Did the Himalayan Crystallines extrude partially molten from beneath the Tibetan Plateau?

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Abstract: The hypothesis that the Himalayan crystalline core originated by ductile channel flow of partially molten mid-crust from beneath the Tibetan Plateau is critically reviewed. The proposal that widespread shallow anatexis exists beneath southern Tibet today is inconsistent with numerous observations (e.g. 'bright spots' restricted to a single rift and evidence that they represent aqueous fluids rather than molten silicate; the seismogenic southern Tibetan Moho; ^{3}He/^{4}He data indicating the presence of mantle heat and mass in the rift valley; the likelihood that any melt present is due to late Neogene calc-alkaline magmatism; the lack of Tertiary migmatites in the crustal section exposed in the uplifted rift flank of the Yangbajain graben; the lack of Gangdese zircon xenocrysts in the Greater Himalayan Crystallines (GHC); and the broadly coherent stratigraphy in the GHC). Evidence advanced in support of this model is equally or better explained as resulting from localized Neogene calc-alkaline magmatism. A recently developed rapid denudation/channel flow model does explain key petrogenetic and thermochronological features of the Himalaya, but is inconsistent with several geological constraints, most notably the small portion of the collision front over which focused erosion has localized exposure of the GHC. It is concluded that no evidence has yet been documented that requires the existence of partially molten crust flowing in a channel from beneath the Tibetan Plateau to form the Himalaya.

The Earth is an exceptionally complex system that preserves only a partial record of its evolution over a timescale that is difficult to conceive in its depth. Thus geologists tend to describe Earth history by interweaving quantitative modelling with storytelling. The advantage of this approach is obvious. For example, the development of the plate tectonic paradigm through 'geopoesy' permitted geologists to create a vision of planetary dynamics by temporarily overlooking quantitation of the underlying physical processes (Hess 1962; Wilson 1963; cf. Heirtzler & Le Pichon 1965). The disadvantage, however, is that much of what we observe and conclude exists in the form of words and thus is ambiguous or open to misinterpretation in a way that purely mathematical theories are only rarely subject to.

The current controversy regarding the proposal that the Himalaya originated via crustal channel flow from beneath Tibet – leading to the Geological Society of London conference on 'Channel Flow, Ductile Extrusion and Exhumation of Lower–mid-Crust in Continental Collision Zones' – is in part fuelled by imperfect translations between observation and inference, and qualitative and quantitative models. The base of this hypothesis rests on a series of factual observations, but some interpretations arising from these data have been poorly justified. This in turn has fed a growing number of offshoot models that may or may not subscribe to all the underlying assumptions of the root hypothesis. Deconstructing the myth that the crystalline core of the Himalaya formed by the extrusion of shallowly formed migmatites originating north of the Indus Tsangpo suture requires that the cross-pollination between qualitative and quantitative texts be separated and analysed in isolation.

This review begins by summarizing the consensus view of the geological setting of the Himalayan–Tibetan orogen and then outlines the salient petrogenetic features of the range that any successful evolutionary model must satisfactorily explain. The qualitative shallow-Tibetan-anatexis model (Nelson *et al.* 1996) is described, and is followed by a discussion of observations that appear inconsistent with this hypothesis. The work of the Dalhousie group to numerically model the origin of the Himalayan core via crustal channel flow from beneath the Tibetan Plateau (Beaumont *et al.* 2001, 2004; Jamieson *et al.* 2004) is then critically examined.

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Geological setting of the Himalaya and Tibet

Background

Immediately prior to the onset of the Indo-Asian collision between 60 and 50 Ma (Yin & Harrison 2000; Zhu *et al.* 2005), the northern boundary of the Indian shield was almost certainly a thinned margin on which Proterozoic clastic sediments and the Cambrian–Eocene Tethyan shelf sequence were deposited (Brookfield 1993). South-directed thrusts in the central Himalaya, including the Main Central Thrust (MCT), Main Boundary Thrust and the Main Frontal Thrust (Fig. 1A; Le Fort 1996), appear to sole into a common decollement, the Main Himalayan Thrust (MHT; Fig. 1B; Zhao *et al.* 1993; Brown *et al.* 1996). In general, the MCT places high-grade gneisses of the Greater Himalayan Crystallines (GHC) on top of the Lesser Himalayan Formations (LHF), comprised largely of intermediate to low-grade schists, phyllites, carbonate and minor metavolcanics and gneisses (Fig. 1B). The protoliths of the Lesser Himalayan formations and Greater Himalayan Crystallines are interpreted, respectively, to be Middle and Late Proterozoic clastic rocks (Parrish & Hodges 1996). Geochronologic studies (e.g. Parrish & Hodges 1996; Vance & Harris 1999) suggest that high-grade metamorphism first affected the protolith of the Greater Himalayan Crystallines during an early Tertiary, or Eohimalayan, phase of crustal thickening (Le Fort 1996). The Main Boundary Thrust juxtaposes schists of the Lesser Himalayan Formations (and locally Carboniferous to Permian Gondwanan sequences) against unmetamorphosed Miocene–Pleistocene molasse (Siwalik Group), and the Main Frontal Thrust places Siwalik strata over Quaternary deposits of the Gangetic plain (Fig. 1). Estimates of the amount of slip along the MHT based on balanced cross-section reconstructions (Coward & Butler 1985; Srivastava & Mitra 1994; Hauck *et al.* 1998; DeCelles *et al.* 2001; Murphy & Yin 2003) are consistent with a displacement of greater than 400 km.

The GHC are juxtaposed below lower-grade Tethyan shelf deposits by the South Tibetan Detachment System (STDS; fig. 1; Burchfiel *et al.* 1992). The timing of thrusting along the MCT is not well known but constrained by the knowledge that the GHC (i.e. the MCT hanging wall) was deforming at *c.* 22 Ma (e.g. Hodges *et al.* 1996; Coleman 1998) and that a broad shear zone beneath the GHC was active between about 8 and 4 Ma (e.g. Harrison *et al.* 1997). The STDS is known to have been active in several locations between 17 and 11 Ma (e.g. Edwards & Harrison 1997; Murphy & Harrison 1999), and may have been active earlier. While it is often assumed that slip along the MCT was simultaneous with displacement on the STDS, this is established in only a few cases locally (e.g. Hodges *et al.* 1996) and the generality of this assumption remains unproven (Murphy & Harrison 1999).

If, as originally assumed, the clastic package on the leading edge of India was metamorphosed via thrust imbrication to form the GHC, then it follows that exhumation of this package was via thrust-induced erosion (see review in Le Fort 1996). Following documentation that the STDS, which separates the GHC and Tethyan metasedimentary rocks, was a low-angle normal fault, it was speculated that the crystalline core of the Himalaya was exposed with no net horizontal extension between the STDS and MCT through gravity sliding (Burg *et al.* 1983; Burg & Chen 1984), orogenic collapse (Dewey 1988), rigid wedge extrusion (Burchfiel & Royden 1985) or ductile wedge extrusion (Grujic *et al.* 1996; Vannay & Grassemann 2001; Vannay *et al.* 2004). More recently, Grujic *et al.* (2002) proposed that the GHC was extruded as a low-viscosity fluid channel between two parallel shear zones.

Recent reviews of the current state of understanding of the evolution of the Himalayan–Tibetan orogen are given in Hodges (2000) and Yin & Harrison (2000), but two salient features of Himalayan geology stand out. Any successful model of the petrogenesis of the crystalline core of the Himalayan range must adequately explain the origin of the classic inverted metamorphic sequences and the paired leucogranite belts.

Inverted metamorphism

The juxtaposition of the GHC and LHF across the MCT is associated at most locations in the Himalaya with an increase in metamorphic grade with higher structural position (i.e. shallower depth; (Fig. 1B; e.g. Arita 1983; Pêcher 1989). The GHC vary substantially in thickness across the Himalaya. For example, the MCT hanging wall thickness increases from about 2 km in the central Himalaya (84°E; Colchen *et al.* 1986) to 20 km in Bhutan (89°E; Grujic *et al.* 1996), due to variable initial thickness, the MCT cutting up-section at certain locations, and imbrication within the MCT hanging wall. Thermobarometric studies of the GHC indicate a general decrease in pressure and temperature with increasing distance up-section in the GHC (see review in Harrison *et al.* 1999). Typically, pressures of *c.* 8 kbar were achieved adjacent to the MCT (kyanite grade) during the early

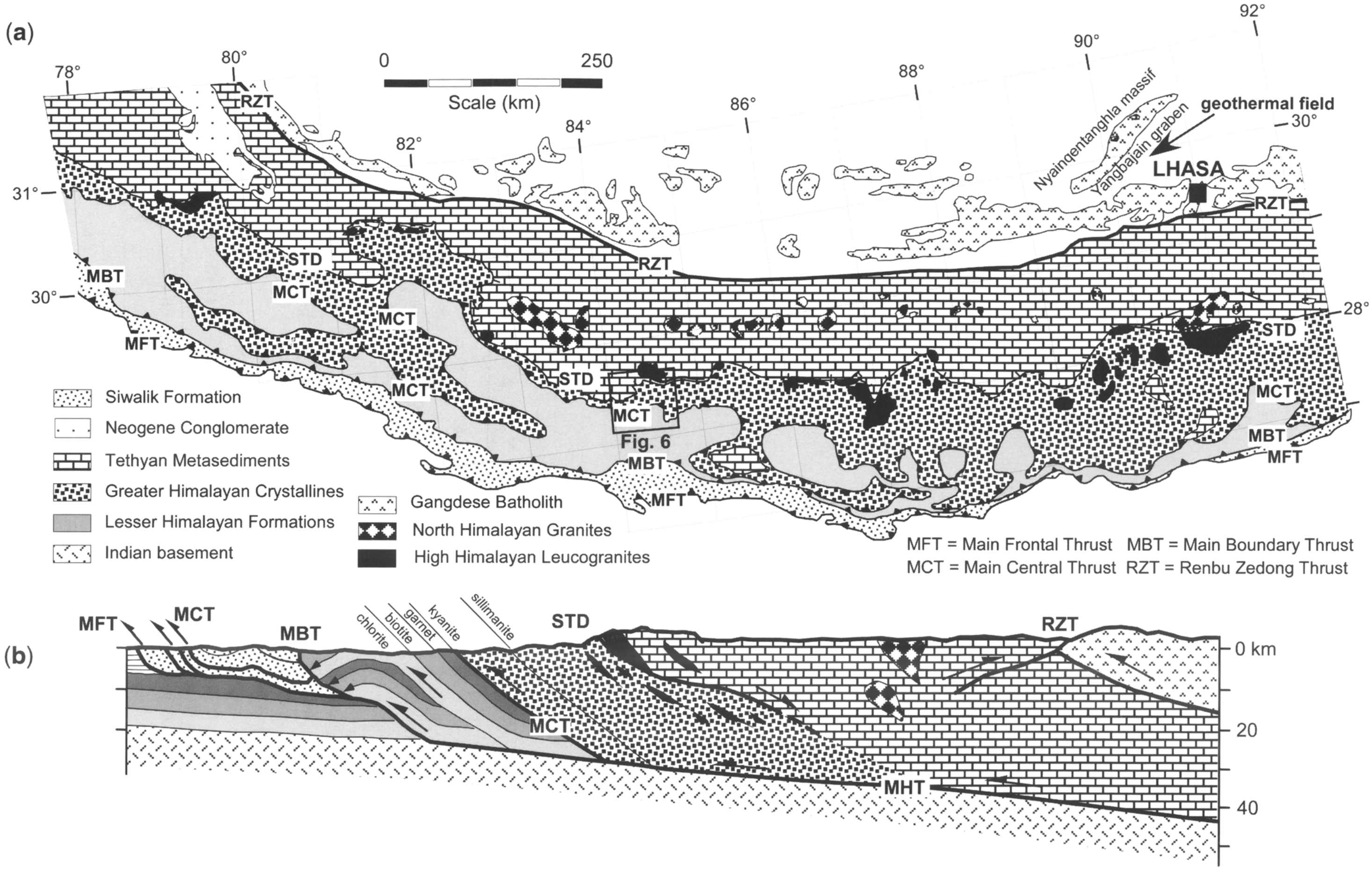

Fig. 1. (**A**) Geological map of the Himalaya and southern Tibet, modified from Harrison *et al.* (1999). (**B**) Generalized cross-section through the central Himalaya at 87°E illustrating the juxtaposition of the major lithostratigraphic units across the major Himalayan faults, inverted metamorphism and plutonic belts; modified from Schelling & Arita (1991) and Zhao *et al.* (1993).

Miocene, whereas peak pressures at the structurally highest levels were only about 3–4 kbar (sillimanite grade). Higher pressures (up to 10 kbar) detected locally are generally ascribed to an earlier Barrovian metamorphism termed the Eohimalayan phase (Le Fort 1996). The region approximately bounded by the garnet isograd in the Lesser Himalayan Formations and the MCT hanging wall gneisses of the GHC is typically characterized by a highly sheared, 4–8 km thick zone of distributed deformation with a top-to-the-south shear sense, referred to as the 'MCT Zone' (Fig. 1A; Hubbard 1996). Although a variety of models have been proposed linking early Miocene anatexis with the inverted metamorphic sequences, recent studies (Harrison *et al.* 1997, 1998; Catlos *et al.* 2001) showed that the dominant Tertiary recrystallization of elements of the MCT footwall largely occurred in the Late Miocene/Pliocene.

Paired leucogranite belts

An apparently unique feature of the Himalayan range is the presence of two, roughly parallel, syn-collisional granite belts, the High Himalayan leucogranites (HHL), which crop out along the crest of the range, and the North Himalayan granites (NHG; Fig. 1A). The HHL form a discontinuous chain of generally sill-like bodies adjacent to the STDS (Fig. 1B) emplaced at temperatures of *c.* 700–750°C (Montel 1993). The HHL belt varies in age from 24.0 to 17.2 Ma, but most of the large granite bodies constituting the majority of the leucogranite were emplaced between 23 and 19 Ma (Harrison *et al.* 1998)

The North Himalayan granite belt trends parallel to, and *c.* 80 km to the north of, the HHL (Fig. 1). Granitoids of the northern belt appear in general to have an elliptical outcrop pattern (e.g. Lee *et al.* 2004). They differ from the HHL in their emplacement style (Fig. 1) and possibly higher melting temperatures (>750°C), suggested by non-eutectic compositions and high light rare earth contents coupled with low monazite inheritance (Debon *et al.* 1986; Schärer *et al.* 1986; Montel, 1993; Harrison *et al.* 1997; Lee *et al.* 2004; cf. Zhang *et al.* 2004). With minor exception, crystallization ages of the North Himalayan belt range from 17.6 to 9.5 Ma (Harrison *et al.* 1997).

Tibetan rifts

Although convergence between India and southern Asia continues today, the Tibetan Plateau is currently experiencing east–west extension (Molnar & Tapponnier 1978; Armijo *et al.* 1986; England & Houseman 1989; Yin 2000). In southern Tibet, extensional strain has been accommodated by a series of generally north–south trending rifts (Fig. 2; Armijo *et al.* 1986; Yin *et al.* 1994; Yin

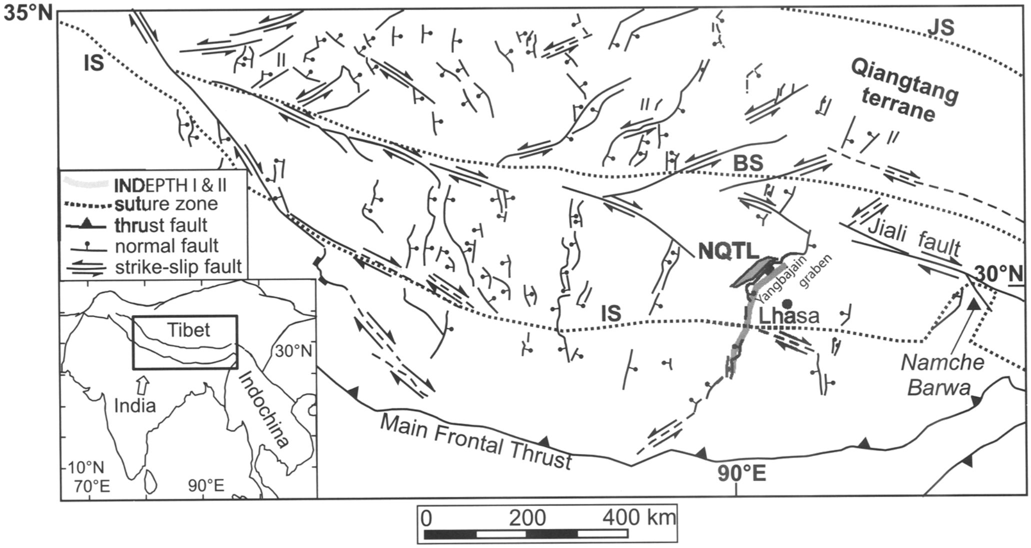

Fig. 2. Neotectonic map of southern Tibet indicating location of the INDEPTH I and II seismic reflection surveys (thick grey line) within the Yadong–Gulu rift. NQTL indicates the location of the Nyainqentanghla massif, the uplifted rift flank of the Yangbajain graben. BS, Bangong–Nujiang suture; IS, Indus–Yarlung suture; JS, Jinsha suture. Modified from Kapp *et al.* (2005).

2000; Blisniuk *et al.* 2001; Taylor *et al.* 2003). Numerous mechanisms have been proposed to explain their development including: expansion of the Himalayan arc (Molnar & Lyon-Caen 1989; Ratschbacher *et al.* 1994), strain partitioning due to oblique convergence between India and southern Asia (Seeber & Armbruster, 1984; Armijo *et al.* 1986; McCaffrey & Nabelek 1998), convective removal of mantle lithosphere and associated plateau uplift (England & Houseman, 1989; Harrison *et al.* 1992; Molnar *et al.* 1993), gravitational collapse due to maximum sustainable elevation (Molnar & Tapponnier 1978; Armijo *et al.* 1986; Tapponnier *et al.* 1986; Dewey 1988), the influence of the Pacific margin causing east–west extension in east Asia (Yin 2000), and concentrated contraction along the central segment of the Himalayan arc (Kapp & Guynn 2004). There are relatively few constraints on the timing of rift initiation across the Tibetan Plateau (Yin *et al.* 1994; Coleman & Hodges 1995; Harrison *et al.* 1995; Blisniuk *et al.* 2001; Stockli *et al.* 2002; Taylor *et al.* 2003), but extension across the Yadong–Gulu rift (Fig. 2), the largest rift in southern Tibet, appears to have been underway by 9 Ma (Harrison *et al.* 1995; Stockli *et al.* 2002).

The shallow Tibetan anatexis model

The Zhao and Morgan hypothesis

Zhao & Morgan (1985, 1987) developed a model for the evolution of Tibet in which plateau uplift was driven hydraulically via a low-viscosity middle and lower crust beneath the Tibetan Plateau. This approach was a radical departure from previous models that assumed either rigid plate-like behaviour (Argand 1924; Tapponnier *et al.* 1986) or vertically homogeneous mechanical properties (Dewey & Burke 1973; England & Houseman 1988). The models of Zhao & Morgan (1985, 1987) were tuned to match an uplift history derived from palaeo-botanical results (e.g. Guo 1981) in which plateau growth was essentially a Quaternary phenomenon. With mounting observations that conflicted with this uplift history, and criticism of the method of translating plant fossil data into palaeo-elevation information (e.g. Dewey *et al.* 1988; England & Houseman 1988), the Zhao & Morgan hypothesis was relegated to the ranks of less-favoured models (e.g. Harrison *et al.* 1992).

INDEPTH

Between 1992 and 1995, project INDEPTH (INternational DEep Profiling of Tibet and the Himalaya) undertook a near-vertical incidence common-midpoint (CMP) reflection survey, as well as companion wide-angle reflection, broadband earthquake and magnetotelluric (MT) studies, along a roughly north–south profile within the Yadong–Gulu rift of southern Tibet (Fig. 2; Zhao *et al.* 1993; Brown *et al.* 1996; Makovsky *et al.* 1996; Nelson *et al.* 1996; Wei *et al.* 2001; Xie *et al.* 2004).

The CMP reflection profile revealed a set of prominent reflectors ('bright spots') at depths of 15 to 20 km, beginning in the south at the Indus–Yarlung suture and ending at the north end of the Yangbajain graben, which is the central portion of the Yadong–Gulu rift (Fig. 2). The properties of these reflectors, and their coincidence with a low-velocity zone and electrically conductive crust, led Nelson *et al.* (1996) to suggest that they mark the top of a mid-crustal partial melt layer. Passive seismic results of Li *et al.* (2003) suggested that the *c.* 20 km thick layer below that horizon was partial melt, albeit of low melt content. This interpretation was extended to suggest that a fluid, partially molten mid-crustal layer produced by crustal thickening exists throughout southern Tibet (Nelson *et al.* 1996).

Nelson *et al.* (1996), noting the roots of their model in the work of Zhao & Morgan, proposed that Neogene underthrusting of Indian crust had acted as a plunger, displacing the molten middle crust to the north while at the same time contributing to this layer by melting and ductile flow. In this model, the region between the MCT and STDS is the earlier extruded equivalent of this partially molten region (Fig. 3). The northward younging of the Himalayan granite belts is thus interpreted to reflect a semi-continuous record of this partially molten, mid-crustal layer.

Supporting evidence

Given the unlikelihood of water-saturated anatexis (Clemens & Vielzeuf 1987; cf. Nelson *et al.* 1996), crustal melting at depths of 15 to 20 km requires temperatures appropriate to vapour-absent melting reactions (i.e. >700–750°C; Patiño Douce & Harris 1998). The INDEPTH team (Nelson *et al.* 1996) argued that the high heat flow measured adjacent to the Indus–Yarlung suture (Francheteau *et al.* 1984; Jaupart *et al.* 1985) was consistent with shallow Tibetan anatexis and later noted that the upper crustal residence of the Curie isotherm in southern Tibet implied a temperature of about 550°C at a depth of 15–20 km (Alsdorf & Nelson 1999). Gaillard *et al.* (2004) argued that the similarity between electrical conductivities inferred from MT measurements in the Yangbajain graben and that observed from experimental crystallization studies of leucogranites was evidence in support of the Nelson *et al.* (1996) hypothesis. Unsworth *et al.* (2005) interpreted MT data from

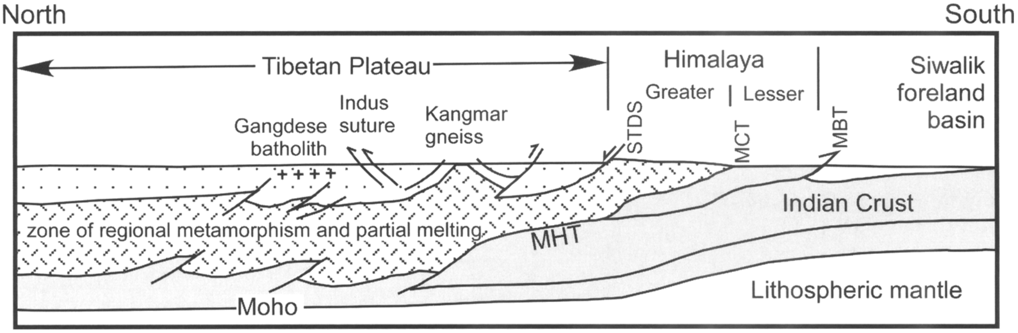

Fig. 3. Interpretive lithosphere-scale cross-section of the Himalaya and southern Tibet illustrating the interpretation of underthrusting Indian crust acting as a plunger causing molten middle crust to be displaced southward toward the Himalaya. Thus the region between the MCT and STDS is the earlier-extruded equivalent of the presently partially molten region beneath southern Tibet. Fault abbreviations are given in Figure 1. From Searle (1999); modified from Nelson *et al.* (1996).

several other transects across the Himalaya into southern Tibet in a similar fashion, and proposed a relationship between crustal viscosity and electrical resistivity that is consistent with the shallow Tibetan anatexis model. Mechie *et al.* (2004) inferred the presence of the $\alpha-\beta$ quartz transition at 18 to 32 km depths in a transect across the Bangong–Nujiang suture (Fig. 2), implying temperatures of 700°C and 800°C, respectively.

During the mid-1990s, thermal models examining the effect of accreting highly radioactive material to the hanging wall of a continental collision under conditions of rapid erosion predicted the necessary high temperatures in the shallow crust (Royden 1993; Huerta *et al.* 1996; Henry *et al.* 1997). For example, assuming a convergence rate of 15 mm a^{-1}, an erosion rate of 1 mm a^{-1}, and radioactive heat production of 2.5 μW m^{-3}, Henry *et al.* (1997) predicted that the 700°C isotherm under southern Tibet would reside at *c.* 15 km depth after *c.* 40 million years of convergence.

In contrast to the highly contentious and longstanding nature of most debates regarding Himalayan–Tibetan tectonics (e.g. see Tapponnier *et al.* (1986) *vis a vis* England and Houseman (1988)), the interpretation of Nelson *et al.* (1996) was quickly adopted by many influential Himalayan workers. Searle (1999, p. 239) wrote that 'similar processes of ... melting and leucogranite genesis are occurring today in this zone beneath the Tibetan Plateau as were occurring during the early and mid-Miocene along the High Himalaya' (Fig. 3). Hodges *et al.* (2001, p. 802) concluded that 'A channel of middle to lower crustal material extrudes southward from the central Tibetan Plateau between the [STD] and [MHT]' and that 'rocks currently exposed in the Greater Himalayan Zone ... represent the modern leading edge of this feeder channel' (p. 806). Grujic *et al.* (2002, p. 178) similarly inferred that 'the [GHC] of Bhutan originated as an orogenic channel that projects for over 200 km to the lower crust of the Tibetan Plateau'. Despite this apparently high level of consensus, there are numerous lines of evidence that seriously challenge the shallow Tibetan anatexis model.

Critique of the shallow Tibetan anatexis model

Is the thermal structure and fluid activity beneath the Yadong–Gulu rift representative of Tibet?

The INDEPTH I and II seismic reflection profiles, which imaged $\ll$1% of the southern Tibetan crust, were undertaken along rift valleys whose existence is owed to crustal-scale (Masek *et al.* 1994) or lithospheric-scale (Yin 2000) extension. Extensive surveys north of the Yadong–Gulu rift (Haines *et al.* 2003; Zhao *et al.* 2001) did not image bright spots suggesting that they may be limited to southern Tibetan rift valleys.

Based on similar electrical conductivities inferred from INDEPTH MT surveys to those observed in crystallization experiments, Gaillard *et al.* (2004) suggest that leucogranites are currently forming at shallow levels beneath the Yangbajain graben (Fig. 1). Their interpretation is non-unique and belied by the implausibility of us witnessing widespread anatexis across southern Tibet today. For example, leucogranites make up only about 3% of the present exposure of the Himalaya (Le Fort 1986). The HHL plutons are typically sill-like bodies of 200–800 m thickness emplaced at

15–20 km depth (Scaillet & Searle 2004) and thus are expected to crystallize within *c.* 10^5 years of emplacement (Carslaw & Jaeger 1959). If Himalayan leucogranites are 'progressively younger, frozen, snapshots of the partially molten mid-crustal layer' (Nelson *et al.* 1996, p. 1687) and can thus be taken to represent the melting history of the material extruded from beneath Tibet from 24 to 9 Ma (i.e. the known age range of Himalayan leucogranites), then the likelihood of us presently witnessing such an event in a Himalayan-sized portion of southern Tibet is less than one part in 5000 (i.e. 0.03 × (<100 ka/15 million years)).

Unsworth *et al.* (2005) collected additional MT data from transects to the west and east of the Yadong–Gulu rift which revealed high electrical conductivities at middle and lower crustal depths. While these data may well be characteristic of the subsurface electrical resistivity of the Himalaya, I note that these surveys were also undertaken within or adjacent to north–south trending rifts. Furthermore, their model relating crustal viscosity to electrical resisitivity requires multiple, nested assumptions – most importantly the untestable premise that the low resistivity is dominantly due to the presence of partial melt. The observation that only the upper portion of the GHC experienced Tertiary partial melting (Colchen *et al.* 1986; Inger & Harrison 1992, 1993) appears to be inconsistent with the Unsworth *et al.* (2005) interpretation.

Because mantle-derived magmatism is commonly associated with continental rifts, it would first seem appropriate to assess the likelihood that geophysical signals of fluid and thermal activity in the Yadong–Gulu rift reflect the emplacement of such magmas before ascribing them to crustal thickening processes. In fact, geochemical and geological investigations described in later sections are consistent with the addition of mantle-derived heat and mass in the Yangbajain region throughout the Late Neogene. Thus it seems unlikely that the thermal structure beneath the Yadong–Gulu rift is representative of the Tibetan crust in general.

Is shallow anatexis consistent with the cold southern Tibetan Moho?

Owens & Zandt (1997) found that the seismic velocity structure beneath southern Tibet was indicative of a generally cold crust. Indeed, the lower crust and/or upper mantle beneath southern Tibet, particularly in the region adjacent the Yadong–Gulu rift, is seismogenic (Chen & Kao 1996; Jackson 2002) (Fig. 4). In order for this region to be seismogenic under the strain rates relevant to the Indo-Asian collision, the Moho temperature would have to be less than about 700°C (Ruppel & McNamara 1997; McKenzie *et al.* 2004; cf. Beaumont *et al.* 2004). Thus the shallow anatexis model requires an inverted geotherm between *c.* 15 and 90 km depth under southern Tibet.

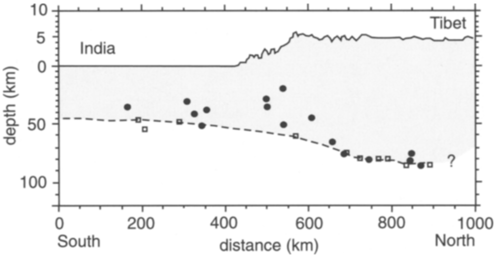

Fig. 4. Cross-section along 90°E from Jackson (2002) showing earthquake focus depths (filled circles) and Moho depths (open squares). Earthquakes beneath southern Tibet are occurring at depths of 70–90 km implying a Moho temperature of less than *c.* 700°C.

Mechie *et al.* (2004) observed P- but not S-wave arrivals along a transect from NW of the Nyainqentanghla massif to the south-central Qiangtang Block. From this they inferred the presence of the α–β quartz transition at 18 to 32 km depths which implies high temperatures (700°C to 800°C, respectively). While this interpretation is plausible, it is non-unique. Furthermore, their seismic lines lie in part in Late Cenozoic rifts (see Fig. 2) and thus may not be representative of Tibetan crust in general. Specifically, the highest inferred geotherm lies within the Shuang Hu rift with more southerly, cooler portions in small rifts which represent the terminations of conjugate strike-slip faults (Taylor *et al.* 2003).

Do 'bright spots' represent melts rather than aqueous fluids?

Makovsky & Klemperer (1999) concluded that the velocity properties of the 'bright spots' beneath the Yangbajain graben are best interpreted as porous regions containing about 10% saline aqueous fluids (or >15%; Li *et al.* 2003). This conclusion is consistent with the high electrical conductivity of the mid-crust. The presence of active hydrothermal fields within the Yangbajain graben (Fig. 1; Cogan *et al.* 1998) tends to support this view, although it seems probable that rift-related magmatism is driving the hydrothermal system (see below).

Are $^3He/^4He$ data consistent with shallow anatexis?

The isotopic composition of helium from geothermal springs in southern Tibet defines two domains (Yokoyama *et al.* 1999; Hoke *et al.* 2000) (Fig. 5).

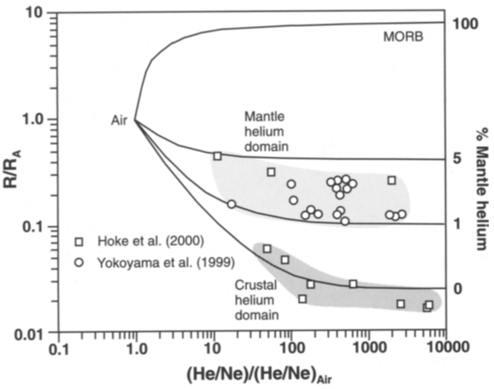

Fig. 5. Plot of $^3He/^4He$ ratio (=R) of thermal spring waters from the Himalaya and southern Tibet relative to modern atmosphere ($=R_A$) against the sample He/Ne ratio relative to that in air. Because of the negligible helium in air, the horizontal axis permits assessment of the fraction of ^3He from a mantle source *versus* contamination by air. The data define a low $^3He/^4He$ 'crustal helium domain', largely restricted to the Tethyan Himalaya, and a high $^3He/^4He$ 'mantle helium domain', most notably from the Yangbajain geothermal field. A simple mixing model indicates a mantle contribution of between 1 and 5% ^3He (from Hoke *et al.* 2000).

South of the Indus–Tsangpo suture, $^3He/^4He$ isotope ratios are typical of radiogenic helium production in the crust. North of the suture there is a resolvable ^3He anomaly. $^3He/^4He$ ratios in hydrothermal fluids sampled directly above the Yangbajain bright spots contain the ^3He anomaly indicative of a mantle contribution (Yokoyama *et al.* 1999; Hoke *et al.* 2000). Hoke *et al.* (2000) argued that this reflects degassing of volatiles from Quaternary mantle-derived melts intruded into the crust. Given the common relationship between mantle-derived melts and continental rift environments, and the fact that mafic magmas will tend to pond at a depth of 15–20 km (Glazner & Ussler 1988), the helium isotope data are inconsistent with the notion that equilibrium anatexis brought on by crustal thickening is responsible for the bright spot and MT anomalies in the Yangbajain graben.

Does crustal thickening explain Tibetan crust thermal anomalies better than episodic calc-alkaline magmatism?

Calc-alkaline magmas are documented to have been emplaced semi-continuously within the Gangdese batholith (the Andean-type arc) between the closure of the Tethys ocean at 60–50 Ma and *c.* 8 Ma (Honneger *et al.* 1982; Schärer & Allegre 1984; Xu *et al.* 1985; Coulon *et al.* 1986; Debon *et al.* 1986; Xu 1990; Miller *et al.* 1999, 2000; Harrison *et al.* 2000; Williams *et al.* 2001; Chung *et al.* 2003; Kapp *et al.* 2005). Given the mantle signature in He isotopes from some southern Tibetan hot springs, it is reasonable to assume that this process continues to the present day (Hoke *et al.* 2000). Thus the locally high heat flow and hydrothermal activity in southern Tibet today (Francheteau *et al.* 1984) is more plausibly due to the continued emplacement of calc-alkaline magmas than crustal thickening.

Is the geology and geochemistry of the uplifted Yangbajain rift flank consistent with shallow anatexis?

The Nyainqentanghla massif (Fig. 1), which bounds the western margin of the Yangbajain graben, was exposed by a SE-dipping detachment fault which, beginning at about 8 Ma, exhumed an oblique section of crust in its footwall (Harris *et al.* 1988*a*, *b*, *c*; Pan & Kidd 1992; Harrison *et al.* 1995; Kapp *et al.* 2005). Dating of footwall exposures reveals a collage of intrusions including 22 to 8 Ma calc-alkaline granitoids suggestive of continuous or episodic Miocene magmatism (Liu *et al.* 2004; Kapp *et al.* 2005). Geochemical and isotopic analyses show a Gangdese-arc affinity indicating significant mantle heat and mass transfer in their formation and are inconsistent with derivation from the Indian craton (Kapp *et al.* 2005). The undeformed nature of the footwall Cretaceous and Miocene granitoids suggests that the Mesozoic–Cenozoic Lhasa block experienced only upper-crustal penetrative deformation. Coupled with the lack of migmatites exposed in the massif, this fact indicates that the exposed crust was never a zone of anatexis nor involved in large-scale crustal flow (Kapp *et al.* 2005).

Is the absence of Gangdese zircons in the GHC consistent with the shallow anatexis model?

The northern portion of the Yadong–Gulu rift is separated from the Himalaya by the Cretaceous–Tertiary Gangdese batholith (see Fig. 1). Although the shallow anatexis model specified that partially molten (likely Tibetan) crust is being extruded southward (Nelson *et al.* 1996) from a region through which calc-alkaline magma continued to be injected, not one U-Pb zircon age of the >1600 samples thus far measured from the GHC (including the North Himalayan Gneiss Domes) is younger than 500 Ma (Parrish and Hodges, 1996; DeCelles *et al.* 2000, 2004; Myrow *et al.* 2003). It seems unlikely that either Indian or Tibetan crust could have been extruded from beneath Tibet through a still-active magmatic zone without incorporating any zircons of Gangdese affinity.

Would the GHC extruded from beneath Tibet contain a definable stratigraphy?

The Greater Himalayan Crystallines are characterized by a broadly defined stratigraphy (Formations I to III; Colchen *et al.* 1986). Formation (FM) I, the basal unit, comprises metapsammitic gneisses; Fm II is directly above and dominated by calc-silicates; Fm III is a *c.* 490 Ma augen gneiss sheet that crops out continuously at the top of large segments of the GHC (Le Fort *et al.* 1986; Foster 2000; Miller *et al.* 2001; G. Gehrels pers. comm., 2003) (Fig. 6). This coherence provides a clear constraint on the level of stratigraphic disruption that can take place during extrusion from beneath

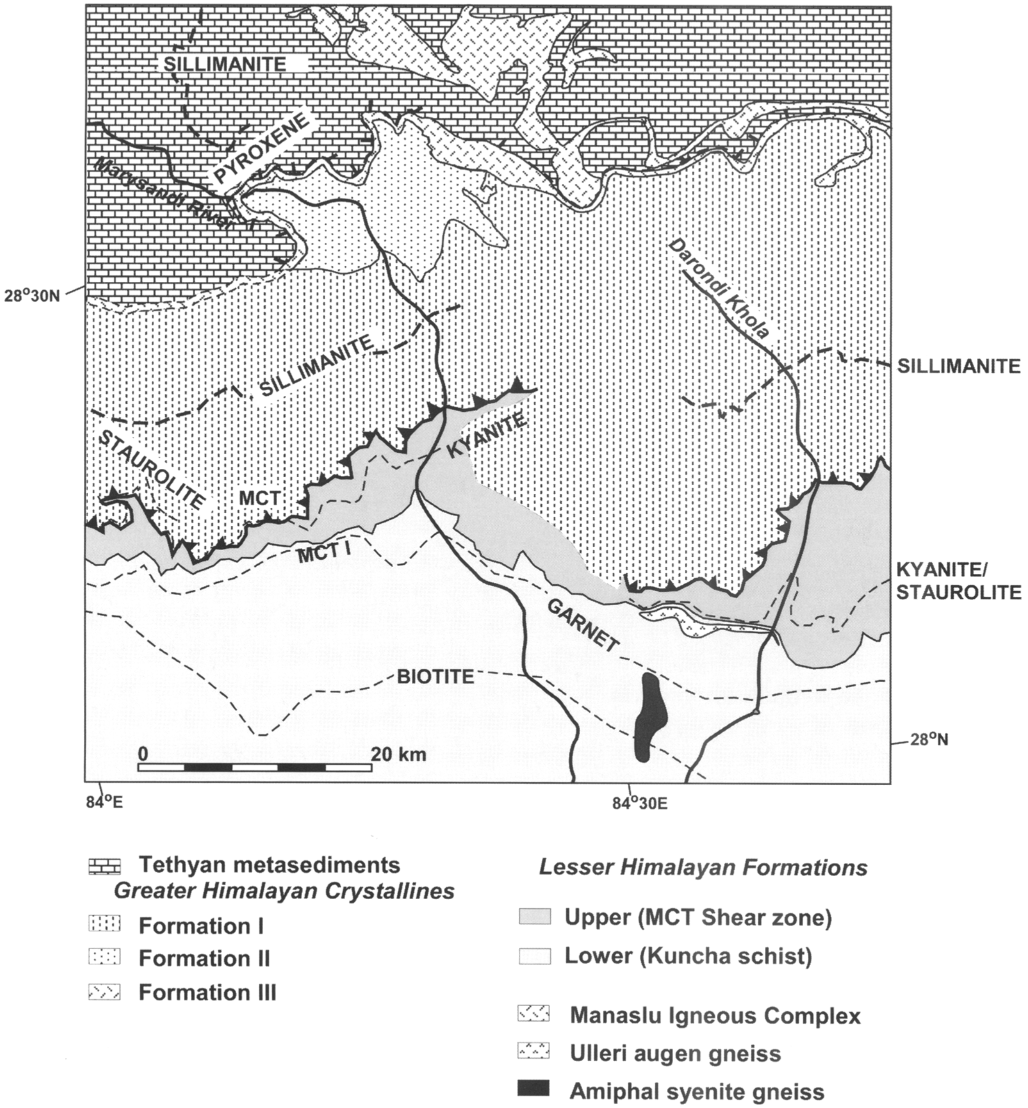

Fig. 6. Geological map of a portion of the central Nepal Himalaya showing the distribution of rock units in the Greater Himalayan Crystallines (from Colchen *et al.* 1986). The generally coherent stratigraphy, particularly that of Fm III, is taken as evidence that the GHC was unlikely to have been ductilely extruded from beneath the Tibetan Plateau.

the Tibetan Plateau under ductile flow. Although difficult to assess quantitatively, it seems improbable that the regularity of the lower contact of Fm III could have been maintained during a 1000 km + round trip.

Summary

Eight questions relating to the shallow anatexis hypothesis (Nelson *et al.* 1996) are raised in this section. The interpretation of shallow bright spot anomalies beneath the Yangbajain graben as due to *in situ* anatexis is highly non-unique. More likely they reflect the presence of saline aqueous fluids, observable at the surface as hot springs and geysers, driven by heat originating in the mantle. The location and nature of the seismic and MT anomalies under Yangbajain are consistent with the documented Neogene magmatic history, as recorded in the uplifted rift flank, and the active hydrothermal system in the graben. Helium isotope ratios from the Yangbajain geothermal field, and >800°C peak magmatic temperatures of young granitoids in the Nyainqentanghla massif (Kapp *et al.* 2005), record a flux of juvenile heat and mass throughout the Neogene consistent with episodic emplacement of calc-alkaline magmas or lithospheric-scale rifting. The oblique crustal section exposed in the uplifted Yadong-Gulu rift flank reveals no evidence of shallow anatexis prior to rift initiation at *c.* 8 Ma. The lack of Gangdese-age zircon xenocrysts in the GHC is inconsistent with southward flow of crust across the suture. The coherence of lithostratigraphy within the GHC appears more consistent with thrust imbrication than ductile flow.

Accretion/rapid denudation models

Thrust ramp models

During the period of INDEPTH deployment, numerical models were developed which indicated that a thermally mature continental collision zone could evolve a steady-state, near-isothermal structure where the mid-crust has been exposed by rapid denudation at the range front (e.g. Royden 1993; Huerta *et al.* 1996; Henry *et al.* 1997). These calculations appeared to provide support for shallow Tibetan anatexis.

Harrison *et al.* (1999) pointed out that models involving the accretion of highly radioactive material to the hanging wall of a continental Himalayan collision under rapid erosion (e.g. Royden 1993; Huerta *et al.* 1996): (1) required several times more Palaeogene sediment and a far greater depth of Himalayan exposure than known; and (2) were inconsistent with both synchroneity (at *c.* 23 Ma) of intrusion of HHL magmas along the 2000 km length of the collision front and the distinctive isotopic characteristics of the GHC and LHF.

By emphasizing erosion over accretion, the model of Henry *et al.* (1997) circumvented criticisms of type (2), but required uniformly rapid erosion from a region equivalent to the *c.* 200 km wide zone between the trace of the Himalayan thrust system and the Indus–Tsangpo suture. In fact, the level of exposure throughout the vast majority of this region is at greenschist facies with only minor amounts (<15 km) of post-Oligocene exhumation indicated for much of this area (e.g. Ratschbacher *et al.* 1994). The deep crustal exposures are largely restricted to the GHC, which form a rather narrower (i.e. 5–100 km wide) aperture than required by the Henry *et al.* (1997) model. The fact that the Tethyan sediments have not been completely removed from atop the heat-producing-element-enriched Indian supracrustal section represents a severe shortcoming of this model. Indeed, once the Tethyan 'cap' is replaced and a thrust flat introduced into the model, the *c.* 700°C isotherm under southern Tibet drops from *c.* 15 km to *c.* 35 km (e.g. Henry & Copeland 1999). Thus, by the close of the twentieth century, there appeared little in the way of support for the shallow-Tibetan-anatexis model. The landscape changed dramatically with the publication of Beaumont *et al.* (2001).

Focused denudation-induced channel flow

Challenged by the model of Nelson *et al.* (1996), Beaumont *et al.* (2004, p. 28) developed a plane-strain, coupled, thermomechanical model assuming a brittle–ductile crustal rheology with a stepped viscosity decrease at 700°C, and applied it to the case of the Himalayan collision. By building a high plateau and permitting focused erosion over a narrow aperture at the southern edge of a plateau, the weak, partially molten Indian crust beneath Tibet is extruded along a channel between the MCT and STD to the topographic surface, thereby forming the GHC. The original article (Beaumont *et al.* 2001) was followed by companion papers (Beaumont *et al.* 2004; Jamieson *et al.* 2004) that provided additional documentation for the model and its application to Himalayan tectonics, metamorphism and melting. This framework was far more successful in reconciling model results with petrological, geochronological and geophysical observations of the Himalaya than earlier accretion/erosion treatments. For example, they showed that following *c.* 55 Ma of Indo-Asian convergence in the 'detached foreland thrust' mode of deformation, their model could reproduce: (1) the pressure at peak temperature within the GHC; (2) the age at which peak temperature was achieved in the GHC and LHF; (3) the broad ages of the paired granite belts; (4) the general form of pressure–temperature paths in the GHC; (5) the appropriate magnitude of Tertiary sediments shed from the range; and (6) anatexis within the mid-crust. This success represented a substantial leap forward, but the model nonetheless faces numerous challenges.

Limitations of the focused denudation-induced channel flow model

In addition to being subject to many of the same limitations previously enumerated for the shallow-Tibetan-anatexis model, the focused denudation-induced channel flow model (Beaumont *et al.* 2001, 2004; Jamieson *et al.* 2004) is inherently restricted in making detailed comparisons between model results and the observed features of Himalayan geology by: (1) the 2D nature of the model which cannot accurately represent the 3D evolution of an orogenic system that includes, for example, substantial lateral extrusion (e.g. Tapponnier *et al.* 1986); (2) the lack of coupling of crust–mantle deformation in the model; (3) an initial model temperature structure at *c.* 55 Ma that is isothermal across the subduction zone (100 million years of Tethys subduction would have significantly depressed isotherms in the wedge); and (4) the assumption of a homogeneous crust ('models with homogeneous crust are unlikely to be representative of natural crustal composition'; Beaumont *et al.* 2004, p. 22). With regard to the latter, Beaumont *et al.* (2004, p. 22) emphasized that while 'channel flows can develop even where deformation of heterogeneous lower crust leads to complex middle and lower crust geometry and composition', natural channels resulting from heterogenous crust 'may be difficult to recognize using geophysical techniques'.

Extrusion of lower crust by channel flow is driven by a high and extensive plateau and enabled by highly focused erosion at the range front. Thus, choice of elevation and erosion histories are key to determining which of the many modes of deformation will be activated in a particular model. Of concern is the need to initially build an 8 km high proto-plateau in order to stimulate the channel tunnelling mode (Beaumont *et al.* 2004). Furthermore, the form of the growth history of the plateau, spreading north and south from an initial mountain belt in central Tibet (fig. 11 in Beaumont *et al.* 2004), appears inconsistent with what is known about the evolution of Tibet (see Murphy *et al.* 1997; Yin & Harrison 2000; Tapponnier *et al.* 2001; Yin *et al.* 2002).

Although the requirement that Himalayan erosion be forestalled *c.* 30 million years in order to generate the detached foreland thrust mode is highly specific, it is consistent with the known spatial and temporal distribution of sediment shed from the Himalaya (Yin & Harrison 2000).

Problems with predictions of the channel flow/rapid denudation model

The synchronous pulse of large HHL plutons at 22 ± 1 Ma (see Harrison *et al.* (1997) for a review) across the collision front (with no older plutons of comparable size known) is difficult to reconcile with models in which the thermal budget is dominated by radiogenic heating (e.g. Royden 1993; Huerta *et al.* 1996; Henry *et al.* 1997; Beaumont *et al.* 2001, 2004). Given that several tens of millions of years are required by the radiogenic heating/rapid erosion mechanism to create conditions suitable for melting, small variations in heat generation and/or thermal properties would likely result in the diachronous appearance of melting across the collision front. Instead, the synchroneity of major melting appears more consistent with a mechanism that produces localized thermal anomalies (e.g. minor shear heating). Similarly, the 'detached foreland thrust' mode is subject to the same inconsistencies with large-scale geological observations as the shallow anatexis model.

One prediction of a model invoking mid- or lower crustal flow is that crust–mantle deformation should be decoupled. Flesch *et al.* (2005) evaluated the nature of mechanical coupling through the Tibetan lithosphere by comparing present-day surface (from GPS and slip rates on active faults) and mantle (from SKS shear-wave splitting data assuming anisotropy is a mantle phenomenon) deformation fields. They found that both data-sets could be reconciled if Tibetan lithospheric deformation were vertically coherent (i.e. the maximum shear direction from surface deformation is parallel to the fast polarization direction of olivine). This would only be possible if both velocity boundary and gravity-induced stresses are transmitted to the mantle. While such strong crust–mantle coupling rules out weak southern Tibetan lower crust, the large misfit between surface (from GPS) and mantle (from shear-wave splitting) deformation fields in southeastern Tibet and Yunnan requires complete crust–mantle decoupling there (as suggested by Clark & Royden 2000).

An underlying assumption of the Beaumont *et al.*-type model, and a requirement to create conditions amenable for extrusion by channel flow, is that Indian lithosphere is underthrust well beneath Tibet before its mantle lithosphere is subducted (i.e. advancing subduction). However, by comparing post-50 Ma reconstructions of block motions within Asia with tomographic imagery of subducted lithosphere, Replumaz *et al.* (2004) determined that the Indian plate has continuously overridden its own sinking mantle (i.e. there is no advancing subduction). Thus India does not appear to underthrust Tibet north of the Indus–Yarlung suture. Replumaz *et al.* (2004) concluded that their observation 'provides further evidence against models of plateau build-up involving Indian lithosphere'.

Arguably the most significant criticism of the Beaumont *et al.* model is its requirement of highly focused erosion that limits the range front to a narrow zone of crystalline rock. In strong contrast, the GHC nappe extends up to 150 km south of the Himalayan front (Fig. 1B) over >70% of the range (Fig. 1A) (Upreti & Le Fort 1999).

Uniqueness of predictions of the channel flow/rapid denudation model

As remarked earlier, the channel flow (Beaumont *et al.* 2001, 2004; Jamieson *et al.* 2004) model reconciles a variety of petrological, geochronological and geophysical observations of the Himalaya, notably thermobarometric data for the GHC and thermochronological results in the GHC and LHF. In fact, the model of Harrison *et al.* (1998) achieved much the same results using a thermal model in which it was assumed that thrust motion follows fault–bend–fold kinematics (Suppe 1983). Harrison *et al.* (1998) proposed that the origin of the inverted metamorphic sequences and paired granite belts was linked to minor shear heating on a continuously active thrust that cuts through Indian supracrustal rocks that had previously experienced low degrees of partial melting during a protracted thickening phase in the absence of significant denudation. Numerical simulations assuming a relatively low shear stress of 30 MPa on the shallow Himalayan decollement beginning at 25 Ma triggered partial melting reactions leading to formation of the HHL chain between 25 and 20 Ma and the NHG between 17 and 8 Ma. Late Miocene, out-of-sequence thrusting within the broad but steeply dipping shear zone beneath the MCT provides a mechanism to bring these rocks to the surface in their present location and explains how the inverted metamorphic sequences formed beneath the MCT.

In fact, the particle paths of Indian crust created in the Himalayan orogenic wedge in the Beaumont *et al.* (2001) model are similar to those in Harrison *et al.* (1998). This underscores the need for any quantitative model of Himalayan petrogenesis to invoke: (1) an early phase of crustal thickening without significant erosion; (2) advection of footwall rocks into the MCT hanging wall; and (3) a steep MCT ramp to explain the two granite belts and young recrystallization ages within the 'inverted' metamorphic sequences, and the thermobarometric results. It also illustrates that the key petrological, geochronological and geophysical constraints on the evolution of the Himalaya can be equally well or better explained by simple thrust kinematics without an appeal to channel flow.

Conclusions

I conclude with reference to the summary statement in the announcement of the meeting on which this volume is based: 'In the Greater Himalayan ranges much discussion at recent meetings has centered around whether the middle or lower crust acts as a ductile, partially molten channel flowing out from beneath areas of over-thickened crust like the Tibetan plateau' (M.P. Searle, pers. comm. 2002). In evaluating the basis of several popular models that advance this hypothesis, both qualitatively and quantitatively, I conclude that there is no observational evidence that requires, or in many cases would even lead one to speculate on, the existence of partially molten middle crust flowing in a channel out from beneath the Tibetan Plateau. Thus the answer to the question posed in the title of this paper is: there is no evidence directly supporting extrusion of partially molten Tibetan crust into the Himalayan core, and there are several lines of contradictory evidence.

The proposal of widespread shallow anatexis beneath southern Tibet (Nelson *et al.* 1996) is inconsistent with a wide variety of observations (restriction of bright spots to rifts and evidence that they represent aqueous fluids, a seismogenic south Tibetan Moho, $^3He/^4He$ data indicating mantle heat and mass, existence of late Neogene calc-alkaline magmatism, lack of migmatites in the uplifted rift flank of the Yangbajain graben, lack of Gangdese zircon xenocrysts in the GHC, coherence of the GHC stratigraphy).

The success of the Beaumont *et al.* (2001) channel flow model in reproducing aspects of Himalayan petrogenesis underscores an emerging consensus that signature features of the Himalaya require an early phase of crustal thickening in the absence of significant erosion, advection of footwall rocks into the MCT hanging wall, and a steep, late-Neogene MCT ramp. While intellectually appealing, the Beaumont *et al.* (2001) model is inconsistent with several geological constraints, most notably the remarkably small portion of the collision front in which erosion localized exposure of the GHC to a narrow zone.

Whether or not the arguments advanced in this paper convince the reader of the lack of evidence supporting the shallow-Tibetan-anatexis hypothesis or the underlying assumptions of the channel flow model, it is inarguable that ambiguities in interpretation (e.g. the potential for thermal interference between Neogene calc-alkaline magmatism and heating resulting from crustal thickening) prevent definitive selection from among the various proposed models. This raises the question: What kind of new observations are required to break out of the current debate?

One advance that would have immediate impact is to undertake reflection profiling outside the rifts. Placing future transects firmly in the framework of late Cenozoic tectonics would permit us to assess the validity of the criticism that any reflection profile following crustal thinning features is unrepresentative of the Tibetan crust as a whole. The development of geophysical methods that could remotely observe directional flow in the mid-crust would directly test the hypothesis that the GHC represents the extrusion of anatectic material from shallow depths beneath Tibet. Refinement of tomographic imaging showing the fate of subducted Indian lithosphere would help clarify the general framework of numerical models attempting to reproduce the petrogenesis of the Himalayan crystalline core.

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