

CHAPTER 4. The Himalayan inverted metamorphism problem.

4.1. Introduction

Previous strategies approached the problem of the origin of Himalayan inverted metamorphism by combining multiple heat sources within the Earth in proportions designed to match the observed anomalous gradient. A single episode of slip along the Main Central Thrust (MCT) was assumed, and footwall pressure-temperature (P-T) conditions were absent. This led to suggestions that tectonic structures can accommodate stresses exceeding that observed at plate boundaries (e.g., England et al., 1992), radiogenic nuclides within the Earth are key heat producers (e.g., Huerta et al., 1998), and magma bodies trigger crustal-scale faulting (e.g., Hollister, 1993). Despite their debated applicability to the Himalaya, these ideas are used to describe similar phenomenon elsewhere (e.g., Parrish, 1995; Neves et al., 1996; Carson et al., 1997).

An alternative means to decipher the source of the anomalous thermal gradient, described in section 4.2 of this chapter, is to establish the metamorphic P-T-t conditions of rocks separated by the MCT. Justification of this approach is presented in section 4.3. To accomplish this goal, samples were collected from the MCT hanging wall and footwall along river drainages in India (Bhagirathi River, Garhwal Himalaya), central (Marysandi River, Darondi Khola) and eastern Nepal (Dudh Kosi). Section 4.4 details their mineral assemblages and locations.

4.2. Detailed description of the research question

This study tests the hypothesis that inverted metamorphism in the MCT footwall forms from the accretion of successive footwall slivers to the hanging wall during Late Miocene out-of-sequence thrusting within the MCT shear zone (Harrison et al., 1998).

Three sources of geochronologic information have been exploited from rocks collected roughly perpendicular to MCT strike. Monazite grains appear in footwall rocks around the garnet isograd, whereas allanite is common at lower metamorphic grades. These minerals incorporate Th and can be dated using *in situ* Th-Pb ion microprobe techniques (Harrison et al., 1995; Catlos et al., 2000). Allanite is often the precursor of monazite in pelitic schists (Smith and Barreiro, 1990; Wing et al., 1999; cf. Kingsbury et al., 1993). The earliest metamorphic event affecting footwall rocks may be constrained by allanite ages, whereas monazite ages are useful to provide information about recrystallization events. In addition, K-Ar ages muscovite ages yield cooling ages (e.g., McDougall and Harrison, 1999) and can be an additional constraint.

Thermobarometric information from garnet-bearing samples collected along the MCT also help to critically evaluate the Harrison et al. (1998) model. Garnet zoning often spans million-year time-scales in the mid- to lower crust, making phase equilibria a useful tool to deduce metamorphic P-T histories (e.g., St. Ogne, 1987; Kohn et al., 1992, 1993; Spear, 1993; Geyra et al., 2000). If the inverted metamorphism is the result successive footwall slivers accreting to the MCT hanging wall, garnets collected adjacent to the fault should reflect this history in their composition. Monazite inclusions are commonly found in Himalayan garnets, and have the potential to temporally constrain estimated P-T paths.

4.3. Justification of the research question

The variety of geologic processes occurring within the Himalaya has made these mountains a target for those seeking to understand the effects of mass movement of the Earth's crust. The P-T-t histories of rocks separated by the MCT have implications that transect the boundaries between traditional fields of geology, from deciphering tectonic control of climate to explaining magma genesis in convergent plate tectonic settings. The following list is an attempt to outline the significance of the understanding Himalayan inverted metamorphism by obtaining geochronologic and thermobarometric data from rocks adjacent to the MCT.

1. *Thermobarometry and geochronology of rocks related to Himalayan inverted metamorphism and anatexis can evaluate the feasibility of the models that seek to explain the phenomena.* Understanding the range's inverted metamorphism has implications for deciphering the role of Earth's heat sources (e.g., shear stress along tectonic structures, the input from magma bodies, radiogenic elements) and mechanisms of heat transfer (e.g., advection, accretion-erosion processes). Numerous models proposed for the origin of Himalayan geologic components are inapplicable to the orogen (see Harrison et al., 1999a). Some studies report hanging wall P-T conditions inconsistent with the sample's mineral assemblage (e.g., Brunel and Kienast, 1986; Vannay and Grasemann, 1998), and high-grade rocks from the Greater Himalayan Crystallines may be subject to retrograde reactions that lead to erroneous results (Kohn and Spear, 2000). P-T-t constraints are required to constrain the hypotheses, and a serious lack data exists from the strata of rocks that show inverted metamorphism.

2. *Using the Himalaya as an example can elucidate processes that shaped older collisional systems.* The Himalaya is a fundamentally unique orogen: inverted metamorphism, parallel chains of granite bodies, large-scale normal faulting, and laterally continuous tectonic structures and lithologies coexist in a single range (e.g., Le Fort, 1996). The arrangement of its geologic components is unseen elsewhere, but those who seek to decipher the histories of older collisional systems frequently cite the Himalaya. For example, models of its inverted metamorphism are exported to explain similar phenomenon in the southeastern Canadian Cordillera (Gibson et al., 1999), and São Francisco Craton, southeast Brazil (Neto and Caby, 1999). The Himalaya is an actively deforming orogen and offers a range of valuable geologic analogues. Understanding its evolution contributes broadly to the knowledge of convergent plate tectonic settings.

3. *MCT shortening estimates are useful to investigate the mechanisms involved during large-scale deformation due to continental collision.* The MCT is thought to accommodate a significant amount convergence between India and Asia (e.g., Srivastava and Mitra, 1994), but strike slip faults to the north (e.g., Tapponnier et al., 1982) and the active thrusts to the south (e.g., Yeats et al., 1992) compete for slip partitioning. Quantifying the amount of crustal shortening with the aid of geochronologic and thermobarometric data from rocks adjacent to the MCT elucidates the structural geometry of the Himalaya, and plays an important role in evaluating models of the India-Asia collision (e.g., Tapponnier et al., 1990; Houseman and England, 1996).

4. *Timing MCT slip has implications for understanding out-of-sequence thrusting in convergent settings.* Establishing the sequence of deformation events recorded by the faults in contractional terrains has an impact on cross-section restoration, the expectation of rock permeability, petroleum discovery, seismic hazard assessment, and understanding the development of accretionary prisms (e.g., Gray and Mitra, 1999). An argument voiced against the advocacy of out-of-sequence thrusts is that they are unobserved in well-dated orogens (Woodward, 1987). Extensive geochronologic studies are required to interpret the relationships among faults responsible for building the Himalaya.

5. *The slip history of the MCT inextricably links to climate.* The tectonic evolution of Himalaya is the primary cause of monsoon initiation and evolution in southeast Asia (Naidu, 1998; Valdiya, 1999), and sediments shed off the range flow into deep ocean basins and dominate submarine topography (e.g., Malod et al., 1997). The landscape is the result of a complex interplay among slip along its fault systems and erosion due to glaciation and monsoonal precipitation (Beaumont et al., 1992; Avouac and Burov, 1996; Heuberger and Ibetsberger, 1996; Schramm et al., 1998; Brozovic and Burbank, 2000). The MCT marks the present-day break in slope and is the dominant crustal shortening mechanism in the Himalaya. Its slip history has direct implications for understanding past atmosphere and ocean circulation, and the tectonic impact of physical weathering (e.g., Copeland, 1997). These processes affect vegetation (e.g., Quade et al., 1995), sediment and carbon burial rates (e.g., Harrison et al., 1993; Derry and France-Lanord, 1996), global climate (e.g., Tajika, 1998) and atmospheric CO₂ levels (e.g., Kerrick and Caldeira, 1993, 1999).

6. *The deformation history of rocks associated with the MCT is useful for deciphering mechanisms involved in the generation, transport, and emplacement of magma in orogenic belts.* Anatexis is frequently observed in orogenic belts (e.g., Samson, et al., 1995; Harrison et al., 1997a; Pereira and Shaw, 1999), but the processes involved between the inception of anatexis and final solidification in high crustal levels are debated (e.g., Wickham, 1987; Druguet and Hutton, 1998; Harrison et al., 1999a). MCT slip has been linked to Himalayan anatexis (e.g., Le Fort, 1975), and its hanging wall is thought to be the protolith of the High Himalayan leucogranites (e.g., Harris et al., 1993; Barbey et al., 1996). Detailed petrology and geochronology of rocks associated with the MCT is required to elucidate the processes involved in their migration through the lithosphere.

7. *In situ techniques preserve a link between the metamorphism and time.* The *in situ* method presented here signals a serious shift from the traditional geochronologic approach that employs mineral separation. An ion microprobe makes dating small grains (~15 μm) and zones within larger grains feasible, and textural relationships are preserved, allowing less ambiguous age interpretations. Garnet P-T paths have the potential to be temporally constrained by their monazite or allanite inclusions. The $\pm 2\%$ uncertainty in the Th-Pb monazite ages obtained using an ion microprobe are favorable compared to highly uncertain U-Pb age results typical seen for Himalayan monazites (e.g., Nazarchuk, 1993; Hodges et al., 1996; Coleman, 1996b, 1998; Simpson et al., 2000). This study is an example of using an *in situ* method for rocks that experienced multiple episodes of deformation.

4.4. Sample selection and petrography

4.4.1. Central Nepal, Marysandi River and Darondi Khola transects

Samples were collected along two cross-strike transects in central Nepal along the Marysandi River (Fig. 4.1) and Darondi Khola (Fig. 4.2). Cross-sections along these transects are shown in Figure 4.3. Based on field observations along the Marysandi River transect, Colchen et al. (1980) mapped the MCT near the town of Bahundunda. The augen gneiss that defines Arita's (1983) MCT-I is not observed along the Marysandi River transect, whereas the Ulleri augen gneiss outcrops along the Darondi Khola. Along the Marysandi River transect, rocks from the MCT shear zone (= upper Lesser Himalaya) were collected between the MCT and the MCT-I. The MCT-I is defined by Colchen et al. (1980) as the contact between aluminous and carbonate schists of the upper Lesser Himalaya and those of the Kunchha Formation of the lower Lesser Himalaya (Figs. 4.1-4.3). The base of the MCT shear zone is arbitrarily assigned, since the boundary between rocks of the upper and lower Lesser Himalaya metasediments is unclear (see Upreti, 1999).

Lower Lesser Himalaya samples contain garnet + biotite + chlorite + muscovite ± tourmaline ± plagioclase ± epidote (allanite) ± monazite ± zircon + ilmenite + quartz. One sample along the Marysandi River transect (MA63) has the assemblage chloritoid + biotite + muscovite + ilmenite + quartz. From the Lower Lesser Himalaya to the MCT shear zone, the rocks follow a systematic progressive metamorphism, and temperature and pressure appear to increase. The staurolite and kyanite isograds appear within the MCT shear zone and these samples typically have garnet + biotite + chlorite + muscovite

± kyanite ± staurolite + plagioclase ± tourmaline ± epidote (allanite) ± monazite ± zircon + quartz + ilmenite. Staurolite-bearing samples were only found along the Darondi Khola. MCT shear zone samples collected along the Khudi Khola are a graphitic schists and marls (MA78-81). A sequence of marls, graphitic marls, and quartzites is observed within the MCT shear zone along these transects, but this thesis focuses only on the garnet-bearing assemblages in metapelites.

Rocks of the Greater Himalayan Crystallines have the assemblage garnet + biotite + chlorite + muscovite ± kyanite ± sillimanite ± tourmaline + plagioclase ± apatite ± epidote (allanite) ± monazite ± zircon + quartz + ilmenite. Along the Darondi Khola, kyanite is absent. Kyanite is present in samples collected along the Marysandi River transect, and structurally higher samples contain sillimanite. The appearance of sillimanite in the Greater Himalayan Crystallines is consistent with a pressure decrease via the reaction of kyanite → sillimanite. Sample MA18 contains both kyanite and small mats of fibrillose sillimanite. Sample MA11 is a garnet-bearing tourmaline leucogranite collected near the possible South Tibetan Detachment System (STDS) near the town of Chame along the Marysandi River transect.

Textural observations of pelitic rocks suggest monazite forms from allanite breakdown at ~500°C (Smith and Barreiro, 1990), and along transects in central Nepal, allanite is the rare-earth bearing accessory mineral within the chlorite and biotite zones. Above the garnet isograd, no readily apparent correlation exists between the presence of allanite and monazite with metamorphic grade.

4.4.2. Eastern Nepal, Dudh Kosi-Everest transect

Samples were collected south of Mt. Everest in a ~45 km transect along the Dudh Kosi drainage (Figs. 4.4, 4.5), extending ~1 km south of the MCT shear zone to the base of the Khumbu icefall within the Greater Himalayan Crystallines. Detailed petrologic descriptions of rocks collected along the Dudh Kosi have been previously reported (Hubbard, 1989; Pognante and Benna, 1993).

The lower Lesser Himalaya (Okhaldhuga Unit), consists of a low-grade green phyllite with the mineral assemblage chlorite + plagioclase + muscovite + rutile + tourmaline + epidote (allanite) + quartz ± garnet. Garnets in this formation are only found near the contact between the overlying augen gneiss, and are small (~1-2 mm), euhedral, and in close association with chlorite. Pods of quartz and plagioclase are sometimes found in these rocks.

Above the lower Lesser Himalaya, the Phaplu augen gneiss is a ~4 km thick package. The augen gneiss is a blue-grey rock that contains rounded quartz + K-feldspar + plagioclase + biotite + muscovite + chlorite + sphene + rutile + sillimanite + allanite. Sample ET38 may represent the protolith of the Phaplu augen gneiss. ET38 is comprised of small, euhedral garnets (<0.5 mm-sized) encompassed in larger grains of hornblende + quartz + plagioclase + biotite + chlorite + muscovite + rutile. ET38 also contains ~500 µm-sized grains of matrix monazite and zircon.

Above the Phaplu augen gneiss, the upper Lesser Himalaya is a ~5 km thick sequence of quartzite, graphitic and garnet-bearing schists, and augen gneiss. Monazite is found within the upper Lesser Himalaya in pelitic bulk compositions south of the

sillimanite isograd. The garnet-bearing assemblages of the upper Lesser Himalaya contain garnet + sillimanite + biotite + albite + tourmaline + ilmenite + monazite ± allanite + quartz. Pognante and Benna (1993) observed kyanite in a single sample along this transect, but it is absent in the rocks sampled for this dissertation. Small mats of fibrous sillimanite appeared in the rock matrix, and biotite and plagioclase are typical inclusions in garnet. Sample 85H20g, collected ~5 km east of the Dudh Kosi drainage, has a similar upper Lesser Himalayan assemblage, but contains staurolite and no sillimanite.

Along the Dudh Kosi-Everest transect, Lombardo and Rolfo (2000) report a complicated MCT zone with three sheets sandwiched between the base of the Greater Himalayan Crystallines and the lower Lesser Himalaya. The presence and location of these structures are inconsistent with our observations (Figs. 4.4, 4.5). Mineral assemblage and structure continue uninterrupted across the MCT, located near the town of Poyan (see also Hubbard 1988). The location of the fault is based on the appearance of Greater Himalayan Crystallines migmatites and an apparent decrease in strain (Hubbard, 1988; Lombardo et al., 1993).

In eastern Nepal, the Greater Himalayan Crystallines are separated into different gneiss units (e.g., Pognante and Benna, 1993; Carosi et al., 1999a). The base, called the Barun Gneiss, is a complex of migmatized paragneiss with minor metabasites, calc-silicate rocks and marbles. The middle unit, the Namche Migmatite Orthogneiss, is thought to be a pre-Himalayan granitoid that intruded a sequence of metasedimentary rocks and was subsequently metamorphosed. The contact between the Barun Gneiss and

Namche Migmatite Orthogneiss is unclear in the field because both units have a similar assemblage: biotite + muscovite + albite + sillimanite + quartz \pm garnet \pm tourmaline + ilmenite + zircon \pm monazite. The location of the contact in Figure 4.5 is based on Lombardo et al. (1993). The upper paragneiss unit, called the Black Gneiss, may have been the sedimentary cover of the Namche Migmatite Orthogneiss (Pognante and Benna, 1993). Along the Dudh Kosi-Everest transect, folds within upper structural levels of the Greater Himalayan Crystallines (Figs. 4.5, 4.6) have been linked to extension along the STDS (e.g., Carosi et al., 1999b).

Tourmaline leucogranites intrude the Namche Migmatite Orthogneiss and both cross-cut and follow the ductile deformation. The leucogranites have the mineral assemblage: quartz + albite + biotite + sillimanite + tourmaline \pm apatite + monazite + zircon. The injection complex increases in outcrop from the town of Ghat to Tengpoche, but near Pherice little leucogranite appears (Fig. 4.6). Rocks collected near Pherice (samples ET1-5) contain green biotite + tourmaline + plagioclase + muscovite + sillimanite + apatite + rutile + quartz \pm garnet \pm allanite.

4.4.3. Northern India, Bhagirathi River transect

Samples GM74 and GM85 were collected beneath the MCT along the Bhagirathi River, Garhwal Himalaya, India (Fig. 2.6 in this dissertation or Fig. 8 of Metcalfe, 1993). GM85 has the mineral assemblage garnet + biotite + chlorite + muscovite + plagioclase + tourmaline + rutile + allanite + quartz, whereas GM74 has a similar assemblage, but contains monazite, and no allanite or garnet.

4.5. Summary

Previous results from rocks collected in central Nepal suggest the inverted metamorphic sequences beneath the MCT ramp formed during reactivation of the thrust following ~10 m.y. of inactivity (Harrison et al., 1997b, 1998). This idea directly impacts our understanding of the origin of inverted metamorphism and the stages of mountain building in collisional plate tectonic settings. To further explore the hypothesis, metamorphic histories were obtained from thermobarometric analyses of garnet-bearing assemblages, combined with *in situ* ion microprobe Th-Pb ages of monazite and allanite occurring as inclusions in garnet and within the rock matrix, and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of muscovite grains. This chapter attempts to justify this approach. Sample locations and assemblages of rocks collected from two drainages in central Nepal (Marysandi River, Darondi Khola), eastern Nepal (Dudh Kosi-Everest transect), and the Garhwal Himalaya, India (Bhagirathi River) are described.