Metamorphic Constraints on the Thermal Evolution of the Central Himalayan Orogen [and Discussion]

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Metamorphic constraints on the thermal evolution of the central Himalayan Orogen

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Recent studies that integrate conventional thermobarometry of pelitic mineral assemblages with thermodynamic modeling of garnet zoning reveal complex Tertiary *P–T* paths for the Greater Himalayan metamorphic sequence in the central Himalaya. Viewed in light of our current understanding of the structural evolution of the Himalaya, these data provide insights into the relations between tectonic and thermal processes during orogenesis. In this paper, we present an interpretive model for tectonothermal evolution of the Greater Himalaya in the central part of the range. This model involves: (1) middle Eocene–early Oligocene burial to depths of more than 30 km during the early stages of collision between India and Asia; (2) early–late Oligocene uplift and cooling; (3) late Oligocene heating and renewed burial synchronous with the early stages of anatectic melting and leucogranite plutonism; (4) latest Oligocene–middle Miocene rapid uplift and continued leucogranite production associated with ramping on the structurally lower Main Central Thrust and tectonic denudation on structurally higher low-angle detachment systems; and (5) middle Miocene–Recent rapid cooling during the final stages of uplift to the surface.

Introduction

Although the current thermal structure of the lithosphere can be inferred from geophysical measurements, exhumed igneous and metamorphic rocks provide our only direct evidence of the thermal evolution of the deeper levels of ancient orogenic belts. Numerical experiments indicate that tectonic processes control the thermal evolution of mountain belts, and thus the pressure–temperature (*P–T*) paths pursued by metamorphic rocks within orogens (Oxburgh & Turcotte 1974; England & Richardson 1977; England & Thompson 1984). Clearly, if we can reconstruct the *P–T* history of a metamorphic terrane, then we should be able to use this information to assess the relative importance of different heat-transfer mechanisms associated with tectonic activity.

In theory, the Himalayan Orogen provides one of the world's great laboratories for the study of thermal processes because (1) the metamorphic core of the belt is immense (more than 100000 km^2 of exposure); (2) it contains abundant assemblages appropriate for *P–T* studies; and (3) extreme relief and the moderate northward dip of metamorphic units yield exposures of crustal sections that commonly exceed 10 km in thickness. Although there have been many studies of the distribution of metamorphic assemblages in the Himalaya and some attempts to estimate the peak *P–T* conditions of metamorphism by comparing observed assemblages with experimentally constrained petrogenetic grids (see Windley (1983), Le Fort (1986) and Pêcher & Le Fort (1986) for reviews), there have been very few quantitative studies of the *P–T* evolution of Himalayan metamorphic terranes. In 1985, we began studying the thermal history of three transects through the metamorphic core of the central Himalaya: the Dudh Kosi–Hongu–Hinku section of eastern Nepal, the Burhi Gandaki–Darondi section of central Nepal, and the Alaknanda–Dhauli section of north–central India. Our results, combined with those of Brunel & Kienast (1986) in eastern Nepal and Le Fort *et al.* (1987) in central Nepal, document a complex thermal history spanning much of Tertiary time, and they indicate a close relation between tectonic processes and thermal evolution. In this paper, we review the available data from the central Himalaya and discuss their implications for the relations between metamorphism and tectonics in the central Himalayan Orogen.

TECTONIC SETTING OF THE CENTRAL HIMALAYA

The product of the Eocene collision between India and Eurasia and subsequent intraplate deformation, the Himalaya can be divided into six tectonic zones running parallel to the length of the orogen. From north to south, these are: (1) the Transhimalayan Zone; (2) the Indus–Tsangpo Suture Zone; (3) the Tibetan Sedimentary Zone; (4) the Greater Himalayan Metamorphic Sequence; (5) the Lesser Himalayan Nappe Sequence; and (6) the Subhimalayan Zone (figure 1). The Transhimalayan Zone is dominated by calc-alkaline batholiths, which range in age from roughly 110 to 40 Ma (Brookfield & Reynolds 1981; Honegger *et al.* 1982; Maluski *et al.* 1982; Schärer *et al.* 1986), and which are thought to have been produced during northward subduction of Tethys beneath the southern margin of Eurasia before India–Eurasia collision. The Indus–Tsangpo Suture Zone consists of Mesozoic

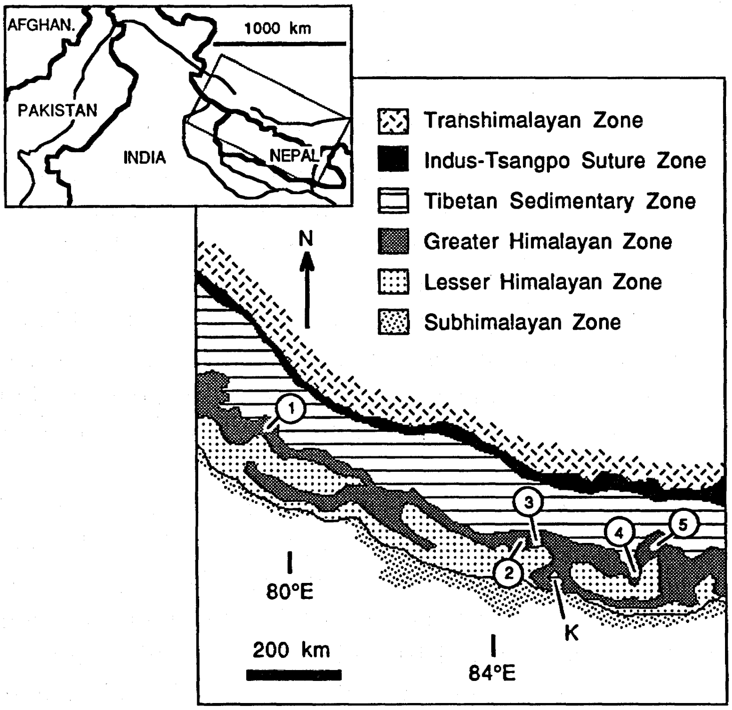

FIGURE 1. Generalized tectonic map of the central Himalaya after Le Fort (1975) and Pêcher & Le Fort (1986). Box in inset map shows the approximate boundaries of the central Himalaya. Circled numbers refer to *P–T* studies reviewed in the text: (1) eastern Garhwal (Hodges & Silverberg 1988); (2) west–central Nepal (Le Fort *et al.* 1986); (3) east–central Nepal (Hodges *et al.* 1988); (4) Everest region (Hubbard 1988); and (5) Makalu region (Brunel & Kienast 1986). K indicates location of Kathmandu.

ophiolites, arc volcanic rocks, and flysch marking the initial zone of collision (Gansser 1964; Bally *et al.* 1980). Various lines of geological and geophysical evidence, most of them indirect, imply that this collision began between 40 and 50 Ma (see Molnar 1984, for a review). South of the suture, the Tibetan Sedimentary Zone includes the miogeoclinal succession developed along the passive northern margin of India from Cambrian–Eocene(?) time (Gansser 1964; Le Fort 1975). The zone is structurally complex, exhibiting S-vergent recumbent folds and thrusts, N-vergent 'back-folds' and 'back-thrusts', and extensional structures with a variety of orientations, all of which developed during several late Cretaceous–Holocene(?) events (Le Fort 1975; Searle 1983; Burg & Chen 1984). For many years, unmetamorphosed rocks of the Tibetan sedimentary sequence were thought to rest unconformably on the metamorphosed 'Precambrian basement' of the Greater Himalayan Metamorphic Sequence (Gansser 1964). Recent mapping of the base of the Tibetan sedimentary sequence near the eastern Nepal–Tibet and Bhutan–Tibet borders (Burg *et al.* 1984; Burchfiel *et al.* 1986; Burchfiel, K. V. Hodges & L. H. Royden, unpublished data), as well as in Ladakh, India (Herren 1987), demonstrates that the contact in these areas is a N-dipping, low-angle normal fault zone of probable Miocene age. Similar observations in central Nepal (Caby *et al.* 1983) and Garhwal, India (Valdiya 1986), indicate that a major structural discontinuity may characterize the Tibetan Zone–Greater Himalayan Zone contact in many segments of the orogen.

Crystalline rocks of the Greater Himalayan Zone occur both in a continuous belt, which roughly coincides with the physiographic Greater Himalaya, and in klippen and half-klippen extending into the physiographic Lesser Himalaya. The zone is characterized by amphibolite facies pelitic to psammitic schists and gneisses, calc-silicate marbles, quartzites, amphibolites, and coarse orthogneisses (Le Fort 1975). Detailed structural studies of the Greater Himalayan Zone (Pêcher 1978; Brunel 1983) indicate polyphase deformational histories, but few workers have demonstrated the existence of major structural discontinuities within the sequence. In many areas, multiple generations of two-mica granitic dikes and sills invade the Greater Himalayan metamorphic rocks, and a series of Upper Oligocene–Miocene leucogranite plutons (e.g. Makalu, Manaslu, Bhagirathi-Badrinath and Nanga Parbat) lie near the top of the zone (Le Fort 1975, 1981). The Greater and Lesser Himalayan Zones are separated by the Main Central Thrust (MCT), a structurally complex zone up to 10 km thick (Pêcher 1978; Brunel 1986). The Lesser Himalayan nappe sequence consists primarily of low-grade metasedimentary rocks with metavolcanic intervals, but the structurally highest portions of some sections contain amphibolite facies assemblages (Le Fort 1975; Valdiya 1980). Unlike the Greater Himalaya, some of the least-metamorphosed strata in the Lesser Himalaya have yielded fossils ranging in age from Upper Precambrian to Lower Eocene (see Stöcklin 1980, for a succinct review). Detailed studies of the Lesser Himalaya in Garhwal (Valdiya 1980, 1981) and in western Nepal (Frank & Fuchs 1970) have demonstrated that the zone is structurally complex, but poor exposure generally limits the quality of mapping in the physiographic Lesser Himalaya and, thus, our understanding of structures. The base of the Lesser Himalayan Zone is defined as the Main Boundary Thrust (MBT) zone, a series of N-dipping faults with a cumulative displacement of demonstrably tens (Heim & Gansser 1939; Stöcklin 1980) and probably hundreds of kilometres (Powell & Conaghan 1973; Molnar 1984). The Miocene–Pleistocene Siwalik molasse (Gansser 1964; Johnson *et al.* 1979), which constitutes the bulk of the Subhimalayan Zone, forms the footwall of the MBT.

Despite the abundance of mesoscopic and macroscopic structures within the six tectonic zones of the Himalaya, most Himalayan geologists believe that much of the convergence within the range was accommodated along the Indus–Tsangpo Suture, the Main Central Thrust, and the Main Boundary Thrust. Various lines of structural, stratigraphic, and geochronologic evidence imply that the suture behaved as an intercontinental subduction zone by Eocene time, accommodating the initial collision of India and Eurasia. With continued convergence, the MCT and MBT formed as intracontinental subduction zones, permitting large-scale imbrication of the downgoing Indian Plate. Although the MBT cuts Plio-Pleistocene molasse units and must be very young, the age of the MCT is less certain. In some areas (e.g. Garhwal) (Valdiya 1980), the age of fossil assemblages exposed beneath klippen of MCT zone rocks in the physiographic Lesser Himalaya require the fault zone to be post-early Eocene. The most often cited argument for the age of the MCT depends on the assumption of a genetic relationship between the thrust and the Upper Oligocene–Miocene leucogranites of the Greater Himalaya (Le Fort 1975). If the south-vergent MCT has a late Oligocene–Miocene age, it could be part of a kinematically complicated group of structures that include north-directed back-thrusts and low-angle normal faults in the southern Tibet (Burg & Chen 1984). Burchfiel & Royden (1985) have suggested that the extensional structures in this group accommodated gravitational collapse of the Miocene topographic front as it was being built by movement on the MCT. By analogy with the western Alps (Milnes 1978), it is tempting to ascribe the present steep dip of the Indus–Tsangpo Suture, as well as the back-thrusts and spectacular back-folds south of the suture, to a ramp in the MCT where it projects beneath southern Tibet. Lyon-Caen & Molnar (1983) attributed the broadly antiformal nature of the Lesser Himalaya, and the presence of erosional remnants of the Greater Himalayan metamorphic sequence within the physiographic Lesser Himalaya, to a similar ramp structure in the MBT.

Inverted metamorphism in the central Himalaya

Most models of the thermal history of the Himalaya have focused on one of the most distinctive and controversial characteristics of the metamorphic core of the orogen: 'inverted metamorphism'. Throughout the central and eastern portions of the mountain belt, the basal Greater Himalayan Zone contains mineral assemblages characteristic of intermediate P–T metamorphism (kyanite + staurolite grade). The grade of metamorphism increases structurally upward to upper amphibolite facies (sillimanite ± cordierite) at the structural level occupied by the Upper Oligocene–Miocene leucogranite plutons (Gansser 1964; Thakur 1976). This apparently inverted metamorphic gradient is mimicked in some sections through the Lesser Himalaya; in central Nepal, the metamorphic grade ranges systematically from chlorite roughly 10 km below the principal structural discontinuity in the MCT zone to kyanite + staurolite at the thrust (Pêcher 1978). Pêcher (1978) and Caby *et al.* (1983) concluded that there is no apparent metamorphic discontinuity associated with the MCT in several central Nepal sections. This view has been disputed by Stöcklin (1980) who found a distinct metamorphic discontinuity across the Mahabarat Thrust, which he considered to be part of the MCT beneath an erosional outliner of the Greater Himalayan sequence (the Kathmandu nappe). In eastern Nepal (Brunel & Kienast 1986) and in Garhwal (Heim & Gansser 1939), the MCT has been mapped as a major metamorphic break, separating kyanite grade rocks in the hanging wall from chlorite grade rocks in the footwall.

Many mechanisms have been invoked to explain inverted metamorphism in the Greater and

Lesser Himalaya (Le Fort 1975, 1981; Thakur, 1980). These include: (1) thermal perturbations and local inversions of the geothermal gradient associated with the intrusion of the Greater Himalayan leucogranites; (2) recumbent folding and/or thrust imbrication of pre-existing 'normal' metamorphic sequences; (3) shear heating along the MCT; and (4) conductive heating of the Lesser Himalaya and concomitant cooling of the basal Greater Himalaya as a result of 'hotter-over-colder' thrusting. In recent years the last of these possibilities has become widely accepted. Such a model (figure 2) is especially appealing because it explains the observed isograd distribution and also provides a mechanism for producing the Greater Himalayan leucogranites: shear heating along the MCT and/or the release of Lesser Himalayan volatiles through prograde metamorphism might trigger anatectic melting near the base of the Greater Himalayan Zone (Le Fort 1975, 1981).

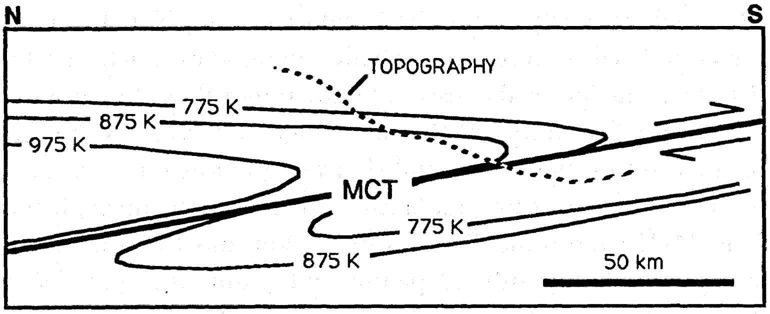

Figure 2. The Le Fort (1975) model for the development of inverted isograds in the Greater Himalaya.

If the Le Fort (1975, 1981) model is correct, then numerical models of the thermal effects of thrust faulting and subsequent uplift (Oxburgh & Turcotte 1974; England & Richardson 1977) suggest that metamorphic temperatures near the base of the Greater Himalayan sequence initially should have decreased during heating of the Lesser Himalayan footwall and subsequently increased as the rock column attempted to attain thermal equilibrium. If an influx of fluids from the devolatilizing footwall triggered the development of syntectonic metamorphic assemblages near the base of the hanging wall, and if an appropriate combination of rapid uplift and low radioactive heat production in the footwall prevented substantial re-equilibration of these assemblages during transport to the surface, then thermobarometric studies of the Greater Himalaya could yield direct evidence of the magnitude and length-scale of the temperature inversion caused by thrusting.

AVAILABLE CONSTRAINTS IN THE P–T EVOLUTION OF THE CENTRAL HIMALAYA

Within the central Himalaya, there have been five quantitative metamorphic studies that provide general insights into the thermal evolution of the Greater Himalaya and specifically yield some of the information necessary to evaluate the model of Le Fort (1975, 1981). From northwest to southeast (figure 1), the sampling areas for these studies were: (1) eastern Garhwal, India (Hodges & Silverberg 1988); (2) west–central Nepal (Le Fort *et al.* 1986); (3) east–central Nepal (Hodges *et al.* 1988; Hodges *et al.*, in preparation); (4) the Everest region, eastern Nepal (Hubbard 1988); and (5) the Makalu region, eastern Nepal (Brunel & Kienast 1986). A detailed discussion of the petrologic techniques used in these studies is well beyond the scope of this paper. Suffice it to say that three well-calibrated pelitic thermobarometers provided the bulk of the P–T data: the garnet–biotite geothermometer (Ferry & Spear 1978), the garnet–plagioclase–aluminum silicate–quartz geobarometer (Newton & Haselton 1981), and the garnet–muscovite–biotite–plagioclase geobarometer (Ghent & Stout 1983; Hodges & Crowley 1985). Those readers interested in the accuracy and precision limits of these thermobarometers should refer to Hodges & Crowley (1985) and Hodges & McKenna (1987). In addition, the studies by Hodges & Silverberg (1988), Hodges *et al.* (in preparation) and Hubbard (1988) include attempts to reconstruct the P–T paths followed by individual samples through a combination of Gibbs's method modelling of garnet zoning (Spear & Selverstone 1983) and garnet inclusion thermobarometry (St-Onge 1987).

Eastern Garhwal, India (*Hodges & Silverberg* 1988)

In the Garhwal Himalaya, northwest of the Nanda Devi massif (figure 1), the Main Central Thrust Zone is a complicated duplex system, which may be as much at 10 km thick in some sections (Valdiya 1980). The footwall consists of unmetamorphosed to weakly metamorphosed sedimentary rocks of late Precambrian–Eocene(?) age, whereas the hanging wall includes amphibolite facies rocks of probable Precambrian age (Valdiya 1980). The Alaknanda and Dhauli Valleys of eastern Garhwal provide natural cross sections through the 10–12 km thick hanging wall of the MCT (figure 3). The lower 3.1 km and the upper 6.9–8.9 km of these sections are composed predominantly of pelitic and psammitic gneisses; the intermediate 3.8–5.8 km of section is dominated by impure quartzites. Petrographic examination revealed that the two different pelitic–psammitic packages corresponded to two distinctive textural suites. Suite I includes samples collected within 3.1 km structurally above the MCT. These are

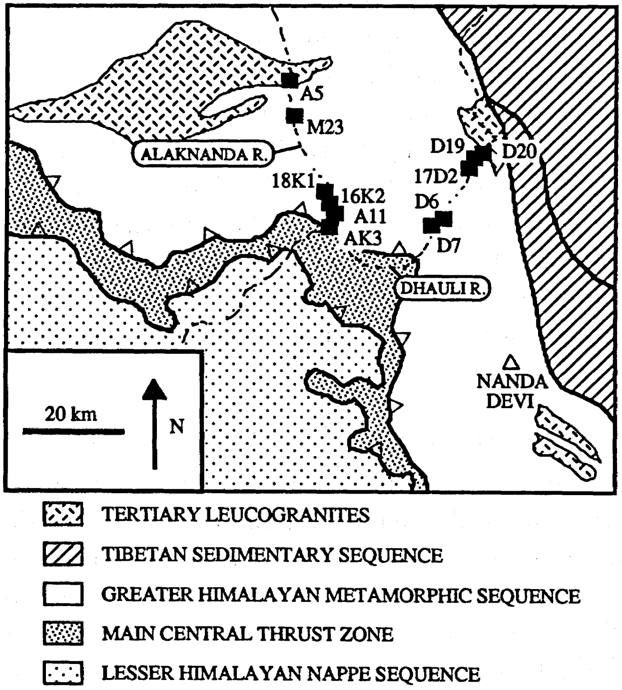

FIGURE 3. Generalized tectonic map of the Alaknanda–Dhauli area, Garhwal, showing sample localities. From Hodges & Silverberg (1988).

characterized by the assemblage: quartz ± muscovite + biotite + plagioclase + garnet ± kyanite. Garnets in Suite I samples are subhedral to anhedral, and were clearly prekinematic with respect to a prominent shear foliation defined by muscovite + biotite ± secondary chlorite. Because Hodges & Silverberg (1988) interpreted this foliation to have been related to movement on the MCT, they believed that these garnets grew before development of the thrust. Suite II samples, collected further than 6.0 km structurally above the thrust zone, contain quartz + biotite + muscovite + plagioclase + garnet ± microcline ± sillimanite. Garnets in these samples are subhedral and synkinematic with respect to the dominant muscovite + biotite + fibrolitic sillimanite schistosity in the rocks. Hodges & Silverberg (1988) inferred that this amphibolite facies schistosity developed significantly before the greenschist facies shear foliation observed in the structurally lower Suite I samples. Despite the clear textural distinctions between the Suite I and Suite II samples, existing geologic maps of the area (Valdiya 1979) indicate no major structural discontinuities between the upper and lower pelitic to psammitic sequences.

Conventional rim thermobarometry, garnet inclusion thermobarometry, and Gibbs's method modelling of garnet zoning yield P–T paths for the Suite I samples (AK3, A11, D7, D6, 16K2 and 18K1), which indicate nearly 15 km of uplift subsequent to tectonic burial at depths of at least 36 km. The Suite II samples give very different P–T paths that indicate an 80–90 K temperature increase and 5–7 km of burial. The apparent differences in Suite I and Suite II thermal histories, despite the lack of post-metamorphic structural discontinuity between the two samples suites, suggest that the different assemblages grew during two distinct metamorphic events: an early high P–high T event (M1), and a subsequent moderate P–high T event (M2). Preliminary Ar–Ar data for hornblende from the basal part of the sequence (P. Zeitler 1987, unpublished data) suggest a pre-late Eocene age for the first metamorphic event. Hodges & Silverberg (1988) believed that this event was associated with the early stages of India–Asia collision. M2 effects are strongest in the upper portions of the Greater Himalayan metamorphic sequence, near large leucogranite plutons (figure 3) and within a zone of intense migmatization. These relations suggest that the second metamorphic event was clearly related to leucogranite magmatism. In Garhwal, available geochronologic data (Seitz *et al.* 1976; Stern *et al.* 1988) do not closely constrain the age of these granites, but we infer a late Oligocene(?)–Miocene age by analogy with other Greater Himalayan leucogranites that have been dated more precisely (Schärer 1984; Deniel 1985; Schärer *et al.* 1986).

West–central Nepal (*Le Fort et al.* 1986)

Le Fort *et al.* (1986) presented conventional rim thermobarometric data for samples collected in the Kali Gandaki drainage south of Annapurna (figure 1). The samples represent the lower 3 km of the Greater Himalayan sequence and include one sample collected 200 m below the MCT zone (figure 5). In general, apparent temperatures increase downward between 3 and 1 km above the thrust; one sample indicates a moderate decrease in temperature just above the MCT (figure 6*a*). Le Fort *et al.* (1986) interpreted the low garnet–biotite temperature for the sample collected just above the thrust as indicative of conductive cooling of the hanging wall during thrust emplacement (figure 2). The thermobarometric pressure gradient is roughly twice that of a normal lithostat (figure 6*b*), indicating substantial re-equilibration of the samples during uplift.

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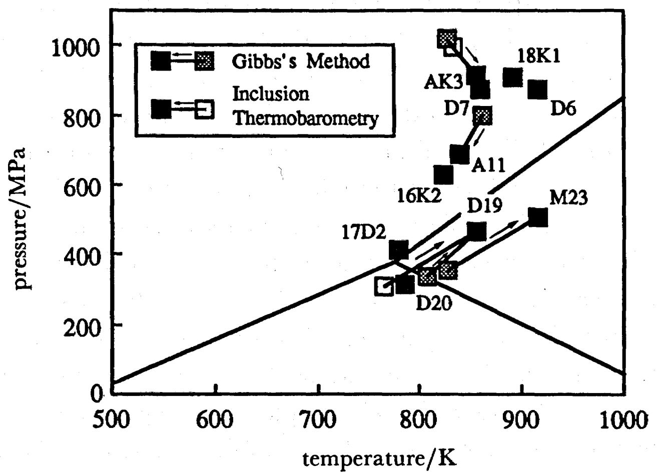

Figure 4. P–T paths for the samples shown in figure 3. Arrows indicate core to rim P–T trajectories calculated by using Gibbs's method (core P–T indicated by shaded boxes, rim P–T indicated by solid boxes) and inclusion thermobarometry (core P–T indicated by open boxes, rim P–T indicated by solid boxes). From Hodges & Silverberg (1988).

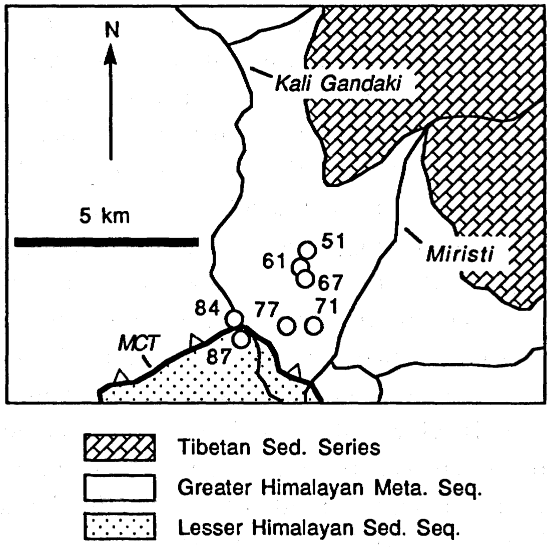

Figure 5. Simplified tectonic map of the Kali Gandaki–Miristi area, west–central Nepal, showing sample localities. After Le Fort *et al.* (1986).

East–central Nepal (*Hodges et al.* 1988)

Hodges *et al.* (1988) studied a suite of pelitic samples from the Darondi and Burhi Gandaki drainages southeast of Manaslu (figure 1). These samples represent a 12 km structural cross section of the Greater Himalayan sequence (figure 7). Caby *et al.* (1983) and Pêcher & Le Fort (1986) documented textural evidence for two prograde metamorphic events in the area: an early, high P–high T phase, and a later, intermediate P–high T phase. Thermobarometric data indicate that the second event was sufficiently widespread and intense that no record of the high P–high T event was recorded by mineral chemistry. There is excellent correspondence between the thermobarometric pressure gradient and a nominal lithostatic gradient (*ca.* 27 MPa km^{-1}; figure 8*a*). This result is not predicted by thermal models of simple burial

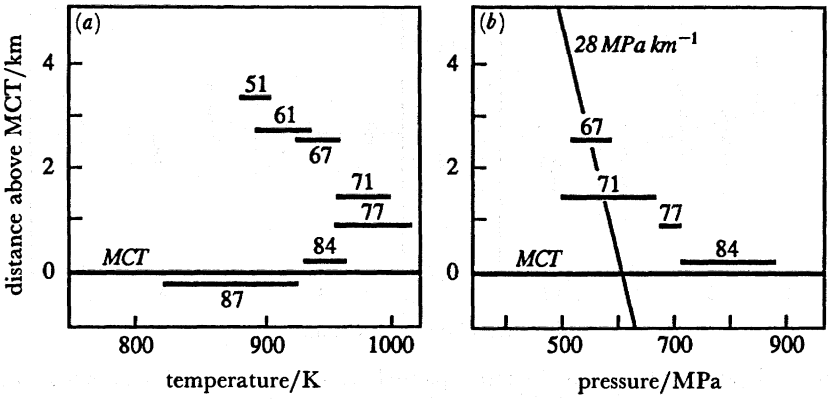

FIGURE 6. (*a*) Calculated temperatures for figure 5 samples plotted against structural distance from the MCT. (*b*) Calculated pressures against structural distance from the MCT. Reference lithostatic gradient (28 MPa km^{-1}) shown for reference. After Le Fort *et al.* (1986).

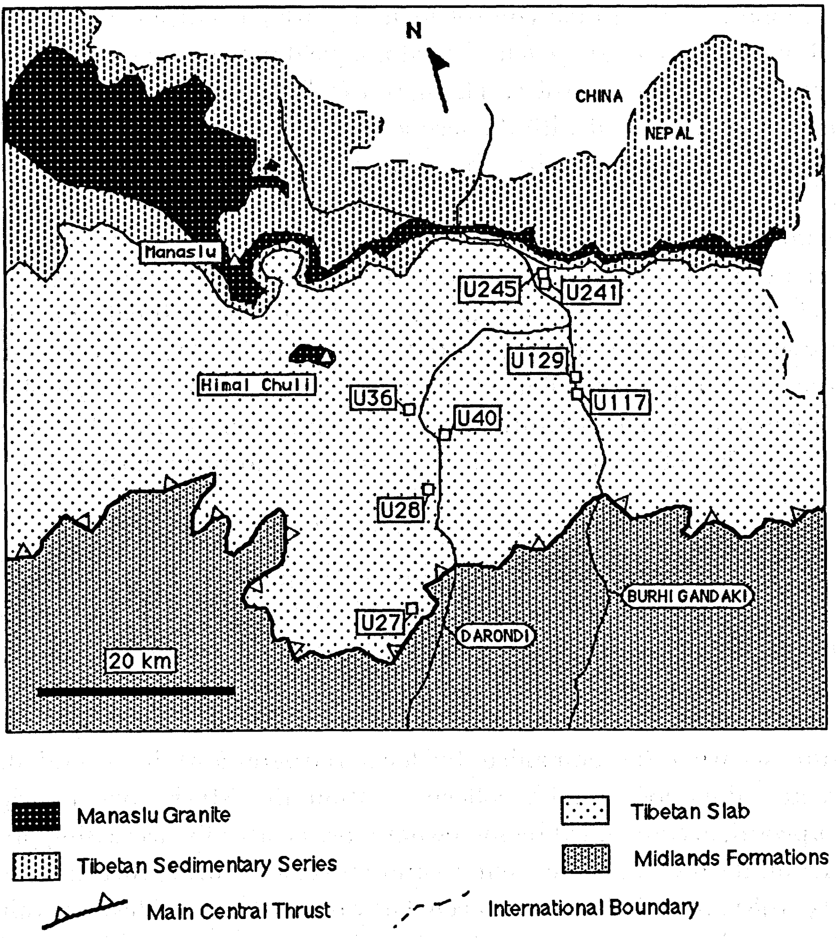

FIGURE 7. Simplified tectonic map of the Burhi Gandaki–Darondi region, east–central Nepal, showing sample localities. After Hodges *et al.* (1988).

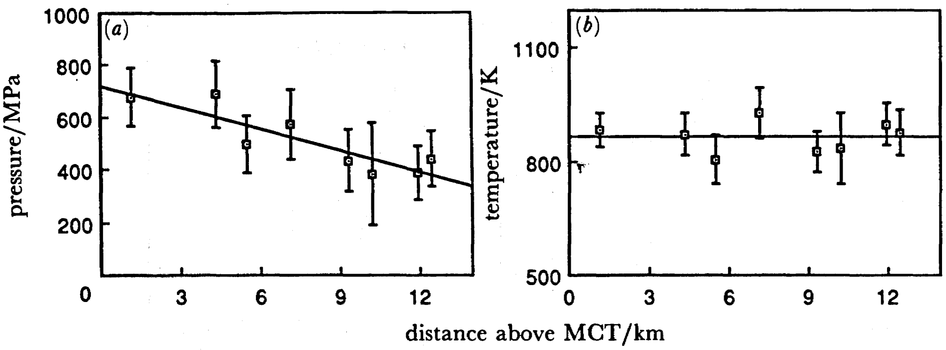

FIGURE 8. (*a*) Pressure estimates for the figure 7 samples plotted against structural distance above the MCT. Line indicates least-squares regression of the data, yielding a gradient of 27 MPa km^{-1} (P/MPa = 723–27z/km). (*b*) Temperature estimates for the Figure 7 samples plotted against structural distance. Line shows mean $T = 870$ K. From Hodges *et al.* (1988).

metamorphism followed by erosion-controlled uplift, which indicate that rocks at different structural levels in compressional orogens should not yield pressures corresponding to a normal lithostat (England & Thompson 1984; Thompson & England 1984).Thus, the data suggest that the thermal pulse associated with the second metamorphic phase was short lived and was followed by rapid cooling. Despite the reasonable lithostatic pressure gradient, the thermobarometric data indicate that the entire 12 km section was roughly isothermal during the second metamorphic event (figure 8*b*). This surprising result was interpreted by Hodges *et al.* (1988) as a consequence of widespread anatexis during the second metamorphic event, which effectively buffered temperatures throughout the Greater Himalayan sequence.

As an extension of the work described in Hodges *et al.* (1988), Hodges *et al.* (in preparation) have reconstructed P–T paths for four of the Burhi Gandaki–Darondi samples. All of these samples indicate increasing temperature and pressure from core to rim. The pressure increase implies more than 4 km of tectonic burial during the second metamorphic event.

Everest region, eastern Nepal (*Hubbard* 1988)

Hubbard (1988) studied metamorphic conditions along the Dudh Kosi, Hinku, and Hongu drainages south of Mt Everest (figure 1). In this area the MCT is a 3–5 km thick zone, which separates kyanite ± sillimanite grade hanging wall rocks from garnet or biotite grade footwall rocks (figure 9). Within the zone, strain was markedly inhomogeneous. Although narrow, high-tempreature mylonite zones are distributed throughout the sequence, some evidence exists for low-tempreature shearing (accompanied by local retrogression) in several discrete zones. Thermobarometric data for samples collected within the MCT zone indicate increasing temperatures upward, accompanied by somewhat more erratically decreasing pressures (figure 10*a*, *b*). In general, the data indicate a tempreature inversion during thrusting, consistent with Le Fort's (1975, 1981) model. Samples collected at various structural levels within the hanging wall of the MCT yield pressures and temperatures that vary unsystematically. This behaviour was interpreted as a consequence of either: (1) patchy, late-stage heating in the gneiss sequence associated with the injection of leucogranites; (2) post-metamorphic faulting, for which there is some field evidence: or (3) some combination of these. P–T paths calculated for MCT zone samples by using Gibbs's method modelling and inclusion thermobarometry vary from roughly

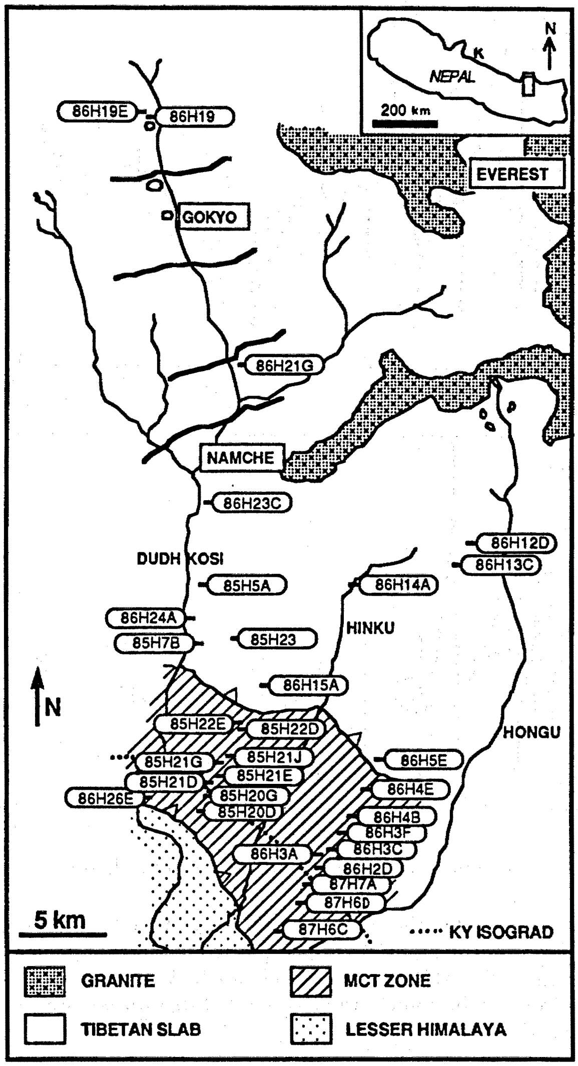

Figure 9. Simplified tectonic map of the Everest region, eastern Nepal, showing sample localities. From Hubbard (1988).

isobaric cooling to roughly isothermal decompression, indicating a complicated thermal history for rock units within the zone before final mineral rim equilibration.

Makalu region, eastern Nepal (*Brunel & Kienast* 1986)

Brunel & Kienast (1986) analysed a collection of pelitic samples from the Greater Himalayan gneisses of eastern Nepal, near Makalu (figure 1). Although most of the samples came from the main outcrop belt of the gneisses in the upper Barun Valley, some were collected from erosional outliers that are part of the Kathmandu Klippe. Together the samples represent the lowermost 3 km of the Greater Himalayan sequence. Two phases of prograde metamorphism were identified petrographically: an early phase, during which kyanite ± staurolite assemblages were produced in the lower part of the section; and a later phase, during which sillimanite ± cordierite assemblages crystallized in the upper part of the section. Garnet–biotite and garnet–plagioclase–aluminum silicate–quartz thermobarometry were used

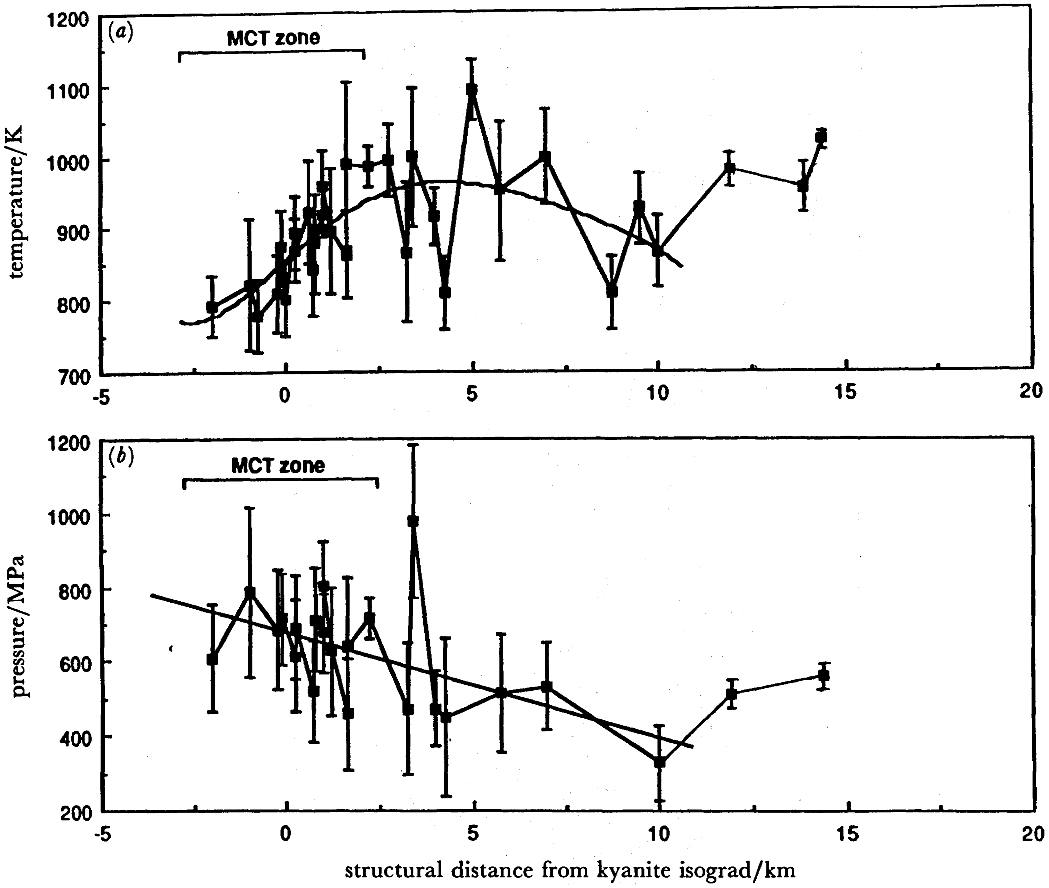

FIGURE 10. (*a*) Temperature estimates for the figure 9 samples plotted against map distance from the kyanite isograd. (*b*) Pressure estimates for the figure 9 samples plotted against map distance from the kyanite isograd. In both diagrams, the limits of the MCT zone are indicated. An approximate 30 °N dip of the MCT zone means that map distances in these diagrams can be converted to approximate structural distances by dividing by 2. From Hubbard (1988).

to estimate conditions of 825–925 K and 600–900 MPa (equivalent to depths of 22–33 km) for the first event near the base of the slab, and 785–990 K and 350–500 MPa (13–19 km) for the second event near the Makalu leucogranite pluton (figure 11). There is no systematic relation between structural level and calculated *P–T* conditions for either event. Based on metamorphic textures and the thermobarometric data, Brunel & Kienast (1986) inferred *P–T* paths that involved: (1) high-pressure metamorphism of the entire Greater Himalayan sequence; (2) decompression of the basal part of the sequence between the two metamorphic events; and (3) selective heating of the upper part of the sequence, associated with intrusion of the Makalu granite, during decompression.

CONTROLLING FACTORS IN THE THERMAL EVOLUTION OF THE HIMALAYA

Although two of the studies outlined above (Hubbard 1988; Le Fort *et al.* 1986) generally support the thermal model of Le Fort (1975, 1981), it seems clear from the data that the Greater Himalayan sequence in Garhwal and Nepal experienced at least two prograde

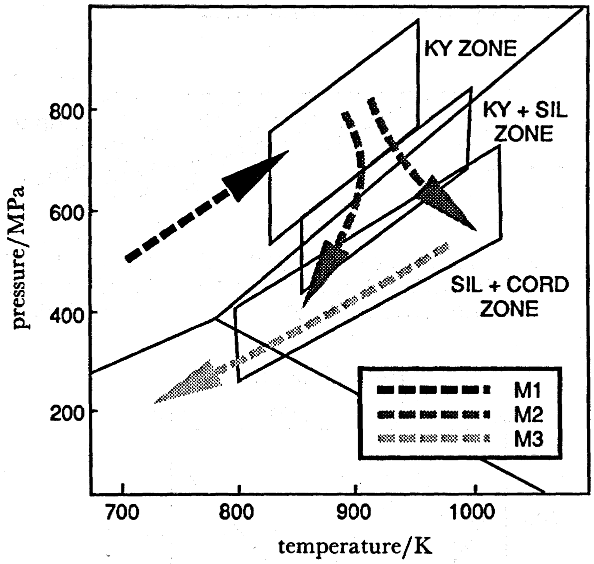

Figure 11. P–T trajectories inferred by Brunel & Kienast (1988) from P–T data for the Makalu area, eastern Nepal. Rhombic fields indicate range of calculated P and T for kyanite, kyanite+sillimanite, and sillimanite+cordierite zone samples. After Brunel & Kienast (1986).

metamorphic events in Tertiary time. This observation implies that the Tertiary thermal structure of the Himalayan metamorphic core was influenced by a variety of tectonic processes in addition to movement on the MCT. It is convenient to think of these processes in the context of five tectonothermal stages in the history of the central Himalaya. These stages are depicted in figure 12 as a series of schematic cross sections through the central Himalaya, accompanied by generalized P–T paths for an arbitrary sample from the middle of the Greater Himalayan sequence.

Early continental subduction: middle Eocene to early Oligocene

Studies of continent–continent collisional belts suggest that some fraction of the post-collisional shortening between the continents involves ‘subduction’ of portions of the continental lithosphere (Hodges *et al.* 1982). This may involve interplate (‘B-type’) subduction of the leading edge of one of the continental masses, or intraplate (‘A-type’) subduction in one or both masses (terminology after Bally 1980). Geologic and geophysical data indicate that the leading edge of India became involved in both of these processes during Himalayan orogenesis (Roecker 1982; Mattauer 1986). Although many studies have emphasized the importance of the Main Central and Main Boundary Thrusts in the development of the Himalaya, recent mapping in southern Tibet (Burg & Chen 1984) and northwest India (Searle 1986) has demonstrated the existence of numerous compressional structures north of and structurally above the Greater Himalayan sequence. Some of these structures appear to have accommodated several tens of kilometres of crustal shortening before development of the MCT (Burg & Chen 1984).

It seems likely that the Greater Himalayan sequence experienced high-pressure, high-tempreature metamorphism as a consequence of early Tertiary A-type and B-type subduction of the Indian Plate margin, and we infer that this was the early metamorphic event recognized in Nepal and Garhwal (figure 12a). Thermobarometric data from several transects indicate

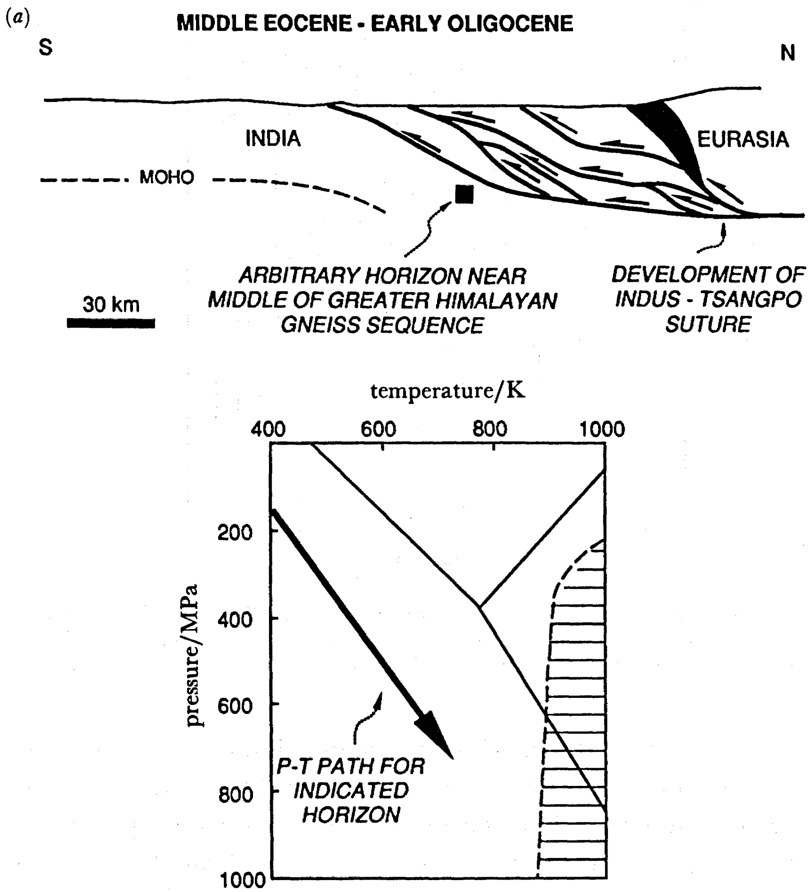

FIGURE 12. Interpretive model for the tectonothermal evolution of the Greater Himalaya in the central Himalaya. Half arrows on the schematic cross sections indicate active structures during the time intervals shown. Solid arrows indicate P–T trajectory during each time interval for the arbitrary horizon marked by a solid box in the cross sections. Field with horizontal lines in the P–T diagrams indicates approximate conditions of water-saturated anatexis of pelites. See text for further explanation.

that the basal portions of the metamorphic sequence were tectonically buried to depths in excess of 30 km.

Early uplift: early to late Oligocene

The Garhwal and eastern Nepal transects yield data which indicate that the Greater Himalayan sequence experienced a minimum of 10 km of uplift after high-pressure, high-temperature metamorphism and before intermediate-pressure, high-temperature metamorphism (figure 9*b*). The Garhwal P–T paths are similar to those predicted by theoretical models of 'erosion-controlled' uplift (England & Richardson 1977), and do not clearly suggest that tectonic denudation played a role in their unroofing. None of the available data constrain uplift rates during this interval.

Late heating and burial: late Oligocene

The top of the Greater Himalayan sequence is characterized by the occurrence of leucogranite sills, dikes and plutons that commonly yield late Oligocene–middle Miocene crystallization ages. Metamorphic studies in Garhwal, central Nepal and eastern Nepal

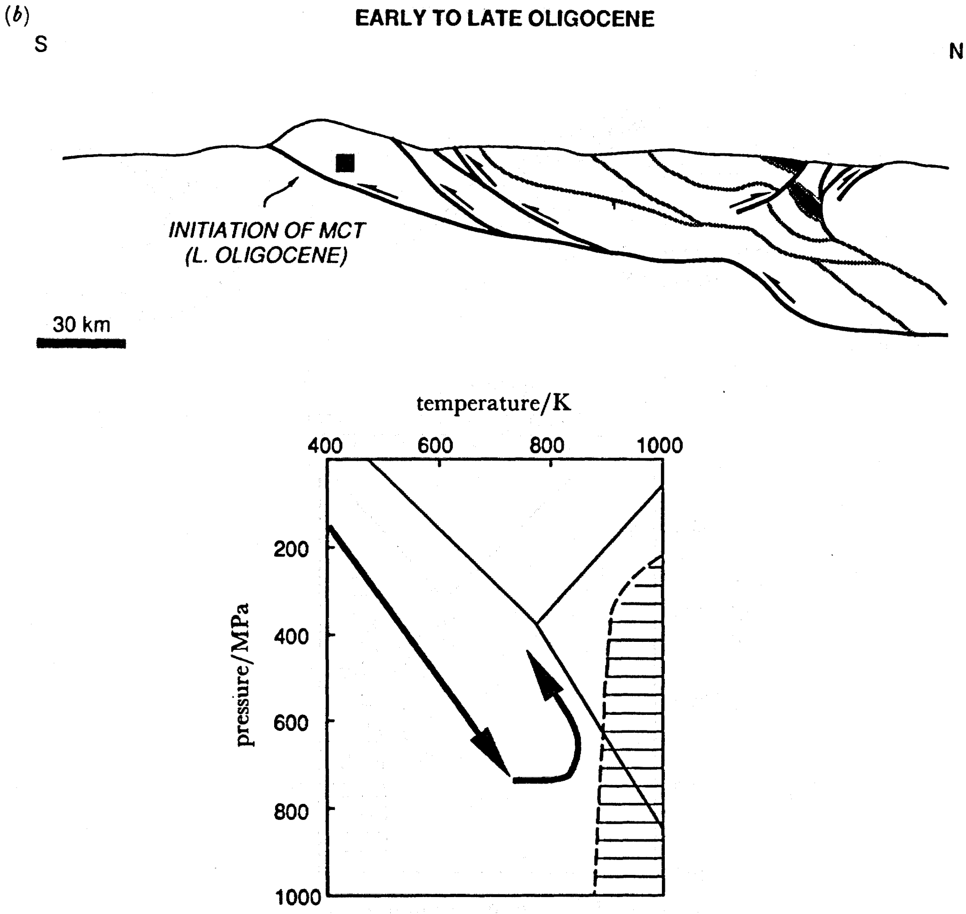

Figure 12. (*b*) For description see opposite.

demonstrate that these granites were intimately associated with sillimanite ± cordierite grade metamorphic assemblages in the surrounding country rocks. An abundance of geochemical data (Le Fort *et al.* 1987) indicates that the granites are anatectic melts of portions of the Greater Himalayan Metamorphic Sequence. In some sections (e.g. Burhi Gandaki–Darondi), the structurally high granite plutons appear to have been derived from the presently exposed, structurally lower portions of the gneiss sequence. In other sections (e.g. Alaknanda–Dhauli), granites are conspicuously rare in the basal part of the sequence, and the granites must be *in situ* melts or, alternatively, they must have an unexposed provenance. Where granites are common throughout the Greater Himalayan sequence, anatexis may have buffered the tempreature of the sequence for a significant period of time (Hodges *et al.* 1988).

The relation between the second metamorphic event, the Greater Himalayan leucogranites, and movement on the MCT remains unclear. Textural relations and thermobarometric data suggest that the intermediate-pressure, high-temperature metamorphic event in central Nepal and in the Dudh Kosi–Hongu–Hinku transect of eastern Nepal was synchronous with early movement along the MCT. However, most transects show some evidence of post-metamorphic movement along the MCT and in some areas the MCT appears to be exclusively post-metamorphic. In practice, the MCT is mapped at the boundary between the physiographic Greater and Lesser Himalaya. It seems clear that this topographic break does not everywhere

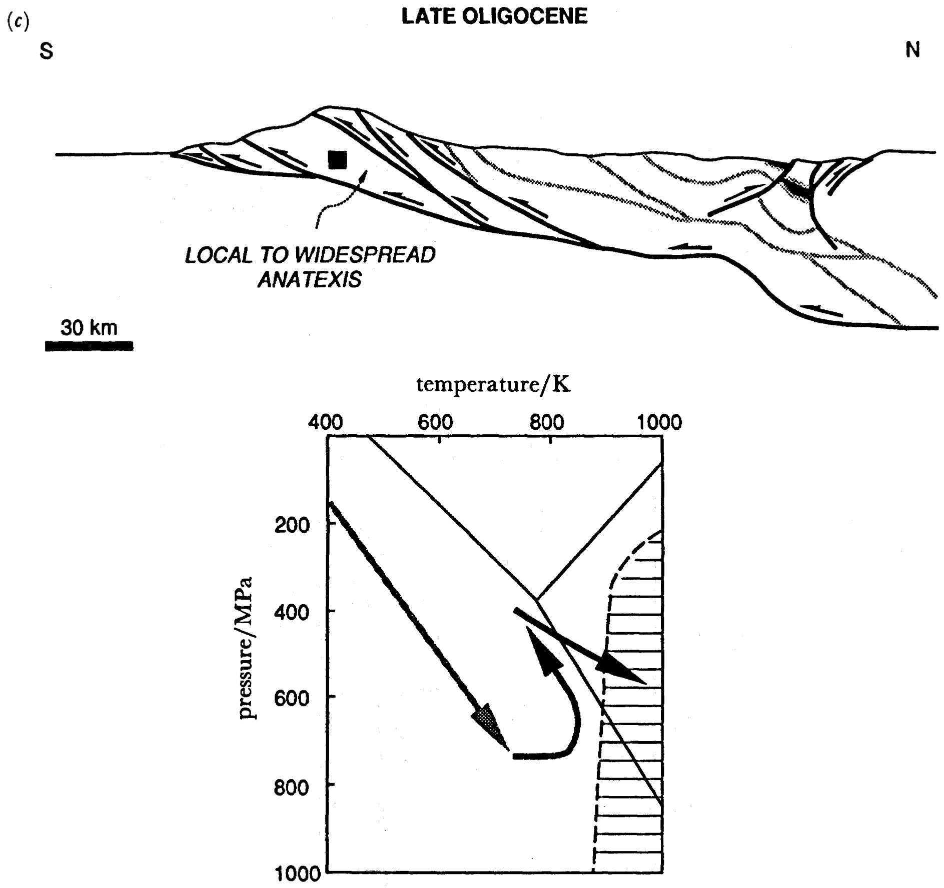

FIGURE 12. (*c*) For description see p. 270.

correspond to the same fault, and this diachroneity is a major contributing factor to the controversy concerning the thermal significance of the 'MCT'.

Some of the most thought-provoking results of the Garhwal and east–central Nepal petrologic research were *P*–*T* paths indicative of several kilometres of tectonic burial during intrusion of the leucogranites and second-stage metamorphism. The similarity of these paths for samples from widely separated areas indicates that the burial event affected a large portion of the metamorphic core of the Himalaya (figure 12*c*). Many compressional structures in southern Tibet and northwest India appear to be the right age to account for this burial (Burg & Chen 1984; Searle 1986), but the general lack of detailed mapping in much of the Tibetan Sedimentary Zone limits our understanding of the process.

The ultimate heat source for anatectic melting of the Greater Himalayan gneisses remains the greater unanswered question concerning the thermal evolution of the Himalaya. A variety of explanations have been proposed.

Le Fort (1981) suggested that melting was triggered by the influx of metamorphic fluids from the footwall of the MCT, and that the hanging wall had retained enough residual heat from the first metamorphic event to permit melting. Unfortunately, if the preliminary hornblende Ar–Ar data from Garhwal are to be trusted, then the Greater Himalaya (in that region, at least) had cooled to below 775–825 K (the nominal range of closure temperatures for Ar in hornblende; Harrison 1981) well before the anatectic event.

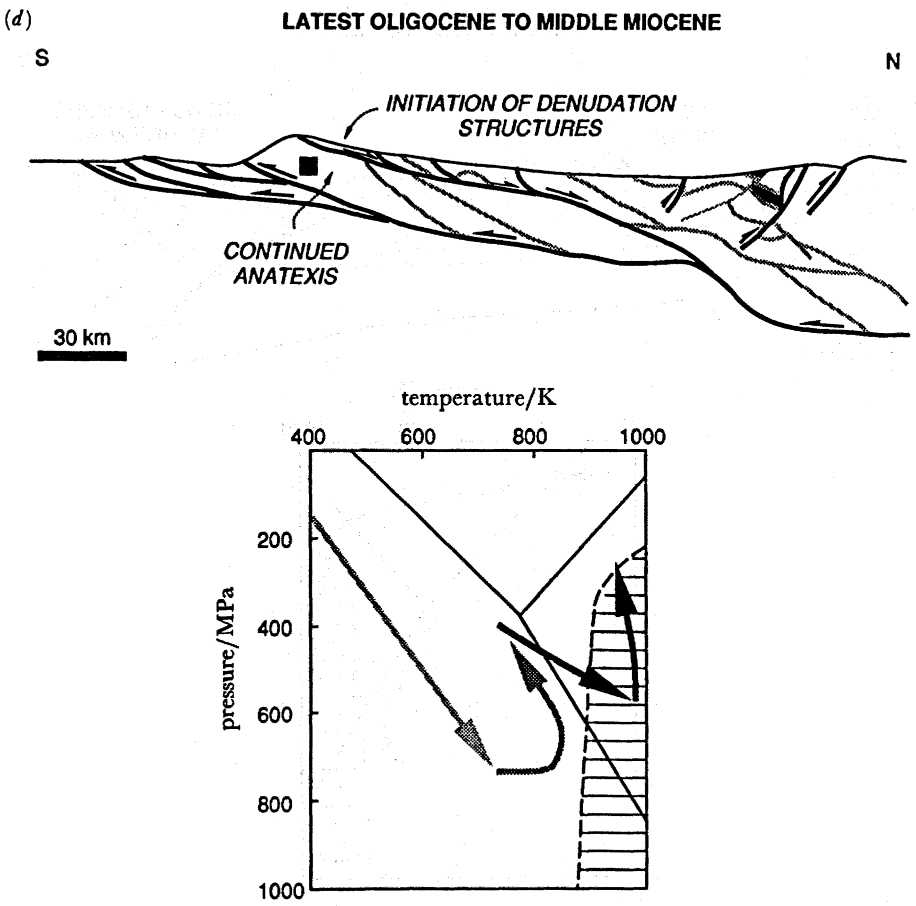

Figure 12. (*d*) For description see p. 270.

Some workers (Le Fort 1975; Scholtz 1980) have attributed the melting to frictional heating along the MCT. Although this phenomenon may have contributed some heat to the system, it is unlikely to have been the dominant cause of melting (Molnar *et al.* 1983).

Bird (1978) proposed that the Greater Himalaya could have been heated as a consequence of delamination of the Indian lithosphere, subduction of the lower lithosphere, and consequence upwelling of the asthenosphere. Stern *et al.* (1988) have suggested that this process may have triggered anatectic melting. This hypothesis is virtually impossible to test, but it seems unusual that it would have produced melting in such a restricted area.

Jaupart & Provost (1985) attributed the melting to 'heat focusing' near the top of the Greater Himalayan sequence. In effect, they suggested that the contrast in thermal conductivity across a thrust contact between the Greater Himalayan gneisses and the Tibetan sedimentary sequence acted as a thermal barrier that led to unusually high temperatures at the top of the gneiss sequence. There are two problems with this model: (1) the predicted temperature discordance is not sufficiently abrupt to produce the distinct metamorphic break observed at this contact; and (2) where the Greater Himalayan sequence – Tibetan sedimentary sequence contact has been mapped as a fault, sense of shear indicators suggest normal rather than reverse movement, and the structure is demonstrably post-metamorphic (Burg & Chen 1984; Burchfiel *et al.* 1986; Herren 1987).

Another possibility is that the limited distribution of anatectic melts reflects local

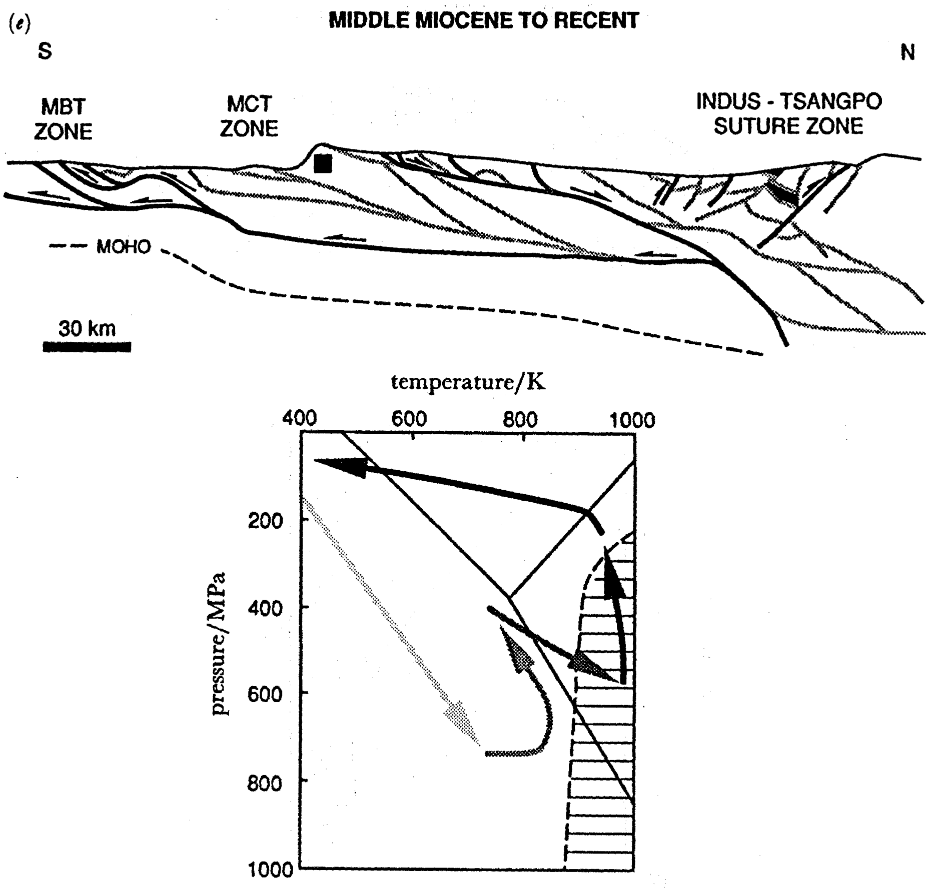

FIGURE 12. (*e*) For description see p. 270.

concentrations of heat-producing elements in the Greater Himalayan sequence (Pinet & Jaupart 1987). We have been impressed by the fact that many of the pelitic samples that we have studied include up to 1 modal % zircon, monazite, apatite and xenotime. Vidal *et al.* (1982) determined U, Th, K concentrations in a few Greater Himalayan gneiss samples from central Nepal that imply heat production rates of up to 3 mW m^{-3}, roughly three times greater than 'nominal' heat production rates in the Earth's crust (Jaupart & Provost 1985). Heat production of this magnitude would have a profound influence on the thermal structure of the gneiss sequence. If the heat-producing elements were unevenly distributed, then it seems plausible that more radioactive portions of the sequence might have melted during late Oligocene burial whereas less radioactive portions did not. Although Pinet & Jaupart (1987) argue for the importance of this process based on the trace-element chemistry of the leucogranites, we know too little as yet about heat-production rates in the gneisses to realistically evaluate the affects of internal heat production on the thermal evolution of the Greater Himalaya.

Tectonic denudation: latest Oligocene to middle Miocene

An increasing body of structural and geochronological data indicate that large-scale low-angle normal faulting occurred along the Greater Himalayan–Tibetan series contact in latest Oligocene–middle Miocene time (Burg *et al.* 1984; Burchfiel *et al.* 1986; Herren 1987).

Although we have no precise estimates, we feel that the amount of tectonostratigraphic throw on these structures must have been large. In the Rongbuk Valley of southern Tibet, for example, the principle normal fault zone places essentially unmetamorphosed Ordovician strata onto Greater Himalayan lithologies, which were apparently metamorphosed to sillimanite grade in late Oligocene–early Miocene time.

The structural characteristics of these fault zones are analogous with the detachment systems that separate metamorphic core complexes of the North American Cordillera from their unmetamorphosed structural cover (Coney 1980). Numerical models of the thermal consequences of detachment development (Furlong & Londe 1986; England & Jackson 1987; Ruppel *et al.* 1988) demonstrate that footwall metamorphic rocks experience P–T trajectories characterized by substantial decompression with little cooling followed by rapid cooling at shallow levels. Three lines of evidence, all circumstantial, suggest to us that tectonic denudation may have had an important thermal effect on the Greater Himalayan sequence (figure 12*d*). First, we have seen little indication in the M2 assemblages from Garhwal or Nepal for substantial re-equilibration during cooling from peak temperatures. Such re-equilibration is ubiquitous in high-grade metamorphic rocks from most compressional belts (Tracy *et al.* 1976; Hodges & Royden 1984), and its virtual absence in the central Himalaya may indicate rapid cooling from near-peak temperatures. Second, the apparent preservation of a lithostatic pressure gradient in the Burhi Gandaki–Darondi section, as well as inverted temperature gradients immediately above the MCT in the Kali Gandaki and Everest transects, suggest 'quenching' of the Greater Himalaya rather than slow uplift.

Our third argument in favour of tectonic denudation involves the observation that leucogranite plutons in the Greater Himalaya yield a range of high-precision radiometric ages: in the Manaslu and Everest leucogranite suites, Deniel *et al.* (1987) and Schärer *et al.* (1986) have documented multiphase intrusive events that occurred over an interval of several million years. Tectonic denudation of the Greater Himalaya after late Oligocene burial could result in a P–T path that remained within the region of water-saturated granite melting over much of the latest Oligocene–middle Miocene interval (figure 12*d*).

Final uplift: middle Miocene to Recent

In the central Himalaya, final uplift of the metamorphic core was accommodated by: (1) simple isostatic readjustment of a thickened crust; (2) movement over ramps in major faults which are structurally lower (e.g. the Main Boundary Fault); and (3) continued tectonic denudation (figure 12*e*). Pressure estimates from the petrologic studies cited above indicate that the Greater Himalaya have experienced roughly 15–20 km of uplift since late Oligocene–early Miocene time, for an average uplift rate of 0.6–0.8 mm a^{-1}. Exactly how much post-Oligocene uplift occurred before the middle Miocene and how much occurred after remains poorly constrained. Based on the arguments presented above, we believe that several kilometres of tectonic denudation occurred before middle Miocene time at rates significantly greater than 0.6–0.8 mm a^{-1}.

CONCLUSIONS

Reconstructions of the P–T evolution of the Greater Himalayan sequence in five widely spaced areas in the central Himalaya suggest a complicated Tertiary thermal history. Several of the areas exhibit clear evidence for an early intermediate-to high-pressure, intermediate-temperature thermal event, followed by a later low-to intermediate-pressure, high-temperature event. We believe that the early event can be attributed to middle Eocene–early Oligocene loading of the sequence as a consequence of intracontinental subduction. The later event appears to be intimately associated with high-temperature movements of the MCT and the generation and intrusion of leucogranites in latest Oligocene–middle Miocene time. Calculated *P–T* paths uniformly indicate that the second event involved several kilometres of tectonic burial, presumably as a consequence of structurally higher thrust imbrications. The lack of substantial high-temperature retrogression of the assemblages produced in the second event, the preservation of inverted temperature gradients and normal lithostatic pressure gradients above the MCT, and the multi-episodic nature of leucogranite production in the Greater Himalaya imply that tectonic denudation by movement on north-dipping normal fault systems resulted in rapid uplift of the sequence over the latest Oligocene–middle Miocene interval.

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Discussion

P. J. TRELOAR (*Department of Geology, Imperial College, London, U.K.*). Professor Hodges equates an 'M1' metamorphism with deformation associated with the MCT, and an 'M2' metamorphism with post-MCT crustal thickening related to breakback thrusting in the MCT hanging wall. 'M1' followed an earlier Barrovian-type regional metamorphism, which I shall call 'M0', which was presumably related to pre-MCT post-collisional crustal thickening. 'M0' may be the same age, tectonically if not necessarily temporally, as the regional metamorphism described in Zanskar where the isograds were subsequently folded (Searle *et al.* this symposium) and in N Pakistan where they were subsequently imbricated during late-stage thrusting (Coward *et al.* this symposium). Is there evidence in Professor Hodges's area that, as in Zanskar and N Pakistan, the 'M0' metamorphism accompanied a normal, as opposed to inverted, thermal gradient? The thrusting along the MCT may be part of the same broad deformation event as both the recumbent folding of isograds in the MCT hanging wall in Zanskar, and the thrusting and imbrication of isograds in N Pakistan along structures that appear to be analagous to the MCT. The continuation of metamorphism post-MCT (the 'M2' event) in Nepal, suggests that metamorphism there continued later into the deformation sequence than in the areas farther west where the MCT-age deformation was not followed by a major late phase of regional metamorphism. Is there a simple regional or thermal explanation for this?

The status of the MCT-related inverted metamorphism seems problematic. Is it: (*a*) a tectonic overfolding of earlier isograds, the original Le Fort model; (*b*) a tectonic imbrication due to post-metamorphic thrusting within the MCT zone; (*c*) an inverted metamorphism driven by downward heating from an overlying slab; or a combination of all three? Searle (this symposium) favours (*a*) for Zanskar and (unpublished) for Darjeeling; Professor Hodges appears to favour (*b*) for the Garhwal schuppen zone; whereas Hubbard (cited by Professor Hodges) appears to favour (*c*) although acknowledging a substantial syn- to post-metamorphic modification of the inverted profile. Is it possible to combine all of these disparate interpretations into a single model, possibly involving a syn-MCT nappe (locally a fold nappe, locally a thrust nappe) developed in the MCT hanging wall. This would have recumbently folded earlier isograds, in places telescoping them or even cutting them out altogether along thrust surfaces along the inverted limb within the MCT zone. The complete cutting out of parts of the metamorphic sequence would create the right local conditions for the Hubbard model of downward heat transfer. In such an overall model the MCT, a ductile shear zone of variable (up to 10 km) thickness, could be viewed as a ductile detachment zone under the nappe within which an earlier metamorphic sequence could be inverted, telescoped and imbricated along a number of shear surfaces with a local, and maybe rare, direct imposition of hot slabs on top of cold ones driving a second stage syn-MCT inverted metamorphism. In such a complicated zone, and the use of the term 'zone' rather than 'thrust' is deliberate, it may not always be possible to separate which of the possible causes of 'inverted metamorphism' is dominant at any particular locality.

K. V. Hodges. Albert Einstein has been quoted as saying that explanations of physical phenomena should be as simple as possible, but no simpler. Inverted metamorphic field gradients are common in a variety of tectonic settings, and it is safe to assume that different mechanisms could be responsible for this phenomenon in different places. In the Himalaya specifically, I am not convinced that a single model satisfies all of the data gathered throughout the orogen. In some areas (such as the Kali Gandaki and Dudh Kosi drainages) the simple Le Fort (1975, 1981) model of conductive cooling of an overthrust MCT nappe appears to be consistent with the vast majority of the petrologic data. In other areas, models involving post-metamorphic imbrications or recumbent folding of pre-existing isograds seem to provide better fits to the data. Dr Treloar's suggestion of a 'unified' hypothesis to explain the general relations between inverted metamorphism and the MCT is certainly worthy of further scrutiny, but I think that we have to be careful not to over-generalize a complicated process. We must recognize that 'Main Central Thrust' has become an unfortunate generic term for any fault zone that separates the Greater and Lesser Himalaya. It is quite likely that the MCT as mapped in Garhwal is totally unrelated the MCT as mapped in Darjeeling. In part, I think that much of the confusion about the relations between the MCT and metamorphism arises because the 'MCT' developed at different times with different thermal significance in different places.

Moreover, polymetamorphism has greatly complicated the issue, at least in the central Himalaya. I am convinced that the occurrence of high-temperature (sillimanite + cordierite ± potassium feldspar) assemblages above lower-temperature (kyanite + staurolite) assemblages in this sector is the consequence of two distinctive metamorphic events. The early (essentially 'Barrovian') event affected the entire Greater Himalayan sequence, whereas the late (essentially 'Buchan') event affected the entire sequence in some areas (e.g. the Burhi Gandaki section) but was restricted to the uppermost portions of the sequence in most other areas. (To specifically answer Dr Treloar's question, there is no convincing evidence from the central Himalaya of inverted thermal gradients during the Barrovian event.) The second event seems intimately related to the generation of the Greater Himalayan leucogranites, and those areas which were most strongly affected by the second event correspond to zones of intense migmatization. In our paper we argue that the second event was associated with several kilometres of tectonic burial, but the dominant heat source for this metamorphism appears to have been within the Greater Himalayan sequence. Several workers have speculated on the possible cause of this metamorphic/anatectic event, and we have tried to summarize their arguments in our paper. I do not think we have sufficient data to critically evaluate the models proposed, but I suspect that the sporadic development of second-event assemblages was caused by locally high concentrations of heat-producing elements within the Greater Himalayan sequence (Pinet & Jaupart 1987).

A. Mohan (*Department of Geology, Banaras Hindu University, India*). My point is regarding Professor Hodges's approach of conventional rim temperature estimates. Garnet profiles from different zones of inverted metamorphic sequences generally reveal prograde zoning from core to near rim. But this trend is often reversed when rim composition is taken into account. Therefore, the near-rim compositions should be used in estimating the temperature.

Professor Hodges shows in his diagrams of P/T against distance from MCT that there are situations when both P and T increase upwards above the MCT, in addition to increasing T–decreasing P points. Why has he dropped those earlier points reflecting increasing P/T and only considered those data with increasing T–decreasing P? That would explain the cause of inversion of metamorphic isogrades through the model proposed by Le Fort (1975). I have thermobarometric data from Sikkim–Darjeeling region for the garnet to sillimanite zones where P increases upwards with increasing T. These suggest that none of the models proposed for the cause of inverted isograds is fully relevant.

K. V. Hodges. I would disagree that the garnet profiles from Himalayan inverted metamorphic sequences are 'generally' indicative of prograde (i.e. increasing temperature growth). In my experience, a variety of zoning patterns indicative of prograde, retrograde, and perhaps even constant temperature growth occur in both M1 and M2 garnets. It is true that many garnets from the Himalaya show a pronounced inversion in their zoning patterns over their outermost 20–150 μm. This inversion is often characteristic of retrograde reequilibration during uplift. I consistently use the outermost rim compositions of phases in mutual contact for thermobarometry because these compositions are the most likely to reflect equilibrium. Rim equilibrium may have been attained substantially after peak temperature during uplift, but it is a fairly straightforward matter to access the higher-temperature portions of the P–T path for a sample by inclusion thermobarometry or thermodynamic modelling. It is tempting to try to reconstruct peak temperatures by using near-rim garnet compositions (rather that outermost rim compositions) as Dr Mohan suggests, but this technique if very dangerous: it is virtually impossible to know with any degree of certainty which part of the garnet profile represents 'peak temperature', and it is even more difficult to establish the composition of other phases that were in equilibrium with the chosen garnet composition without finding inclusions in the garnet. The common practice of calculating a 'peak temperature' by using the core composition of a garnet and the composition of a distant matrix biotite is completely inappropriate because there is no guarantee that the core of the garnet was ever in equilibrium with the biotite.

I believe that the second part of Dr Mohan's discussion refers to Mary Hubbard's data from eastern Nepal. There is certainly some scatter in the data, but we must remember that all measurements are subject to uncertainty. The uncertainties in thermobarometry are rather large (see Hodges & McKenna 1987), and it's not prudent to try to interpret each and every inversion in the apparent P–T gradient when those inversions occur over pressure and temperature ranges smaller than the analytical uncertainties. I think that the preponderance of Hubbard's data favour the Le Fort model, but late- to post-metamorphic imbrication within the MCT zone is likely to have occurred. Dr Mohan's data from Sikkim–Darjeeling may be inconsistent with the Le Fort model, just as our data from Garhwal seem inconsistent. Again, the thermal and mechanical processes that produced inverted metamorphism in the Himalaya are complex, and no single model seems universally applicable.