Pressure-temperature-time path discontinuity in the Main Central thrust zone, central Nepal

Matthew J. Kohn
Department of Geological Sciences, University of South Carolina, Columbia, South Carolina 29208, USA
Elizabeth J. Catlos
Department of Earth and Space Sciences, University of California, Los Angeles, California 90095, USA
Frederick J. Ryerson
Institute for Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, Livermore, California 94550, USA
T. Mark Harrison
Department of Earth and Space Sciences, University of California, Los Angeles, California 90095, USA

ABSTRACT

Metapelites collected in central Nepal reveal a discontinuity in metamorphic pressure-temperature-time (P-T-t) paths near the base of the Main Central thrust zone, despite an absence of obvious structural breaks. Garnets in the structurally lowest rocks grew with increasing T and P (loading), whereas garnets 1–3 km upsection grew with increasing T, but decreasing P (exhumation). Monazite grains in structurally lower rocks yield ion-microprobe Th-Ph ages of 8–9 Ma. Structurally higher monazite grains range from 10 to 22 Ma. The P-T-t paths confirm previous interpretations that footwall metamorphism in part resulted from thrust reactivation ca. 8 Ma, but also reflect thermal relaxation following older (20 Ma or older) thrust movement. The Main Central thrust zone formed during pulses of movement that resulted in progressive transfer of material from the lower to upper plate.

Keywords: Himalaya, P-T-t paths, geothermometry, geobarometry, geochronology.

INTRODUCTION

The Main Central thrust is the single largest structure within the Indian plate that has accommodated Indian-Asian convergence: it extends ~2500 km along strike and has been the site of at least 140 and perhaps >600 km of displacement (Schelling and Arita, 1991; Srivastava and Mitra, 1994). One critical feature of the structure is its inverted metamorphic field gradient; rocks that were once >650 °C now overlie rocks that never reached such high temperatures. The pressure-temperature-time (P-T-t) evolution of these rocks is thought to be diagnostic of the overall thermal and mechanical behavior of the orogen (England and Thompson, 1984; Ruppel and Hodgues, 1994; Harrison et al., 1998; Huerta et al., 1999), but little headway has been made in determining such paths in Nepal, despite numerous thermobarometric studies (see summaries of Guillot, 1999; Macfarlane, 1999). Herein we describe P-T-t paths from rocks collected from within the Main Central thrust shear zone. These paths discriminate among models for the origin of the inverted metamorphism, but also reveal an unexpected discontinuity. The new data alter our understanding of thrust movement in central Nepal and imply kinematic behavior that can be tested in the Himalaya and elsewhere.

BACKGROUND AND SAMPLES

The Main Central thrust is defined (Heim and Gansser, 1939) by the occurrence of high-T, upper amphibolite facies gneisses (Greater Himalayan Sequence) above lower T, greenschist and amphibolite facies rocks (Lesser Himalayan Sequence). The thrust is a thick ductile shear zone, with a continuous decrease in metamorphic grade and temperature downwarp (e.g., Arita, 1983; Pécher, 1989). Models proposed for the apparent grade and temperature inversions in central Nepal include (1) premetamorphic to synmetamorphic (including heating with exhumation), model 2 postmetamorphic thrusting along discrete shear zones (Inger and Harris, 1992; Hubbard, 1996); and (3) continuous symmetamorphic to postmetamorphic shear (e.g., Harrison et al., 1998; Huerta et al., 1998). In general, model 1 implies a clockwise P-T path (including heating with exhumation), model 2 implies prethrusting metamorphic ages and metamorphic repetition, and model 3 implies premetamorphic to symmetamorphic ages and a hairpin P-T path (heating only occurs with loading).

To test these different models, samples were collected in an ~25 km transect along the Darondi River drainage in central Nepal (Fig. 1), representing a structural thickness of ~10 km (Colchen et al., 1986). The contact between the Greater and Lesser Himalayan Sequences is exposed ~2 km south of the northern end of the transect (~1 km structural distance). On the basis of strong top-to-the-south shear senses, we consider all rocks between the Greater Himalayan Sequence and the garnet isograd as part of the Main Central thrust zone. We found no field evidence for any specific structural discontinuities within this zone. Except for differences ascribable to variable protolith composition and competence, all textures and mineral assemblages grade continuously across the transect.

TEXTURES, GARNET ZONING, AND MONAZITE AGES

Samples were investigated for mineral assemblages, textures, compositions, ages, and P-T paths1. In nearly all samples, a single strong foliation due to isoclinal folding is present. Some lower Lesser Himalayan garnets (e.g., DH-75 and DH-28) have spiral inclusion trails in their cores and overprint the main fabric at their rims, indicating syndeformational to postdeformational garnet growth at that level.

1GSAB Data Repository item 2001063. Mineral assemblages, textures, compositions, ages, and P-T paths, is available on request from Documents Secretary, GSA, PO. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.
Thermobarometry and P-T Paths

Thermobarometry indicates a systematic increase in peak P-T conditions from ~525 °C and ~5-6 kbar at the base of the transect, to...
higher Garnet... supports either... and diffusion... of Greater Himalayan garnets indicates... The continuity of... conditions along the traverse... Greater Himalayan rocks yield more... 625°C and... 11–12 kbar near the contact... with the Greater Himalaya, ~8 km structurally upward (Fig. 3). These results are the first clear documentation that... In the second... Greater Himalayan sequence contact...

**Figure 3.** Pressure vs. temperature (P, T) plots for rocks collected along Darondi River traverse. A: Within Main Central thrust (MCT) zone, P-T conditions increase toward Greater Himalayan Sequence. Thermobarometers are from Ferry and Spear (1978), Berman (1990), Graham and Powell (1984, DH-38 only), Kohn and Spear (1989, DH-38 only), and Hoisch (1990), and are internally consistent; different recent calibrations change estimated P and T by ~±25°C and ±0.5–1 kbar, but do not alter overall trends. B: Structurally higher rocks show P-T paths that decrease in P with increasing T. C: Structurally lowest rocks show paths that increase in both P and T. P-T paths were based on approach of Spear and Selverstone (1983) and Spear (1993). See footnote 1 for data and details. D: P-T path predictions of Lesser Himalayan Sequence samples if one-slip event occurs along single Main Central thrust fault (dashed line) or if multiple-slip events occur within ~10-km-thick shear zone (solid line; Harrison et al., 1998). In latter, Lesser Himalayan Sequence rocks are first buried as slip occurs above them, then transferred to upper plate (still at depth), and finally exhumed and cooled as zone of slip progressively moves to lower structural level.

~625°C and ~11–12 kbar near the contact... with the Greater Himalaya, ~8 km structurally upward (Fig. 3). These results are the first clear documentation that P increases upsection within the Lesser Himalayan Sequence, which contrasts markedly with several previous studies that inferred the opposite trend (e.g., Hubbard, 1989; Macfarlane, 1995; Vannay and Hodges, 1996). The apparent baric gradient excludes any possibility of an intact crustal cross section and implies some component of postmetamorphic shearing. The continuity of P-T conditions along the traverse implies distributed shear rather than major discrete shear surfaces. Greater Himalayan rocks yield more scattered P and T values of 625–725°C and 7–11 kbar. Evaluation of retrograde reactions and diffusional homogenization of Greater Himalayan garnets indicates that P-T estimates are minima. Compositional homogenization of Greater Himalayan garnets supports either a higher T or longer time at elevated T compared to the Lesser Himalayan rocks.

P-T paths were determined only with lower Lesser Himalayan Sequence rocks because their garnet and plagioclase grains show regular and easily interpretable prograde zoning. Other garnets from the transect either were compositionally homogenized after growth, or grew in an inappropriate mineral assemblage (i.e., lacking plagioclase). All garnets used for P-T path calculations grew in an assemblage containing biotite and chlorite as Fe-Mg minerals. At the base of the transect, DH-17 and DH-19 garnets grew during an increase in both P and T; however, samples DH-22, DH-23, DH-26, and DH-75 (structurally 1–3 km higher) record little change in P or a decrease in P toward peak T.

**INTERPRETATIONS**

Main Central thrust movement has been complex, with movement ca. 20–25 Ma (Hodges et al., 1996; Coleman, 1998) and ca. 6–8 Ma (Harrison et al., 1997). Two episodes of movement are consistent with monazite ages of ca. 21 Ma in the structurally highest samples and ca. 8 Ma in lower rocks. One explanation for the metamorphic and age distributions involves progressive underplating of material to the hanging wall during the later phase of thrust movement with thermal and mechanical activation of progressively lower rocks in the sequence (Harrison et al., 1998). The Main Central thrust zone then encompasses the highly deformed rocks between at least the garnet isograd and the top of the transect in the Greater Himalaya. The predicted P-T path shows a “hairpin”: an increase in both P and T during loading, followed by a decrease in both P and T during exhumation (Fig. 3D; Harrison et al., 1998). Garnet generally only grows during heating in the observed assemblages (Spear et al., 1990), thereby recording only the loading part of a hairpin path. This model explains the structurally lowest P-T paths that show only heating with loading, and implies significant shearing as much as 8 km below the Greater and Lesser Himalayan sequence contact.

In contrast to the lowest rocks, P-T paths of the structurally higher rocks show exhumation during heating. This result is surprising because (1) it is difficult to explain how such different paths can occur within 1 km of each other without an obvious structural break and (2) it suggests either a different history of thrusting for the higher rocks or an unusual thermal structure. Our preferred interpretation is that the paths determined from the higher rocks are the response to loading from early Miocene movement on the Main Central thrust (Harrison et al., 1998). After the early Miocene thickening and perturbation of isotherms, slowing of movement along the fault zone or quiescence until 8 Ma allowed isotherms to relax and the rocks to continue heating conductively. Postthrusting erosion or extension along the higher level South Tibetan detachment system caused pressure to decrease. This interpretation is supported by ca. 21–22 Ma monazite ages from the uppermost Lesser Himalayan rocks, and by textural overprinting of the main fabric by some Lesser Himalayan garnet rims. Heating continued until ca. 6–8 Ma and renewal of rapid movement along the Main Central thrust, so that relatively young monazites in samples DH-30 and DH-75 grew toward the end of quiescence. Structurally higher samples, heated by prior tectonism, had already cooled by the time lower samples reached peak conditions (e.g., DH-71 vs. DH-75, and DH-75 vs. DH-19). Cooling prevented continued reaction and reequilibration of P-T-T conditions in higher level rocks as the locus of displacement moved progressively downward. This interpretation also implies a significant, yet texturally and structurally cryptic break between DH-19 and DH-22, coinciding with the discontinuity in metamorphic P-T paths.

Alternatively, the exhumation paths may somehow directly reflect 6–8 Ma thrust movement and loading of DH-19 and DH-17, which would require local hanging-wall heating during thrusting and exhumation. High radiogenic heat coupled with continuous accretion and erosion over many tens of million years might result in an inverted thermal gradient (Huerta et al., 1998), and be preserved as an inverted metamorphic gradient. However, this model implies exposure of crustal depths, which are not observed, fails to explain the synchronicity of leucogranite intrusions along the thrust, and requires continuous movement (see Harrison...
et al., 1998). Shearing also provides heat (England et al., 1992), but the differential stress required to produce the observed gradient (≥1 kbar) far exceeds likely rock strengths for the observed conditions (Engelder, 1993; Kong et al., 1997). Thus, whereas local hanging-wall heating is theoretically possible, we do not believe it is justifiable for the Main Central thrust.

Models for movement along the Main Central thrust that invoke only premetamorphic or synmetamorphic thrusting (model 1) fail to account for the co-occurrence of P-T paths in structurally higher rocks that show heating with exhumation and P-T paths in structurally lower rocks that show heating with loading, or for higher P values at higher structural levels. Models that invoke only postmetamorphic thrusting (model 2) do not explain contrasting P-T paths and cannot account for metamorphic monazite ages that are either coeval with or postdate movement on the Main Central thrust or the continuous changes in metamorphic grade and P-T conditions along the transect. Furthermore, none of these models explains the diachronity of metamorphism in the upper versus lower parts of the Main Central thrust zone. Instead, continuous symmetamorphic and metamorphic shear (model 3) and juxtaposition of at least two distinct metamorphic packages explain better the petrologic and geochronologic data. Testing the validity and generality of our results is best accomplished by combining P-T path and T-t studies, in which compositional zoning and metamorphic reactions that are well located in P-T space are precisely linked to time.

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