overturned strata or heat sources that counteract the influence of the asthenosphere (e.g., England and Molnar, 1993). The cause of the phenomenon has implications for establishing mechanisms of heat transfer within collisional belts and the role of heat sources, such as shear heating in fault zones, heat advection by magmas, radiogenic heating, and asthenospheric input.

## **1.2. Models for the evolution of the orogen**

Inverted metamorphism has been associated with areas of extensive thrust faulting (Ernst, 1973; Graham and England, 1976; Spear et al., 1995), where heat is thought to flow from a hot upper plate to a colder lower plate. Some models of Himalayan orogenesis link the apparently anomalous geothermal gradient spatially and temporally with MCT slip (e.g., Le Fort, 1975; England et al., 1992), whereas others suggest a juxtaposition of previously metamorphosed sequences (e.g., Searle and Rex, 1989;

Hubbard, 1996). Recent reviews challenged these ideas and debated their application to the Himalaya (Harrison et al., 1999a; Hodges, 2000).

The MCT has accommodated a significant amount of Indo-Asian convergence (e.g., Shelling and Arita, 1991), but other large-scale structures, including crustal-scale strike-slip faults to the north and active thrusts to the south compete for strain accommodation. The MCT has long been thought to be presently quiescent (Ye et al., 1981; Ni and Barazangi, 1984; Schelling and Arita, 1991; England et al., 1992). The fault has been linked to the generation of numerous geologic elements that characterize the Himalayan range, including hanging wall anatectic granitoids, footwall inverted metamorphism, and crustal-scale extension (Burg et al., 1984; Valdiya, 1988; Burchfiel et al., 1992). Establishing the fault's slip history has implications for understanding the development of these fundamental Himalayan components.

### **1.3. *In situ* methods of analysis**

Quantitative geochemical data that will constrain or test the numerous hypotheses proposed for the origin of MCT inverted metamorphism are notably absent. The primary focus of past investigations has been to establish the metamorphic conditions affecting the hanging wall and upper structural levels of the shear zone, largely ignoring the footwall rocks. The methods previously employed for obtaining the chronology of deformation events were insensitive to the textural relationships between the minerals being dated and those used to estimate pressure and temperature (P-T), making interpretation of the results ambiguous (e.g., Simpson et al., 2000). The Th-Pb ion

microprobe ages presented here are fundamentally different because *in situ* analysis preserves a connection between the thermobarometry and geochronology.

This dissertation focuses on two Th-bearing accessory minerals commonly found in the metapelitic lithologies that dominate Himalayan metamorphic sequences. Monazite, a rare-earth phosphate, sustains little radiation damage (e.g., Meldrum et al., 1998) and remains relatively impervious to Pb loss at high temperatures (e.g., Smith and Gilletti, 1997), and thus is an excellent candidate for geochronology. Monazite inclusions in garnet may be further armored against daughter product loss because of the low solubility and permeability of Pb in the host (Montel, 1999).

Unlike monazite, allanite commonly exists in a metamict state due to damage induced by  $\alpha$  particles emitted by its radioactive constituents (Deer et al., 1993). Allanite is an epidote-group mineral and typically contains high concentrations of Th and U. In this case, the ion microprobe is a useful tool because of its ability to analyze small areas on the grains unaffected by alteration. The mineral is common in a variety of rock types, thus *in situ* ion microprobe method of dating of the phase has broad application. Petrographic observations of Himalayan rocks indicate monazite first appears in the garnet zone, whereas allanite is the principal host of rare-earth elements in chlorite- and biotite-zone rocks.

#### **1.4. General description of the research**

*In situ* Th-Pb monazite and allanite ages and P-T information were obtained from rocks collected along four MCT transects (the Bhagirathi River, NW India, the Dudh

Kosi-Everest, eastern Nepal, the Marysandi River and Darondi Khola, central Nepal). These data are used to constrain and develop a model for the origin of the Himalayan inverted metamorphism, and suggest a striking continuity of tectonic events across the range.

Monazite inclusions in garnets immediately beneath the MCT yield Miocene ages, whereas those collected within the apparent inverted metamorphic sequence are Late Miocene and Pliocene. The youngest, more precise monazite age determined in this study is sample MA86 [ $3.3 \pm 0.1$  Ma ( $1\sigma$ );  $P \sim 7.2$  kbar,  $T \sim 535^\circ\text{C}$ ] collected near the garnet isograd along the Marysandi River transect. The Pliocene age indicates this portion of the MCT shear zone accommodated a minimum of  $\sim 30$  km of slip in the last 3 Ma (i.e., a slip rate of  $>10$  mm/yr), thus accommodating nearly half of the assumed convergence across the Himalaya. Matrix monazite grains collected beneath the MCT in the Garhwal region are  $5.9 \pm 0.2$  Ma, supporting widespread Late Miocene MCT activity across the orogen. Pliocene  $^{40}\text{Ar}/^{39}\text{Ar}$  muscovite ages from rocks along the Darondi Khola suggest rapid exhumation of the MCT shear zone. The youngest monazite grain analyzed along the Dudh Kosi-Everest transect is  $10.3 \pm 0.8$  Ma. The absence of 7-3 Ma monazite in eastern Nepal may reflect a different nappe structure, which obscures the reactivated ramp equivalent exposed in the NW India and central Nepal.

Along the Dudh Kosi-Everest transect, upper Lesser Himalayan monazite grains from three rocks record a clear signal at  $14.1 \pm 0.1$  Ma (MSWD= 8.4), and the  $\sim 23$  Ma age that characterizes the hanging wall is notably absent. Monazite collected within a large-scale fold in the Greater Himalayan Crystallines yield  $\sim 14$  Ma ages, consistent with the

idea that the structures formed due to MCT-related compression. Paleo-Mesoproterozoic ( $1407\pm 35$  Ma) matrix monazite grains are found within an augen gneiss unit located beneath the MCT, whereas Cambro-Ordovician ( $436\pm 8$  Ma;  $548\pm 17$  Ma) inclusions are preserved within garnets of the Greater Himalayan Crystallines. The presence of  $45.2\pm 2.1$  Ma grains from lower structural levels of the Greater Himalayan Crystallines indicates the unit realized conditions conducive for monazite growth during the Eocene.

Garnets from the MCT hanging wall and footwall display different major element zoning, and the patterns are useful for constraining the location of the thrust system that separates the two lithologies. Thermobarometry for MCT footwall rocks in central Nepal show an inverted thermal gradient of  $\sim 18^\circ\text{C}/\text{km}$  and apparent pressure gradient of  $\sim 6$  km/kbar. P-T paths calculated for Lesser Himalaya samples in central and eastern Nepal that preserve prograde compositions show evidence of decompression during heating. However, structurally lower garnets grew during an increase in both pressure and temperature. P-T paths calculated for two upper Lesser Himalayan samples collected  $<1$  km apart in eastern Nepal show a sharp transition from burial to exhumation, suggesting the presence of a previously unseen structural break.

A X-ray element map of a garnet collected from upper structural levels of the Lesser Himalaya along the Marysandi River transect suggests the grain experienced two-stage growth. Allanite inclusions in its core are significantly older ( $\sim 270$  Ma) than rim and matrix monazite ( $6.7\pm 0.3$  Ma). The results suggest allanite formation in Lesser Himalaya rocks is unrelated to MCT slip and may represent metamorphism associated with the older Pan-African orogeny (Le Fort et al., 1986), coupled with variable Pb loss.

The result has implications for the timing and evolution of the inverted metamorphism affecting the MCT footwall.

### **1.5. Organization of the dissertation**

The dissertation is organized into nine chapters. As mentioned in the acknowledgements section, the work presented here is part of collaborative efforts, and is included in several conference abstracts, one published paper, one paper in press, and a paper submitted and in review.

Chapter 2 describes geology of the Himalaya, emphasizing a broad overview of regions where samples were collected for further analysis (NW India, central and eastern Nepal). This chapter also reviews thermobarometric and geochronologic information previously reported for rocks adjacent to the MCT. Careful examination of these earlier studies reveals problems that suggest the quantitative constraints and methods used to generate the data are of limited use. Lack of data from MCT footwall rocks emerges as a common theme.

Chapter 3 reviews several models proposed for the origin of Himalayan inverted metamorphism and magmatism. These aim at expanding our perception of processes that could develop such thermal structure in areas of thickened continental crust, but whether they apply to the Himalaya is debated (see Harrison et al., 1999a; Hodges, 2000 for reviews as well).

Chapter 4 attempts to improve our understanding of the evolution of the MCT by quantifying the deformation history and P-T conditions recorded by the garnet-bearing

rocks collected along the fault. This information can constrain tectonic models for the origin of Himalayan inverted metamorphism and anatexis. This chapter also details the locations and mineral assemblages of rocks analyzed in this study.

Chapter 5 describes the methodology used to obtain the geochronologic and thermobarometric data from rocks collected adjacent to the MCT. Integration of *in situ* dating of monazite grains with P-T constraints has a local application for the Himalaya, but is also a means to decipher the tectonic history of metamorphic terrains elsewhere. The chapter heralds an innovative technique, predictably a focal point for future papers that incorporate petrology, geochronology, and tectonics.

Chapter 6 describes a new method to obtain Th-Pb ages of allanite, a common mineral in a variety of rock types, with  $\pm 10\%$  accuracy using a high-resolution ion microprobe. Knowledge of its composition and substitution mechanisms is essential to understand the relative ionization efficiencies of  $\text{Th}^+$  and  $\text{Pb}^+$  sputtered from this complex phase. Two metamorphic allanite grains from the footwall of the MCT, Nepal Himalaya, and an allanite grain from the Pacoima Canyon pegmatite, California are dated using the technique.

Chapter 7 presents the thermobarometric and geochronologic data obtained from two transects across the Himalaya in central Nepal. The data 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 unrelated metamorphic episodes.

Chapter 8 presents P-T-t information from rocks collected along the Dudh Kosi-Everest transect in eastern Nepal and ~800 km west along the Bhagirathi River in NW India. The data reveal a protracted and complex metamorphic history of the lithologies separated by the MCT, and indicate the striking continuity of tectonic events across the range.

Chapter 9 is the conclusion section of the dissertation. The distribution of ages and thermobarometric information from four MCT transects are consistent with a thermal-kinematic model in which the inverted metamorphic sequences underlying the MCT formed by the transposition of right-way-up metamorphic sequences during Late Miocene-Pliocene shearing. Information reported here quantitatively constrains models aimed at deciphering the origin of inverted metamorphic gradients along large-scale thrust faults, and indicates that *in situ* methods are ideal means for learning the history of deformation recorded by rocks within the Himalayan orogen.