A synthesis of the Channel Flow–Extrusion hypothesis as developed for the Himalayan–Tibetan orogenic system

K. V. HODGES

Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
Present address: School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-1404, USA (e-mail: kvhodges@asu.edu)

Abstract: Surface and subsurface geological features of the Himalayan–Tibetan orogenic system may be explained by three sets of processes: those related to plate convergence, those related to the gravitational spreading of a fluid middle crust beneath the Tibetan Plateau, and those related to aggressive erosion along the southern margin of the plateau. In this paper, the possible relationships among the last two of these—and their tectonic manifestations—are presented in the form of a 'Channel Flow–Extrusion' hypothesis. This hypothesis, deriving from a series of ideas advanced by many geologists and geophysicists over the past two decades, suggests the definition of three phases in the Early Miocene–Recent history of the orogenic system. During Phase I (Early Miocene), the crust of southern Tibet was sufficiently hot and thick to enable lateral flow of a weak middle crust. To the north and east, this flow resulted in the expansion of the Tibetan Plateau. To the south, erosion at the Himalayan front permitted the mid-crustal channel to breach the surface; this process is recorded in the deformational history of the Himalayan metamorphic core and the Main Central and South Tibetan fault systems that bound it. While the lateral expansion of the plateau by mid-crustal flow has continued throughout Neogene time, some evidence suggests that extrusion across the Himalayan front waned substantially during the Middle Miocene–Early Pliocene interval (Phase II). In Middle Miocene time, large magnitude extension of the decoupled upper crust of southern Tibet led to the development of a subsidiary channel; its extrusion explains the existence of the North Himalayan gneiss domes. Phase III (Late Pliocene–Recent) has involved renewed southward extrusion of the main channel due to climatically induced increases in the erosion rate at the Himalayan range front.

Although numerous models have been advanced to explain why orogenic plateaus exist (e.g. James 1971; Dewey & Burke 1973; Powell & Conaghan 1973; Zhao & Morgan 1985; England & Houseman 1988; Isacks 1988; Allmendinger *et al.* 1997), less attention has been paid to the effect of these features, once developed, on the subsequent evolution of the orogenic systems in which they occur. An important characteristic of plateau regions like the Puna-Altiplano and Tibet is that they have much thicker crust than surrounding regions. The associated imbalance in the gravitational potential energy results in the mechanical tendency for a plateau region to spread outward to the extent permitted by the rheology of its crust and the surrounding crust, and the extent to which the plateau region is supported dynamically by plate convergence (Artyushkov 1973; Gratton 1989; Bird 1991).

If significant spreading occurs, we might expect there to be a clear signature of it in the geological record, especially in the form of structural features with kinematics that are better explained by plateau spreading than by plate convergence alone. This appears to be the case in the Himalaya and Tibet (Fig. 1), where a variety of geological and geophysical observations have led to a tectonic model in which lateral spreading of the Tibetan Plateau has occurred throughout much of late Cenozoic time by a combination of faulting in the brittle upper crust, channelized flow of a more ductile middle crust, and aggressive erosion along the Himalayan range front (Beaumont *et al.* 2001; Hodges *et al.* 2001). This paper begins with a review of the history leading up to development of this 'Channel Flow–Extrusion' hypothesis, includes a concise statement of the hypothesis, and ends with suggestions about how the hypothesis might be tested effectively through future studies.

Evolution of the hypothesis

The Channel Flow–Extrusion hypothesis is really a convergence of ideas that were developed to explain the physiography of Tibet and the structural architecture of the southern and eastern plateau margins.

Idea 1: The crust beneath Tibet is partially molten

Early speculation (e.g. Dewey & Burke 1973) that the middle and lower crust beneath the Tibetan

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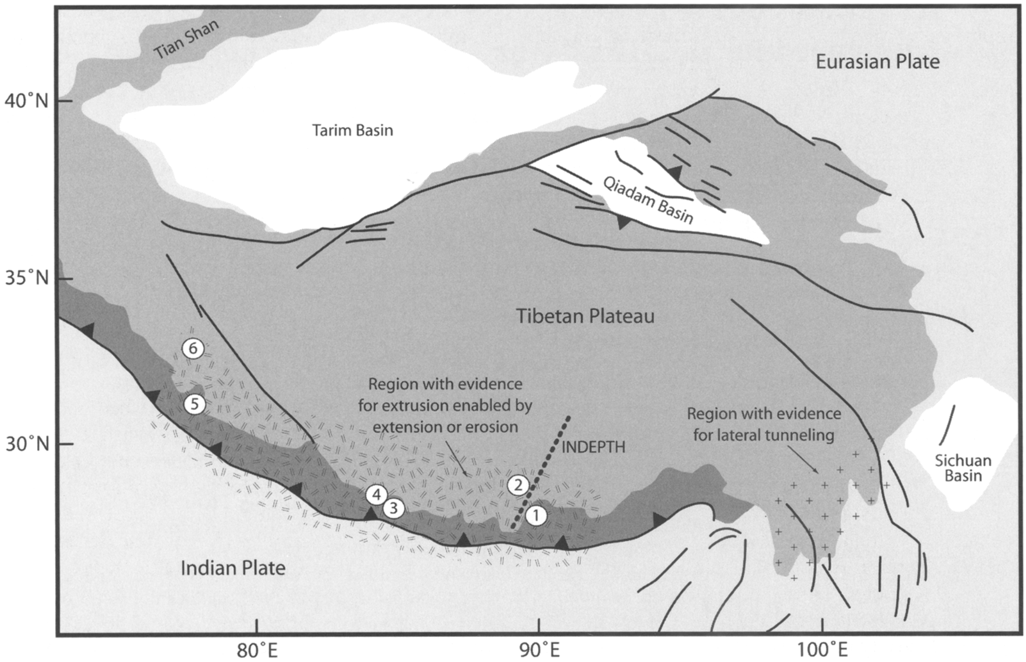

Fig. 1. Generalized map of the Himalayan–Tibetan orogenic system. Medium-grey field indicates region with elevations in excess of 3000 m, including the Tibetan Plateau and the Tian Shan. White regions are sedimentary basins. Dark-grey region encompasses the Himalayan range front. Thick solid lines indicate major transcurrent fault systems and thrust systems (barbed). Thick dashed line indicates only the portion of the INDEPTH reflection seismic line referred to in the text; the complete INDEPTH geophysical continued northward across the plateau. Patterned areas show regions where geological observations led to the development of the Channel Flow–Extrusion hypothesis. Specific localities mentioned in the text are: 1, Yadong cross-structure; 2, Kangmar dome; 3, Marsiyandi Valley; 4, Kali Gandaki Valley; 5, Sutlej Valley; 6, Tso Morari dome.

Plateau may be partially molten received strong support from heat flow measurements in the 1980s that indicated an exceptionally high geothermal gradient (Francheteau *et al.* 1984). Subsequently, Alsdorf & Nelson (1999) showed how satellite magnetic data indicate temperatures in excess of 550°C at 10–20 km depth across much of the plateau. Deep crustal xenoliths from *c.* 3 Ma volcanic fields in the central plateau suggest that temperatures of 800–1000°C were attained at depths of 30–50 km (Hacker *et al.* 2000). Based on a seismic velocity model derived from active- and passive-source seismic data, Mechie *et al.* (2004) inferred the presence of the $\alpha-\beta$ quartz transition, corresponding to a temperature of *c.* 700°C, at depths of 18–20 km beneath the central plateau and roughly 32 km beneath the southern plateau. Comparing this thermal structure with experimental constraints on the conditions required for crustal anatexis (e.g. Holland & Powell 2001; White *et al.* 2001), partial melting might be taking place across much of the plateau at depths greater than about 15 to 20 km.

Evidence for the existence of such melts comes from the seismic character of the Tibetan crust as revealed by analysis of earthquake data. Kind *et al.* (1996), Yuan *et al.* (1997) and Cotte *et al.* (1999) noted the existence of a mid-crustal, low-velocity zone in southern Tibet that suggests the presence of melt. Low velocities in the lower crust of northern Tibet were similarly interpreted by Owens & Zandt (1997). Fan & Lay (2003) documented strong attenuation of *Lg* energy across the plateau, which is readily interpreted as a consequence of partial melting.

Some of the strongest indications of the possible presence of significant volumes of melt were found during geophysical surveys undertaken as part of the multinational INDEPTH project in the 1990s (Nelson *et al.* 1996). Multichannel seismic reflection data collected along a NE–SW transect between 89 and 91°E (Fig. 1) distinguished a prominent subhorizontal band of reflectors at a depth of *c.* 5–6 seconds, or 15–18 km assuming reasonable seismic velocities. These reflectors, which are well-defined from *c.* 29°45′N at least as far north as *c.* 30°35′N, are characterized by extremely high amplitudes compared to other reflectors on the INDEPTH line and are thus commonly referred to as 'bright spots'. Based on the seismic characteristics of the band of bright spots, Brown *et al.* (1996) concluded that it was most plausibly interpreted as an interface between solid rock above and partially molten rock below. However, Makovsky & Klemperer (1999) noted that some characteristics of wide-angle INDEPTH data – most notably the P-wave to S-wave conversion from the bright spots – might be more consistent with the presence of aqueous fluids rather than partial melts.

Magnetotelluric data from southern Tibet confirm the regional extent of the features recorded in the active-source seismic data but do not provide a definitive resolution of the debate regarding their origin. In the 1980s, Sino-French reconnaissance magnetotelluric surveys had indicated the presence of unusually high electrical conductivity in the crust of southern Tibet (Van Ngoc *et al.* 1986). A more detailed study conducted along the INDEPTH transect confirmed the existence of a high-conductivity layer, and showed that it coincided with the bright spots in the seismic profile (Chen *et al.* 1996). Chen and co-workers agreed with the Sino-French team that magma bodies provided a reasonable explanation for the high conductivity. Wei *et al.* (2001) demonstrated that the high-conductivity layer extended well beyond the INDEPTH footprint, but suggested that its magnetotelluric signature might be explained as easily by regionally distributed saline fluids as by a horizon of partial melt. Li *et al.* (2003) suggested that the combined seismic and magnetotelluric data-sets might require an explanation that involved both the presence of aqueous fluids and melts. More recently, Gaillard *et al.* (2004) showed that experimentally determined electrical properties of leucogranitic melts provide an excellent match with the high-conductivity zones observed in Tibet. Makovsky & Klemperer (1999) and Gaillard *et al.* (2004) also pointed out that, even if the bright spots and high-conductivity zone are caused by an aqueous fluid, the necessary fluid concentrations are difficult to reconcile with typical volatile contents of mid-crustal metamorphic rocks without appealing to the dewatering of leucogranitic magmas during the last stages of their crystallization (Scaillet *et al.* 1995).

Idea 2: The Tibetan fluid layer is sufficiently weak to have flowed laterally

Unlike the great mountain ranges that occur along its margins, the interior of Tibet has very limited topographic relief (Fielding *et al.* 1994). The plateau nevertheless occurs at a very high elevation, thousands of metres above the Indian subcontinent to the south, the Tarim and Qaidam basins to the north, and south Asia to the east. Geophysical surveys have shown that the crust beneath Tibet is very thick compared to the crust underlying surrounding regions, and the high elevation of Tibet is an isostatic effect related to this abnormality (Molnar *et al.* 1993). But why is it so flat? One simple explanation may be that the middle and lower crust of the plateau is a fluid that is too weak to support large variations in surface topography and it simply flows laterally under the influence of gravity (Bird 1991; Fielding *et al.* 1994; Masek *et al.* 1994).

If large amounts of partial melting had occurred in the middle and lower Tibetan crust, it seems intuitively obvious that the consequent weakening of the crust could accommodate significant lateral flow. However, the preponderance of evidence suggests the presence of a few weight per cent of melt at most (Hacker *et al.* 2000; Kind *et al.* 2002). A more fruitful way to evaluate the potential for flow is to consider the thermal and compositional dependence of the effective viscosities of metamorphic rocks that are likely candidates for Tibetan middle and lower crust (Brace & Kohlstedt 1980; Ranalli 1997). The most recent rheological studies of rocks that are likely analogues for the middle crust suggest that they would have extremely low viscosities given the geothermal gradient beneath Tibet (Kenis *et al.* 2005). In contrast, the anhydrous xenoliths found in the volcanic fields of north-central Tibet (Hacker *et al.* 2000) – which are the only actual samples we have of Tibetan lower crust – would be very strong and resistant to flow (Jackson *et al.* 2004). The xenoliths may not constitute a representative sampling, however, and several lines of evidence suggest that effective viscosities are, in reality, low throughout much of the middle and lower crust. The gravity spectrum of Tibet strongly suggests a rheologically layered crustal structure that is best modelled with a weak lower crust (Jin *et al.* 1994). Crustal flexural rigidity, as calculated from rift flank uplifts in central and southern Tibet, requires viscosities below *c.* 10^{22} Pa s in the lower crust (Masek *et al.* 1994). Virtually all crustal earthquakes beneath the Tibetan Plateau occur at depths of less than 25 km, suggesting that all deformation in the crust below is aseismic and ductile (Langin *et al.* 2003). More generally, the seismic wave response of the Tibetan crust below about 20 km is consistent with low strength (Owens & Zandt 1997; Yuan *et al.* 1997; Cotte *et al.* 1999), and this conclusion is supported by many other types of geophysical evidence (Klemperer 2006). As Meissner & Mooney (1998) put it, the 'Tibetan Plateau shows much lower viscosities in the middle and lower crust than anywhere else on Earth'.

Given such a rheology, it seems highly probable that at least the middle crust of Tibet might have experienced lateral flow. The earliest quantitative assessment of the implications of this flow on the tectonic evolution of the Himalayan–Tibetan orogenic system was that of Zhao & Morgan (1987), who suggested that injection of Indian crust into a fluid Tibetan lower crust could explain the wholesale uplift of the Tibetan Plateau. While subsequent geological and geophysical research has rendered this model unlikely, several theoretical studies have explored the crustal-scale modes of deformation that might have accompanied flow beneath Tibet (e.g. Bird 1991; Burg *et al.* 1994; Royden 1996; Royden *et al.* 1997; Meissner & Mooney 1998; Shen *et al.* 2001). A key result of all these studies is that brittle deformation in the upper 25 km of Tibetan crust is likely to be almost fully decoupled from ductile flow in the middle crust.

One measure of the possible nature and extent of flow may be the radial anisotropy of Rayleigh and Love wave propagation across the plateau. Shapiro *et al.* (2004) showed that the observed anisotropy was most easily explained by development of a strong preferred alignment of micas, which they interpreted as the result of rotation of micas during flattening and thinning of a laterally extruding channel. The seismic data require that the anisotropy occur in a mid-crustal zone roughly 25–30 km thick, but Shapiro and co-workers could not rule out the existence of a zone up to 50 km thick that extended into the lower crust. Those authors went on to note that 20–40% thinning of the Tibetan crust was required by the seismic data, and that at least half of this was accommodated by outward flow of a material from a mid-to-lower crustal channel under the influence of gravity.

Idea 3: The Tibetan Plateau has grown eastward by lower-to-middle crustal flow

The eastern margin of the Tibetan Plateau is marked by elevation and crustal thickness gradients that, along some segments, rival those of the Himalayan front. A variety of geomorphic and geochronologic arguments, many based on the incision histories of major river systems, suggest that this part of the plateau has experienced sustained uplift and eastward growth since Late Miocene–Early Pliocene time (Kirby *et al.* 2002; Clark *et al.* 2004; Schoenbohm *et al.* 2004). However, there is little evidence of this growth in the surface structural geology. Virtually all shortening structures along this margin pre-date plateau development, and the only significant structures that are contemporary with plateau growth are strike-slip and associated normal faults that accommodate block rotation around the eastern Himalayan syntaxis (e.g. Burchfiel *et al.* 1995; Kirby *et al.* 2000; Wang & Burchfiel 2000). Moreover, the modern strain field indicated by GPS data implies minimal surface shortening across the margin (King *et al.* 1997; Chen *et al.* 2000; Zhang *et al.* 2004).

Such observations have prompted the development of a model in which eastward plateau growth reflects flow in the middle crust (Fig. 2). This idea can be traced to seminal papers by Gratton (1989) and Bird (1991). It was expanded on subsequently by Westaway (1995), Royden *et al.* (1997) and Clark & Royden (2000). The last of these papers emphasized the progressive development of the plateau by eastward flow of a middle-to-lower

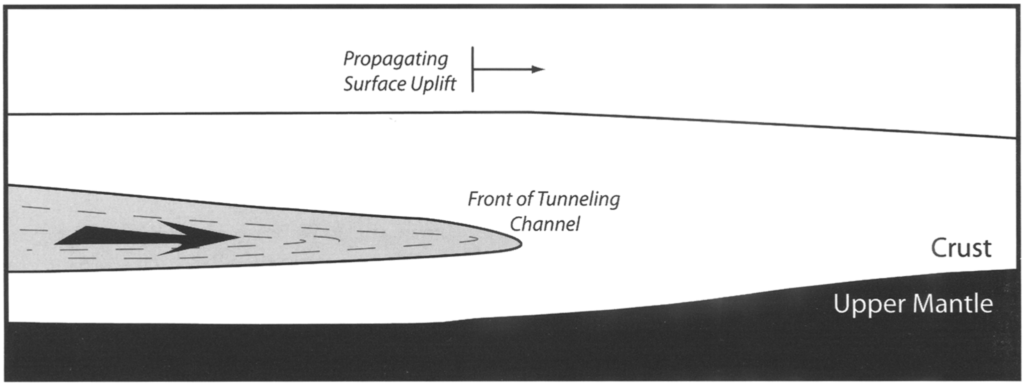

Fig. 2. Schematic cross-section of a tunnelling mid-crustal channel. Flow from left to right, driven by the gravitational potential energy gradient between thicker and thinner crust, results in inflation of the thinner crust and surface uplift that propagates in the direction of flow.

crustal channel since at least Middle Miocene time. An important component of the Clark & Royden (2000) model is that lateral extrusion of the lower crust depends on the rheology of adjacent crustal sections (cf. Westaway 1995). If the adjacent lower crust is weak, lateral extrusion of the channel is relatively easy and the result should be a low topographic gradient at the plateau margin, such as that observed on the southeastern edge of the plateau. If the adjacent lower crust is strong, as appears to be the case in the vicinity of the Sichuan Basin (Fig. 1), lateral flow of the channel is inhibited and an abrupt plateau margin forms.

Idea 4: Miocene slip on Himalayan thrust faults and normal faults was coeval

One of the most crucial observations to contribute to the Channel Flow–Extrusion hypothesis is an apparent developmental relationship between thrust faulting and normal faulting in the Himalaya (Burchfiel & Royden 1985; Searle & Rex 1989). Since the early twentieth century, the basic structure of the Himalaya has been known to be dominated by a series of south-vergent thrust fault systems (Heim & Gansser 1939; Le Fort 1975; Searle 1986; Hodges 2000). The oldest and northernmost of these – the Main Central thrust (MCT) system – places high-grade metamorphic rocks and leucogranites of the Greater Himalayan Sequence on slightly lower grade Precambrian–Palaeozoic metasedimentary and metaigneous rocks of the Lesser Himalayan Sequence (Fig. 3). The Lesser Himalayan Sequence is itself deformed by a complex set of structures that includes the Dadeldhura and Ramgarh thrust systems, as well as the Lesser Himalayan duplex, of DeCelles *et al.* (2001) and Pearson & DeCelles (2005). Collectively, these features will be referred to here as the Lesser Himalayan thrust (LHT) system. Farther south, the Main Boundary thrust (MBT) system juxtaposes Lesser Himalayan hanging wall rocks against footwall deposits of the Siwalik Molasse, and the molasse deposits themselves override the Indian foreland along the Main Frontal thrust (MFT) system. All of these thrust systems apparently sole into a basal Main Himalayan thrust (MHT), which serves as the decollement along which India subducts beneath Tibet (Schelling & Arita 1991; Schelling 1992; Zhao *et al.* 1993; Hauck *et al.* 1998). In general, these fault systems developed progressively from north to south; earliest slip on the MCT, LHT, MBT and MFT occurred at *c.* 22–20 Ma, 15–5 Ma, *c.* 5 Ma, and <3 Ma, respectively (Hodges 2000; DeCelles *et al.* 2001).

It was not until the 1980s that an entirely different kind of fault system was discovered in the Himalaya. Caby *et al.* (1983), Burg *et al.* (1984a), Burchfiel & Royden (1985), Searle (1986) and Herren (1987) noted the existence of a shallowly north-dipping, normal-sense shear zone between the high-grade gneisses and leucogranites of the Greater Himalayan Sequence and low-grade and unmetamorphosed sedimentary rocks of the overlying Tibetan Sedimentary Sequence, and Burchfiel *et al.* (1992) subsequently demonstrated that the shear zone was a regionally important feature that could be traced along much of the length of the Himalaya at the approximate position of the southern margin of the Tibetan Plateau. Several studies have shown that this South Tibetan fault (STF; Fig. 3) system includes strike-slip faults as well as rooted detachments (e.g. Pêcher 1991; Coleman 1996).

Soon after the first reconnaissance studies of the STF system, it became apparent that the earliest normal-sense displacement on the system was roughly synchronous with early slip on the structurally lower MCT system (e.g. Hodges *et al.* 1992, 1993; Searle *et al.* 1992; Searle 1996; Dèzes *et al.* 1999). Such studies confirmed the earlier speculation of Burchfiel & Royden (1985) that the STF and either the MCT or MBT systems were simultaneously active, and that together they accommodated southward extrusion of the Greater Himalayan metamorphic core of the Himalaya. In their diagrams, Burchfiel & Royden illustrated the metamorphic core as a northward-tapering wedge, but noted that this geometry was purely speculative. They presented a simple elastic model illustrating how steep topographic gradients – such as those that now exist along the southern margin of the Tibetan Plateau – can result in a stress field consistent with synchronous slip on shallowly dipping thrust and normal faults in a continent–continent collisional setting. However, Burchfiel & Royden were quick to point out that their use of an elastic model to illustrate their point did not mean that they regarded the deformation as purely elastic. Since 1985, a variety of workers have focused their efforts on understanding strain patterns within the ductilely deformed metamorphic core and the implications of these patterns for the mechanics of extrusion in Early Miocene time (Grujic *et al.* 1996, 2002; Grasemann *et al.* 1999; Vannay & Grasemann 2001; Law *et al.* 2004; Jessup *et al.* 2006).

If the STF system developed as the upper boundary of an extruding channel – a 'stretching fault' following the terminology of Means (1989) – then its protracted deformational history has important implications for the longevity of the extrusion process. Robust geochronologic constraints on the

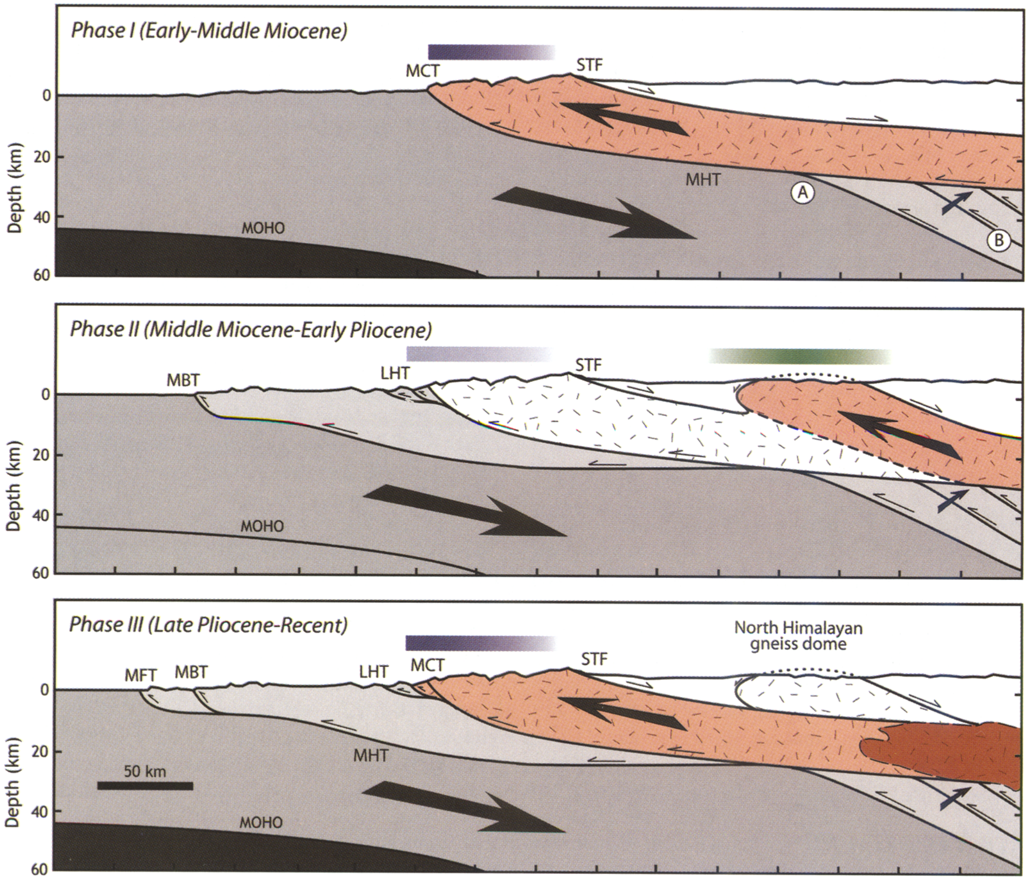

Fig. 3. Conceptual cross-sections illustrating the three phases of channel extrusion at the Himalayan front since Early Miocene time. Dark-grey shading designates the intact, downgoing Indian plate. Fields with light-grey shading, random-dash patterning, and no shading are Indian crust that has been accreted to the overriding plate. Unpatterned material corresponds to unmetamorphosed to weakly metamorphosed Tibetan sedimentary series. Material with random dash patterning includes high-grade metamorphic rocks of extruded channels. The actively extruding material in each frame has a light-red overlay pattern. Previously extruded material has no overlay shading. Note the development of a ductile shear zone (dashed heavy line) at the base of the actively extruding material in the frame for Phase II. The dark-red shading in the Phase III frame indicates partially molten material as imaged in the INDEPTH seismic reflection experiment (Nelson *et al.* 1996). Half-arrows show the slip on various faults. Larger, freeform arrows indicate large-scale kinematics. Circled 'A' indicates the divergence point of the downgoing Indian Plate and the extruding channel. 'B' indicates the hypothetical position of the lower-crustal duplex discussed in the text. Indian plate material accreted to the system across this duplex is continually incorporated into the channel. The blue bars in each frame represent the zone of orographic rainfall, with the colour gradient representing the rainfall gradient in a schematic way – lighter colours indicate lighter rainfall. Note that average rainfall is much lower during Phase II, a speculation based on sedimentological evidence for lower erosion rates. The green bar indicates a zone of extension over the North Himalayan gneiss domes, with the gradient representing intensity of extensional strain in upper crustal material. Acronyms: LHT, Lesser Himalayan thrust system; MBT, Main Boundary thrust system; MCT, Main Central thrust system; MFT, Main Frontal thrust system; MHT, Main Himalayan thrust; STF, South Tibetan fault system.

timing of ductile shearing on STF structures range from about 22 to 12 Ma (Hodges *et al.* 1992, 1996, 1998; Edwards & Harrison 1997; Searle *et al.* 1997, 2003; Coleman 1998; Wu *et al.* 1998; Dèzes *et al.* 1999). In a single field area, it is possible to distinguish multiple episodes of ductile or brittle–ductile deformation that span several million years (Burchfiel *et al.* 1992; Guillot *et al.* 1994; Coleman 1996; Hodges *et al.* 1996; Searle *et al.* 2003; Searle & Godin 2003; Law *et al.*

2004). In most well-studied regions, there are no useful timing constraints on the youngest episodes of displacement, beyond the fact that the youngest strands of the STF cut and must post-date Early–Middle Miocene leucogranites (Hodges 1998). There are two notable exceptions to this conclusion. First, the Yadong cross-structure (*c.* 89°30′E in southern Tibet; Fig. 1), which has been described as a lateral ramp in the Himalayan thrust system (Wu *et al.* 1998), seems more easily interpreted as a left-slip tear fault in the STF system since: (1) apparently offset STF strands terminate into the principal bounding faults of the Yadong cross-structure (the Chomolhari fault system of Wu *et al.*); and (2) the Chomolhari fault system has not actually been mapped north or south of its intersection with the apparently offset strands (Wu *et al.* 1998). Inasmuch as the Chomolhari fault system displays surface evidence for Quaternary slip and is seismically active (Ni & Barazangi 1984; Ekstrom 1987), it stands to reason that the youngest strands of the STF system in the Yadong area have been active recently. Brittle strands of the STF system that may be similarly young have been described by several other researchers in the Tibet–Bhutan border region (e.g. Burchfiel *et al.* 1992; Edwards *et al.* 1996). Second, Hurtado *et al.* (2001) showed that the youngest strand of the STF system in the Kali Gandaki valley of central Nepal (*c.* 83°40′E; Fig. 1) cuts the Quaternary Dangardzong fault, the principal growth structure for the Thakkhola graben, and thus must have experienced Pleistocene slip. This strand can be mapped westward to the Dhaulagiri region, where it offsets glacial moraines (Nakata 1989; Hurtado *et al.* 2001).

Idea 5: The Greater Himalayan channel roots northward into the Tibetan middle crust

Given widespread evidence for high-temperature ductile deformation in the Himalayan metamorphic core and the northward dip of the STF system, it seems reasonable to postulate that the STF may be the upper surface of the mid-crustal fluid layer beneath southern Tibet, and that the Greater Himalayan Sequence is an exhumed portion of the fluid layer itself. The first articulation of this idea may be found in Nelson *et al.* (1996) and was based on the early results of Project INDEPTH.

In the INDEPTH reflection seismic data-set, both the MHT and the basal STF structure are prominent north-dipping reflectors that appear to converge northward beneath southern Tibet because the STF reflector dips slightly more steeply than the MHT reflector (Zhao *et al.* 1993; Hauck *et al.* 1998). The STF reflector can be traced in the subsurface to a distance of at least 30 km north of its surface trace (Nelson *et al.* 1996). Projections farther north differ among different publications by the INDEPTH team. Makovsky *et al.* (1996) interpreted the STF as flattening to subhorizontal and extending northward for at least an additional 30 km at an approximate depth of 20 km beneath southern Tibet. In contrast, Hauck *et al.* (1998) felt that the STF reflector continued downward at approximately the same dip and could merge with the MHT about 60 km north of its surface trace and at a depth in excess of 30 km.

One reason why such varied interpretations are possible is that many strong reflectors in the seismic record, including both the STF and the MHT, begin to lose their definition between 28°30′N and 28°45′N and are impossible to trace north of about 29°45′N. This latitude coincides with the southern extent of the seismic bright spots described by Brown *et al.* (1996). A simple northward projection of the shallow STF reflector of Makovsky *et al.* (1996) and the MHT reflector of Nelson *et al.* (1996) defines a channel that is essentially coincident with the mid-crustal fluid zone as defined by an impressive suite of geophysical data (described above). Subsequent papers by Wu *et al.* (1998), Hodges *et al.* (2001), Beaumont *et al.* (2001, 2004), Hurtado *et al.* (2001), Grujic *et al.* (2002) and Jamieson *et al.* (2004) have expounded further on the tectonic implications of a connection between the extruded metamorphic core of the Himalaya and a weak mid-crustal channel beneath Tibet.

Idea 6: There is a link between monsoon-driven erosion and channel extrusion along the Himalayan front

As noted by Avouac & Burov (1996), focused erosion can have a dramatic influence on the dynamics of middle and lower crustal flow in convergent orogenic systems. Nelson et al (1996), Searle *et al.* (1997) and Wu *et al.* (1998) included rainfall along the Himalayan front in their cartoon depictions of Greater Himalayan extrusion, implicitly suggesting a link between climatic processes and channel extrusion. Hodges (1998) explicitly suggested that coordinated extrusion and erosion played an important role in the Miocene evolution of the Himalaya by dissipating excess gravitational potential energy accumulated during crustal thickening. A few years later, Hodges *et al.* (2001) argued that intense monsoon rainfall focused the flow direction of a mid-crustal channel toward the Himalayan range front. Independently, Beaumont *et al.* (2001) used thermal–mechanical models to demonstrate how such focusing could be a natural consequence of erosion on the flanks of the Tibetan Plateau. Together, these two papers demonstrated how the Channel Flow–Extrusion model could provide an internally consistent explanation for a wide variety of geological and geophysical observations in the Himalaya and southern Tibet.

The Channel Flow–Extrusion hypothesis

Out of these six ideas has emerged the hypothesis described in the following paragraphs. I focus on three phases of the evolution of the Himalayan–Tibetan orogenic system, during which the process of channelized mid-crustal flow had different tectonic manifestations (Fig. 3).

Phase I: Establishment of a steady-state configuration in the Himalaya (Early–Middle Miocene)

Although the Himalayan–Tibetan orogenic system has developed over a period of roughly 50 million years since the initial stages of India–Eurasia collision, there was a fundamental change in its geodynamics in Early Miocene time (Hodges 2000). While some researchers persist in dating the Tibetan Plateau at *c.* 8 Ma – see Molnar (2005) for a recent review of the arguments – I think that the preponderance of evidence suggests that crustal thickening beneath Tibet had progressed sufficiently to enable the development of the southern part of the plateau before 15 Ma (e.g. Turner *et al.* 1993, Coleman & Hodges 1995; Chung *et al.* 1998; Garzione *et al.* 2000*a*, *b*; Williams *et al.* 2001; Garzione *et al.* 2003; Spicer *et al.* 2003; Currie *et al.* 2005). As a consequence, the existence of a weak middle crust beneath the southern plateau can be postulated to date back to the Early Miocene interval, when the MCT system was the active frontal thrust in the Himalaya. At that time, there had developed a sufficient gradient in gravitational potential energy between the plateau and the Indian foreland – and presumably between the southern plateau and points farther north – to enable the lateral flow of the mid-crustal channel (cf. Hodges *et al.* 2001).

Northward and eastward propagation of the channel – a process referred to as 'tunnelling' by Beaumont *et al.* (2001, 2004) – resulted in growth of the plateau without leaving substantial evidence in the surface geology of Tibet. The channelling process effectively decoupled the upper and middle–lower crust, setting the stage for subsequent independent upper crustal and middle–lower crustal responses to continued convergence between India and Eurasia (Royden *et al.* 1997; Chen *et al.* 2000; Clark & Royden 2000; Zhang *et al.* 2004).

A critical element of the Channel Flow–Extrusion hypothesis is that sufficiently aggressive erosion was taking place along the southern flanks of the Himalaya to initiate the 'attraction' of the channel toward the range front in Early Miocene time. Indirect evidence of this having been the case comes from the sedimentary record in both the Bengal and Indus fans, which suggest a rapid flux of sediment from the Himalayan river systems in early Miocene time (e.g. Copeland & Harrison 1990; Amano & Taira 1992; Clift *et al.* 2004). Whether or not rapid erosion was driven then, as it is now, by the Indian monsoon remains an unanswered question. In any event, the hypothesis assumes that erosional removal of overburden along the range front was sufficient to allow the tunnelling channel to break toward the surface (Beaumont *et al.* 2004). The lower bound of this emergent channel was the recently developed MCT system whereas a new zone of shearing with opposing vergence – the STF system – developed to accommodate channel exhumation. Following Hodges *et al.* (1996), such features will be referred to in this paper as 'compensation structures' because they help mitigate the crustal thickness (and thus gravitational potential energy) contrast across the Himalaya.

The top frame in Figure 3 illustrates the tectonic architecture of the Himalaya during Phase I. The hypothesis holds that the STF system can be viewed as the surface expression of the decoupling horizon between the upper and middle crust of southern Tibet. The MCT system is the surface expression of the MHT; beneath the Himalaya, the MHT serves as the lower boundary of the emergent channel. North of point A in Figure 3, the MHT and the lower channel boundary diverge as the Indian plate subducts northward. Between the downgoing plate and the channel, a mid-crustal duplex system (point B) forms as some Indian plate material is scraped off. The continued development of this 'accretionary complex' is crucial to the extrusion process. As the duplex system grows, material that was previously accreted moves northward and upward in the overriding plate, feeding material into the mid-crustal channel (cf. fig. 8 of Searle & Szulc 2005). This provides a constant source of material for recycling toward the erosion front and, because these materials have abnormally high concentrations of radioactive heat-producing elements, it ensures the maintenance of sufficiently high temperatures, and thus sufficiently low viscosities, to support channel flow (Huerta *et al.* 1999; Jamieson *et al.* 2004). Note that, while most of the accreted material is metasedimentary rock with high fluid contents, some are orthogneisses that are relatively anhydrous and thus can be entrained in the channel as rigid pods without the development of a significant metamorphic signature of the channel flow process. As will be seen in the subsequent section on Phase II, such material may retain important evidence of the nature of Eohimalayan metamorphism when eventually exhumed.

During Phase I, near the southern margin of the plateau, a steady state is established locally in which the rate of accretion is roughly comparable to the rate of extrusion and the rate of erosion along the Himalayan front. In general, these rates can be traced by the rate of sedimentation in foreland deposits. In NW India, where deposits of the appropriate age have been most extensively studied, material from the extruding channel was being eroded and transported rapidly to the foreland until about 17 Ma, when erosion rates dropped dramatically in the hinterland and most of the detritus was instead sourced from the Lesser Himalayan Sequence farther south (White *et al.* 2002*b*). Farther east, in western Nepal, this shift occurred somewhat later (*c.* 12–10 Ma; Huyghe *et al.* 2001). In general, it seems that the rate of erosion of Greater Himalayan Sequence rocks dropped significantly across much of the Himalayan front in Middle Miocene or earliest Late Miocene time, although the Bengal Fan detrital record suggests that at least some exposures of the Greater Himalayan Sequence have been eroding and supplying sediment to the fan throughout the Middle Miocene–Recent interval (France-Lanord *et al.* 1993).

Phase II: Establishment of a second emergent channel north of the Himalayan crest and eastward growth of the Tibetan Plateau (Middle Miocene–Early Pliocene)

In the context of the Channel Flow–Extrusion hypothesis, the Middle–Late Miocene decrease in erosion rate of the Greater Himalayan Sequence was contemporaneous with a dramatic slowing of channel extrusion. Large-magnitude slip along the STF and MCT systems had effectively ceased by *c.* 16 Ma throughout much of the Himalaya, although research in the region of southern Tibet north of Bhutan suggests that Phase I STF activity persisted there into the Late Miocene (Edwards & Harrison 1997; Wu *et al.* 1998). Much of the shortening that had taken place on the MCT system was transferred in sequence toward the foreland to the structurally lower LHT system (DeCelles *et al.* 2001), although some out-of-sequence thrusts have been identified within the Greater Himalayan Sequence (Brun *et al.* 1985; Grujic *et al.* 1996, 2002; Hodges *et al.* 1996; Vannay & Hodges 1996; Searle 1999). During the limited extrusion that did occur at the Himalayan front over the Middle Miocene–Early Pliocene interval, the surface expressions of the boundaries of the extruding channel were active structures of the STF system and, successively, the LHT and MBT systems (Fig. 3). But more important extrusion processes were taking place north of the Himalayan range crest.

The thermal–mechanical models of Beaumont *et al.* (2001, 2004) suggest that any mechanism that reduces overburden above a mid-crustal channel, including extensional denudation, will tend to divert channel flow toward the area of denudation. Beaumont and co-workers suggested that upper crustal extension in the region between the Indus–Tsangpo Suture zone and the STF system might be responsible for the emergence of channel material in the cores of the North Himalayan gneiss domes, a belt of metamorphic culminations that stretches across southern Tibet (Burg *et al.* 1984*b*; Hodges 2000; Watts *et al.* 2005). Figure 4 illustrates how this process changed the tectonic architecture of southernmost Tibet during Phase II. I envision upper-crustal thinning occurring along detachment faults similar to those responsible for large-magnitude extension in the Basin and Range province of the North American Cordillera (Wernicke 1985). In this setting, such detachments root into the mid-crustal channel itself, providing an upper boundary for a new subsidiary channel that will be referred to here as the North Himalayan channel.

As the channel front ascends toward the surface, the low effective elastic thickness of the Tibetan upper crust (Masek *et al.* 1994) permits an isostatic response in the detachment footwall (Wernicke & Axen 1988) and the development of a rolling hinge geometry (Wdowinski & Axen 1992; Axen & Bartley 1997). From this perspective, the mylonitic carapaces of the gneiss domes in southern Tibet – as described by Chen *et al.* (1990) and Lee *et al.* (2000, 2004) – are surface expressions of compensation structures related to emergence of the North Himalayan channel. The INDEPTH seismic reflection line captured the subsurface reflections of the south-dipping carapace on the south side of one of the gneiss domes near Kangmar (*c.* 28°30′N; 89°45′E; Fig. 3). As depicted by Nelson *et al.* (1996) and Hauck *et al.* (1998), the shallowly dipping carapace reflectors can be traced downward to a depth of slightly less than 10 km before they are lost. Hauck *et al.* (1998) inferred it to be an old strand of the STF system that had been warped up and over the Kangmar dome as a consequence of the development of an underlying ramp in the MHT. Such a ramp is highly speculative – there is no sign of it on the INDEPTH reflection profiles.

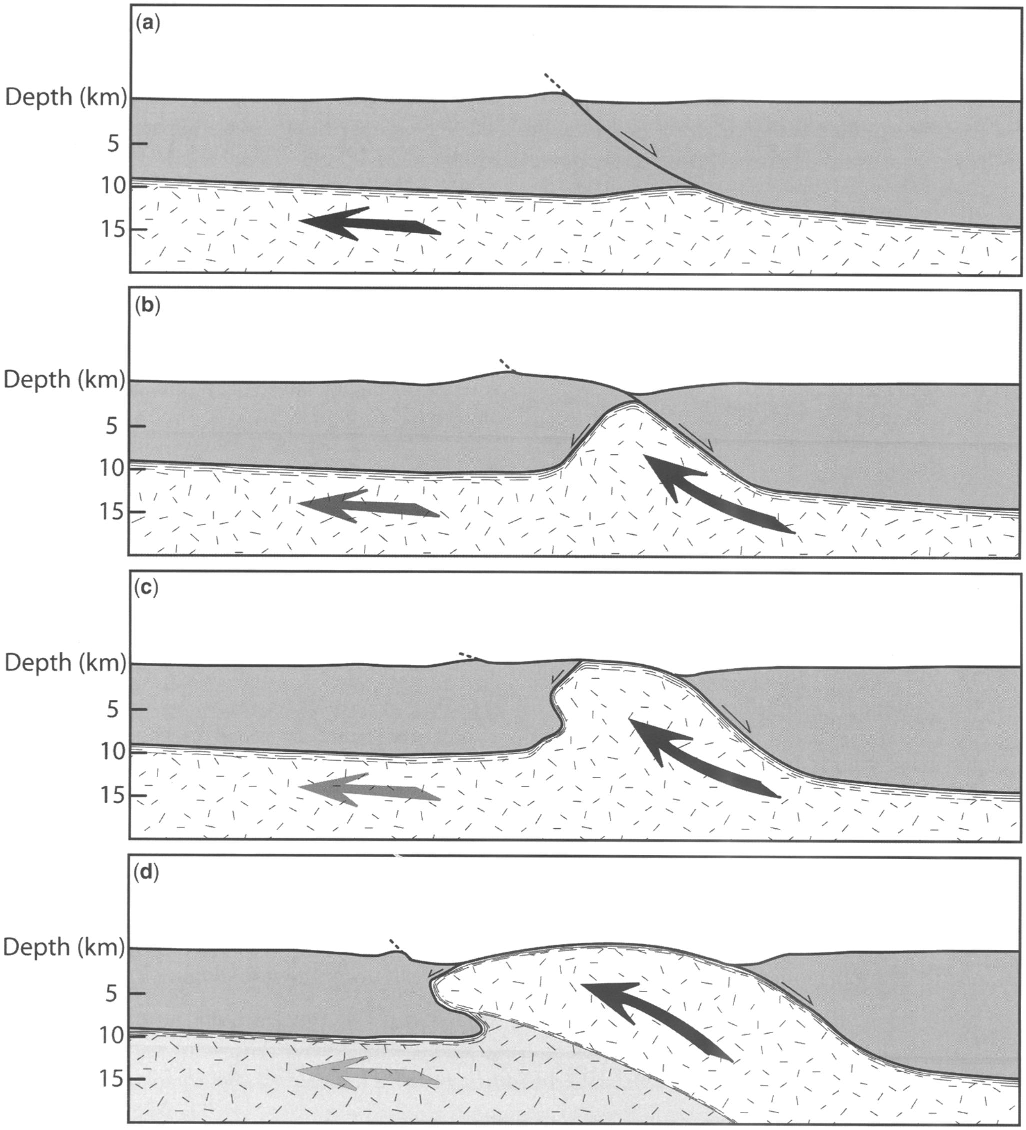

Fig. 4. Conceptual model of the development of a North Himalayan gneiss dome by extrusion enabled by upper-crustal extension (cf. Beaumont *et al.* 2001). Darker-grey shading indicates upper crust. Random dash pattern indicates channel material; light-grey overlay shading designates less active parts of the channel. Half-arrows indicate slip on individual faults. Thin, dashed lines represent mylonite zones. Large, freeform arrows indicate large-scale kinematics; darker arrows designate more rapid movement. **(a)** Upper crustal extension initiates on a major detachment that roots into the top of the mid-crustal channel. **(b)** Material flows upward in the footwall of the detachment and a rolling-hinge geometry develops (Buck 1988; Wernicke & Axen 1988), rotating the surface expression of the detachment to a lower dip angle. **(c)** With progressive extrusion, the mylonitic carapace of the gneiss dome emerges. **(d)** Ultimately, a new, subsidiary channel forms, and the original channel becomes less active.

Moreover, the Hauck *et al.* interpretation is inconsistent with two important sets of observations made by Lee *et al.* (2000) in the Kangmar dome: (1) deformational fabrics in the carapace imply top-to-the-north hanging wall transport on the northern margin of the dome, top-to-the-south transport on the southern margin, and a large flattening strain component at the dome crest; and (2) thermochronologic data from footwall metamorphic rocks indicate exhumation through medium- and low-temperature closure isotherms during the Middle to Late Miocene interval, significantly later than most STF footwall rocks exposed farther south. In my view, a better interpretation is that these mylonites developed independently of the STF system as shown schematically in Figure 4, and that renewed extrusion of the main channel during Phase III (see below) truncated the older mylonitic fabrics of the North Himalayan channel.

In some cases, the cores of the North Himalayan domes preserve an important record of earlier events despite their involvement in Phase I and Phase II deformation. For example, the Tso Morari complex in NW India (*c.* 33°N; 78°E; Fig. 3) is unique in that it contains only one of two known exposures of ultrahigh-pressure (coesite-bearing) mineral assemblages in the Himalaya (Sachan *et al.* 2004). The coesite-bearing mafic eclogites occur as small, isolated lenses in an orthogneiss matrix that represents Indian continental basement, such that the ultrahigh-pressure assemblages record subduction of Indian continental crust during the early stages of collision in Eocene (Eohimalayan) time (de Sigoyer *et al.* 2004; Leech *et al.* 2005). Structural and thermochronologic data suggest that these rocks had been exhumed to mid-crustal levels, equivalent to about 15 km depth, by Early Oligocene time (de Sigoyer *et al.* 2000), but that the final stages of exhumation to the surface did not occur until Middle to Late Miocene time (Schlup *et al.* 2003). I infer that the ultrahigh-pressure core of the dome represents a rigid pod of Indian basement that was accreted to the overriding Eurasian plate early in the collisional process, extruded to mid-crustal levels by a mechanism related to the buoyant force (e.g. Chemenda *et al.* 1996), eventually incorporated into the main Tibetan channel, and finally exhumed as part of the North Himalayan channel during Phase II. If this model is correct, the lack of an Early Miocene metamorphic overprint in these rocks, even though they were entrained in a high-temperature channel, may have been a consequence of low fluid contents in the basement orthogneisses.

Another important Phase II phenomenon was continued eastward tunnelling of the Tibetan mid-crustal channel. By Middle–Late Miocene time, even the eastern margin of the plateau had reached high elevations due to the propagation of the flow front (Kirby *et al.* 2002; Clark *et al.* 2005).

Phase III: Intensive extrusion at the Himalayan front (Late Pliocene–Recent)

Medium-temperature thermochronometers in bedrock samples from the Greater Himalayan Sequence typically record Middle Miocene–Early Pliocene cooling ages. Recent efforts to constrain exhumation rates over that interval from the study of detrital micas in central Nepal (Ruhl & Hodges 2005) suggest values of less than 1 mm a^{-1}. However, fission-track and (U-Th)/He data from the Greater Himalayan Sequence (e.g. Sorkhabi *et al.* 1996; Arita & Ganzawa 1997; Burbank *et al.* 2003; Theide *et al.* 2004; Vannay *et al.* 2004) suggest a transition to much more rapid exhumation rates in Late Pliocene time (Ruhl *et al.* 2005). Potentially related to climate destabilization (Molnar 2004), this increase in the erosion rate reinvigorated extrusion of the Tibetan mid-crustal channel toward the Himalayan range front and the process continues today (Fig. 3).

During this phase, the base of the channel has been the active, surface-breaking strand of the MHT. For much of the time, this may have been the Main Frontal thrust system (Hodges 2000; Lavé & Avouac 2000). In some places and at some times, however, the active channel base appears to have been out-of sequence thrust faults. Some of these faults are probably reactivated older strands of the MCT or LHT systems (Hodges *et al.* 2004); others are newly developed structures (Wobus *et al.* 2003, 2005; Theide *et al.* 2004; Vannay *et al.* 2004).

The upper boundary of the extruding channel has remained the surface trace of the STF system during Phase III, but the specific structures are different from those that were active during Phase I. These youngest faults of the STF system are characterized by brittle fault rocks and, in some cases, show direct evidence of Quaternary activity (Hurtado *et al.* 2001). In some areas – like the Sutlej Valley of NW India (*c.* 31°35′°N; 78°00′E; Fig. 3) – the upper boundary of the extruded zone is a normal-sense shear zone, exposed south of the trace of the STF system, which represents a newly developed compensation structure (Theide *et al.* 2004; Vannay *et al.* 2004).

Locations of channel boundaries are probably governed by summer monsoon precipitation patterns. In the Marsiyandi Valley (*c.* 28°20′°N; 84°25′E), where Quaternary thrust faults around the traditional MCT trace serve as the lower boundary (Hodges *et al.* 2004) and the Phu detachment strand of the STF system serves as the upper boundary (Searle & Godin 2003), recent meteorological studies (Barros *et al.* 2000; Barros & Lang 2003) demonstrate a strong north–south gradient in precipitation across the Himalayan front: the heaviest precipitation falls exclusively between the active thrusts and the Phu detachment (Hodges *et al.* 2004). In the Sutlej Valley, Theide *et al.* (2004) have found precisely the same relationship (based on SSM/I passive microwave satellite precipitation data), but the precipitation maximum falls between a Quaternary out-of-sequence thrust fault roughly 30 km south of the trace of the MCT system and zone of Quaternary normal faults approximately coincident with the MCT trace.

Elsewhere in the system, geomorphic studies of the evolution of river systems in southeastern Tibet and Yunnan (Clark *et al.* 2004; Schoenbohm *et al.* 2004), coupled with cosmogenic nuclide exposure age dating (Ouimet *et al.* 2005), testify to the continued southeastward growth of the Tibetan Plateau during Phase III.

Testing the hypothesis

A hypothesis that cannot be tested is without scientific value, and the Channel Flow–Extrusion hypothesis is no exception. Because, as reviewed here, the hypothesis was developed specifically to explain basic geological and geophysical observations in southern Tibet and the Himalaya, it would be circular reasoning to regard consistency with observations in this particular orogenic system as some sort of 'confirmation' of the viability of the hypothesis. However, three kinds of research might be useful ways to proceed.

Theoretical studies

One class of studies might involve attempts to understand whether or not the physics of mountain building actually demand the development of several phenomena that are crucial to the hypothesis. For example, does the thermal structure of overthickened crust in an orogenic system require the existence of a discrete fluid channel in the middle–lower crust, or are other rheologies plausible? Is it inevitable that such a channel would tunnel laterally through more rigid crust? If such tunnelling occurs, under what conditions is it safe to infer that surface erosion will influence the direction of flow, and under what conditions will a channel be forced to flow upward toward the surface? As impressive as numerical experiments such as those of Beaumont *et al.* (2001, 2004) are, it is important to remember that complex numerical models can be highly idiosyncratic, and cause and effect are not always obvious in them. Many opportunities exist to refine existing theoretical models of channel flow and to study their behaviours, and particularly the sensitivity of those behaviours to alternative choices of starting conditions. The goal of future studies of this sort should be to show that the essential characteristics of the Channel Flow–Extrusion hypothesis are not only viable but are *predictable* consequences of the building of orogenic plateaus.

Tests of predictions in the Himalaya

The Channel Flow–Extrusion hypothesis makes several testable predictions that should encourage the design of new research campaigns. Most importantly, it requires the existence of a Tibetan Plateau – or at least a 'proto-Plateau' in southern Tibet – as far back as Early Miocene time. Although I am persuaded by the arguments for high elevations – and presumably thick crust – in southern Tibet based on stable isotope and leaf physiognomy records (Garzione *et al.* 2000*a*, *b*; Rowley *et al.* 2001; Spicer *et al.* 2003), this issue is far from settled and requires further study. Moreover, the hypothesis requires progressive northward and eastward growth of the Tibetan Plateau from Early Miocene time onward, not wholesale uplift of the plateau at *c.* 8 Ma (Molnar *et al.* 1993). This component of the hypothesis should be testable by expanding studies of palaeo-elevation proxies outside of southern Tibet.

One weakness in the logic behind the hypothesis is that the field evidence for extrusion at the Himalayan front is strongest for the Early Miocene interval (Phase I), yet the argument that high precipitation at the range front attracts the channel to the surface is based on the modern pattern of monsoon rainfall (Phase III). Thus, one useful test of the hypothesis would be to search for evidence of high range front precipitation in Early Miocene time. Perhaps the most fruitful avenue for such work involves a more comprehensive study of the sedimentary record in the oldest foreland sequences as well as the Bengal and Indus fans.

The idea that the North Himalayan gneiss domes are related to a Phase II subsidiary channel is largely speculative. While it is consistent with what is known about the Kangmar and Mabja domes (Lee *et al.* 2000, 2004), many other North Himalayan domes have not been studied, and the hypothesis makes testable predictions about what the strain patterns and timing relationships should be in these metamorphic culminations.

Perhaps the most controversial aspects of the hypothesis concern whether or not Phase III extrusion continues today. Fortunately, these aspects are also the most testable. Since there is little dispute about the existence of active faults at the range front, and since these faults could serve as the lower boundary of the extruding channel, it is not necessary for there to be active, surface-breaking faults near the base of the Greater Himalayan Sequence for the hypothesis to be correct. However, a close link between precipitation patterns and extrusion – as has been postulated here and in Hodges *et al.* (2001) and Beaumont *et al.* (2001) – would favour a more northerly placement of the lower channel boundary than the

MFT trace. Studies are ongoing to determine whether or not active, out-of-sequence thrusts persist along-strike in areas other than central Nepal (Hodges *et al.* 2004; Wobus *et al.* 2005) and the Sutlej Valley (Theide *et al.* 2004; Vannay *et al.* 2004). Phase III extrusion also requires recently active slip on the STF system or on some newly formed compensation structures at deeper or shallower structural levels. None of the available geological data are inconsistent with this requirement, but neotectonic studies of candidate structures are few (Hurtado *et al.* 2001; Vannay *et al.* 2004). To test this part of the hypothesis, we particularly need more focused studies of the youngest, brittle structures of the STF system. The existence of these features has been known for years (Burchfiel *et al.* 1992), but they have received far less research attention than the older, more ductile strands of the STF system. Finally, if the extrusion front truly follows zones of high erosion, along-strike variations in monsoon precipitation intensity (Bookhagen *et al.* 2005) should correlate with the aggressiveness of the extrusion process. Thus, the patterns of Quaternary deformation should vary in a predictable way along strike in the Himalaya.

Tests of the applicability of the hypothesis in other orogenic systems

Even if the Channel Flow–Extrusion hypothesis is valid for the Himalaya and Tibet, its general usefulness for understanding collisional orogenesis remains unclear. In addition to several papers in this volume, the geological literature contains numerous examples of how geological and geophysical observations in other convergent orogenic systems, especially those with continental plateaus (e.g. the Puna-Altiplano and the Colorado Plateau) might be explained by lower or middle crustal flow (e.g. Bird 1991; Hodges & Walker 1992; Lamb & Hoke 1997; McQuarrie & Chase 2000; Gerbault & Willingshofer 2004; Gerbault *et al.* 2005). In each case, the evidence is consistent with the Channel Flow–Extrusion model but could be equally consistent with other models that do not invoke large-scale crustal flow. The great challenge before us is to identify unambiguous indicators of such flow in the geological record. Some of the best places to search for such indicators may be more ancient orogenic systems that offer regionally extensive exposures of the middle and lower crust. One example that has received some attention already is the Grenville orogenic system of North America (Culshaw *et al.* 1997; Jamieson *et al.* 2002), and another – the East Greenland Caledonides–includes especially dramatic exposures of medium-to-high-pressure metasedimentary rocks, with abundant leucogranitic plutons, that may be our best available analogues for the fluid crustal channel beneath Tibet (Hartz *et al.* 2001; Strachan & Martin 2001; White *et al.* 2002*a*; McClelland & Gilotti 2003; Higgins *et al.* 2004; Gilotti & McClelland 2005).

Conclusions

The Channel Flow–Extrusion hypothesis described here offers a useful conceptual framework for understanding the Early Miocene–Recent tectonics of the Himalayan–Tibetan orogenic system. In the hypothesis, the development of the Tibetan Plateau had a strong influence on the evolution of the system, altering it from what it might have been if the only forcing factor had been India–Eurasia plate convergence. Lateral tunnelling of a fluid Tibetan middle crust under the influence of gravity is postulated to have accommodated the eastward growth of the plateau without leaving a structural imprint on the surface geology. Along the southern plateau margin, aggressive erosion is thought to have coordinated with extrusion of the mid-crustal channel to produce a highly effective means of dissipating excess gravitational potential energy stored in overthickened Tibetan crust. According to the hypothesis, Middle Miocene upper crustal extension in southern Tibet enabled the development of a subsidiary channel that resulted in the formation of the North Himalayan gneiss domes. Many components of the hypothesis remain untested, and the design and implementation of such tests should be a top priority for students of Himalayan tectonics.

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