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Bicentennial Review

Channel flow and the Himalayan–Tibetan orogen: a critical review

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Abstract: The movement of a low-viscosity crustal layer in response to topographic loading provides a potential mechanism for (1) eastward flow of the Asian lower crust causing the peripheral growth of the Tibetan Plateau and (2) southward flow of the Indian middle crust to be extruded along the Himalayan topographic front. Thermomechanical models for channel flow link such extrusion to focused orographic precipitation at the surface. Isotopic constraints on the timing of fault movement, anatexis and thermobarometric evolution of the exhumed garnet- to sillimanite-grade metasedimentary rocks support mid-crustal channel flow during the Early to Mid-Miocene. Exhumed metamorphic assemblages suggest that the dominant mechanism of the viscosity reduction that is a requirement for channel flow was melt weakening along the upper surface, defined by the South Tibetan Detachment System, and strain softening along the base, bounded by the Main Central Thrust. Neotectonic extrusion, bounded by brittle Quaternary faults south of the Main Central Thrust, is positively correlated with the spatial distribution of precipitation across a north–south transect, suggesting climate–tectonic linkage over a million-year time scale. A proposed orogen-wide eastward increase in extrusion rate over 20 Ma reflects current precipitation patterns but climate–tectonic linkage over this time scale remains equivocal.

Although our understanding of the creation and subduction of oceanic lithosphere has advanced rapidly over the past few decades, the processes that control mountain building within the continents remain highly contentious. Recent developments in quantitative modelling of lithospheric deformation, coupled with an improved understanding of the mechanical behaviour of crustal materials, have provided a context within which the interactions between surface erosion and deep crustal deformation can now be explored.

Knowledge of the strength of lithospheric materials is essential for understanding their behaviour. The effective viscosity of the lithosphere varies widely, and is determined largely by temperature, composition and, most importantly, the distribution of melt; the viscosity of partially melted protoliths between liquidus and solidus temperatures varies by about 14 orders of magnitude (Cruden 1990). Because (1) temperature generally increases monotonically with depth, thus decreasing the viscosity of a homogeneous body, and (2) viscosity increases across an isothermal boundary from a quartz-dominated fusible lithology to a more refractory one where olivine dominates (i.e. the Moho), the lower crust can form a layer of low viscosity, relative to the bounding lithologies above and below. If viscosities are sufficiently low within this layer, the material within it may flow in response to lateral variations in lithostatic load. Thus lower crustal flow provides a possible means by which lateral pressure gradients equilibrate and so moderate topography and variations in crustal thickness. The same process can occur in the middle crust if highly fusible lithologies, such as pelitic metasedimentary units, predominate.

Crustal flow was first modelled by Bird (1991) in terms of laboratory flow laws. It was proposed initially as a means of modelling the response to extensional tectonics of the Basin and Range province, where a channel of 10–15 km thickness was

inferred to flow as a result of a low viscosity of $10^{17}–10^{19}$ Pa s (Kruse *et al.* 1991). Burov & Diament (1995) argued that a wide range of crustal thicknesses could be explained by a 'jelly sandwich' in which a weak lower crust is sandwiched between a strong brittle–elastic upper crust and an elastic–ductile lithospheric mantle. More recently, a weak lower crust has been proposed to account for the uplift and topographic variations of convergent regimes, as exemplified by the Tibetan Plateau (Royden *et al.* 1997).

This paper reviews the evolution of ideas that has led some geoscientists to believe that mechanical weakening in lower or middle crust explains diverse phenomena observed in many orogenic belts, including the Andes (Gerbault & Martinod 2005), the Appalachian orogenic belt (Merschat *et al.* 2005), the Canadian cordillera (Williams & Jiang 2005) and the Himalayan–Tibet orogen (Grujic *et al.* 2002). Specifically, it examines the quantitative evidence for the hypothesis that flow of a low-viscosity channel is linked to orography and surface precipitation in collisional orogens such as the Himalaya (Beaumont *et al.* 2001).

Modelling the mechanical behaviour of the Tibetan Plateau

The Himalayan arc, and the Tibetan Plateau that lies to the north (Fig. 1), is Earth's type example of continuing collision tectonics. The tectonic regime that exists today is the result of a collision between a northward moving Indian plate and the Eurasian plate at about 50 Ma when convergent velocities decelerated from 150 to 50 mm a^{-1} (Patrait & Achache 1984). Following the initial collision, India has continued to migrate northward by about 2000 km.

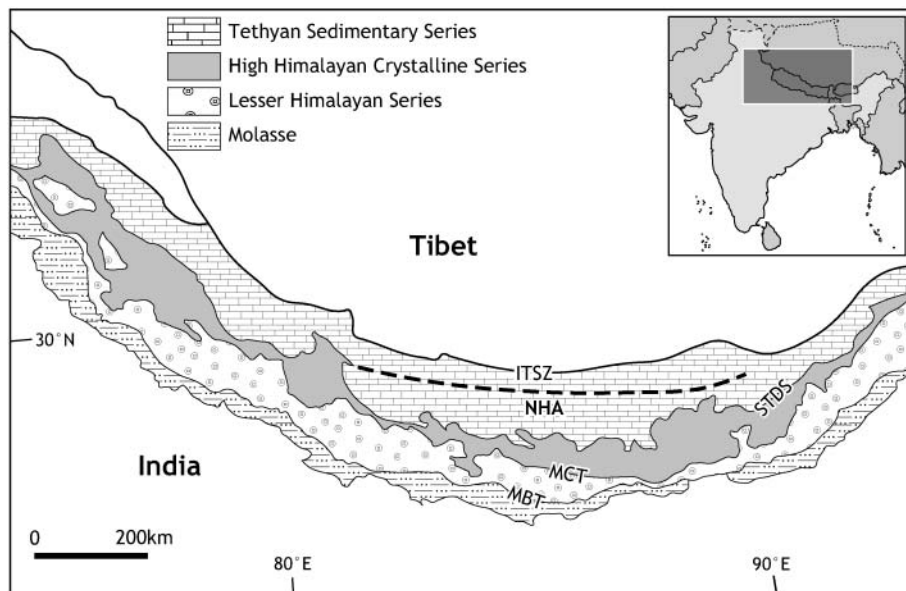To explain the uplift of a wide plateau and the observation that

Fig. 1. Geological sketch map of southern Tibet and the Himalaya. ITSZ, Indus–Tsangpo suture zone; STDS, South Tibetan Detachment System; MCT, Main Central Thrust; MBT, Main Boundary Thrust. Dashed line marks hinge of North Himalayan antiform (NHA).

significant thrusting across much of the plateau surface is largely absent, Zhao & Morgan (1985) were the first to invoke a weak lower crust beneath Tibet (6×10^{18} Pa s). They suggested that Tibet was elevated by hydraulic pressure as the subducted Indian plate was intruded into the weak lower crust of Tibet. However, this is not strictly the first application of a channel-flow mechanism to the uplift of the Tibetan orogen, as Zhao & Morgan required no lateral movement of the weakened layer in response to topographic loading.

Many of the orogen-scale features observed in the Tibetan orogen, such as the diffuse zones of seismicity and the width and height of the plateau, can be explained by assuming that the lithosphere behaves as a continuous medium akin to a thin viscous sheet that homogeneously thickens during the collision of two continental plates (England & McKenzie 1982). Homogeneous thickening of the lithosphere has thermal consequences, one of which is the postulated convective removal of the thickened keel of the lithosphere with consequent isostatic uplift followed by east–west spreading (England & Houseman 1989). Recent tectonic behaviour of the Tibetan Plateau is characterized by east–west extension across north–south-trending graben (Molnar & Tapponnier 1975; Armijo *et al.* 1986), and seismicity over much of the high plateau is characterized by normal faulting focal mechanisms (Chen & Molnar 1983). Other mechanisms have since sought to explain the crustal extension in southern Tibet without recourse to homogeneous thickening of the Tibetan lithosphere; for example, by invoking basal drag from under-thrusting Indian lithosphere beneath southern Tibet (McCaffrey & Nabalek 1998).

Although homogeneous thickening accounts for many of the first-order features of the uplift of a wide plateau at a continental collision zone, it implies that crustal thickening by thrusting is not significant on the scale of the Tibetan Plateau. An alternative treatment of crustal thickening assumes that the crust behaved as a rigid–plastic layer deformed by the motion of two rigid plates according to critical Coulomb wedge theory (Davis *et al.* 1983; Dahlen 1984). In this model, as formulated by Willett *et al.* (1993), thickening is restricted to the crust and the processes involved are treated as essentially brittle, at least in the early stages. In contrast to a thin viscous sheet, where thickening is

homogeneous throughout the lithosphere, the lithospheric mantle of the Indian plate continues to be subducted beneath the Tibetan Plateau and so is not involved in thickening. Willett *et al.* noted that such rigid tectonics would be modified in time by viscous flow induced in the lower crust. The mechanical behaviour of viscous wedges has been more fully discussed by Medvedev (2002).

Many geophysical studies have considered the implications of variations in mechanical strength with depth in the Tibetan lithosphere, as diverse lines of evidence suggest that depth-dependent mechanical behaviour needs to be taken into account to develop more realistic models, particularly during isostatic readjustment following thickening of the lithosphere. Short-wavelength Bouguer anomalies and topographic variations observed on the Tibetan Plateau require compensation within the crust, indicative of a rheologically layered plate (Jin *et al.* 1994), and analysis of digital topography across recent graben from central and southern Tibet suggested a ductile, viscous (*c.* 10^{22} Pa s) lower crust (Masek *et al.* 1994). Such geodetic and geophysical data were invoked by a study by Royden *et al.* (1997) of surface deformation in eastern Tibet, which found little surface evidence for deformation over the past 4 Ma despite abundant evidence for crustal shortening; those workers deduced that upper crustal deformation had been decoupled from the motion of the underlying mantle by a weakened lower crust. They suggested that flow in the lower crust was induced by lithospheric thickening beneath the central plateau causing its peripheral extension. This model allowed differential shortening and thickening of the lower crust around the margins of the plateau without associated upper crustal deformation.

Such an analysis seeks to explain the outward growth of the Tibetan Plateau, rather than provide a mechanism for initial lithospheric thickening. The approach was further developed by Clark & Royden (2000), who modelled the topography of the eastern margin of the Tibetan Plateau in terms of the Poiseuille flow (whereby channel boundaries are assumed to be static) of a Newtonian fluid through a 15 km thick channel within the lower crust. They demonstrated that steep, abrupt margins, such as observed across the southern Himalaya, could result from a fluid of viscosity 10^{18} Pa s whereas low-gradient margins, such as

characterize eastern Tibet, required a more viscous fluid (10^{21} Pa s).

Himalayan tectonics and channel flow

The proponents of a channel-flow model for eastern Tibet did not apply the model to the southern, Himalayan margin, but argued that crustal thickening could be explained there by upper crustal shortening accommodated by folding and faulting (Clark & Royden 2000). The present-day geometry of the high-grade metamorphic rocks of the High Himalaya that are termed variously the Greater Himalayan Sequence or the High Himalayan Crystalline Series (Fig. 1) has been compared with that of the Alpine sedimentary wedge, considered to behave as a Coulomb wedge (Royden & Burchfiel 1987; Platt 1993). The dimensions of the wedge are maintained in a state of dynamic equilibrium by the shear stress along its lower surface. A rapid reduction in the coefficient of friction along the basal surface will result in a decrease in the angle of taper of the wedge and hence instability. In the Himalaya, the proposed wedge is bounded below by the Main Central Thrust and above by the South Tibetan Detachment System (Fig. 2a). The two shear zones have opposite sense of shear and appear to have operated simultaneously, at least during the Early Miocene (Hodges 2000; Godin et al. 2006). Burchfiel et al. (1992) proposed melting in the middle crust at depths of 25–30 km to be the cause of
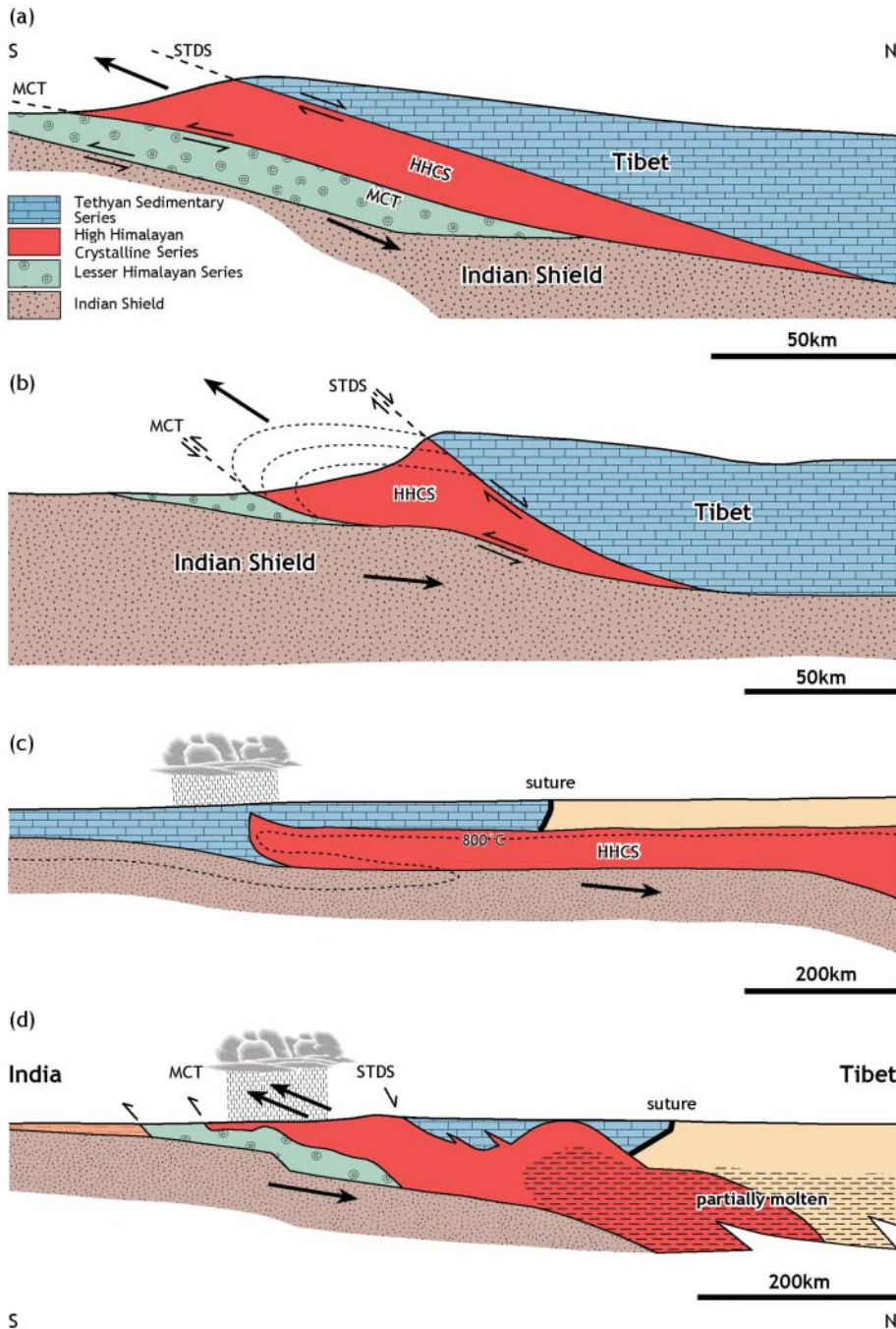

Fig. 2. Four schematic sections showing evolution of mechanical and thermomechanical models of the extrusion of the High Himalayan Crystalline Series (HHCS). (**a**) Orogenic wedge (after Burchfiel et al. 1992); (**b**) pervasive ductile flow, indicated by folded isograds (dashed lines), in wedge (Grujic et al. 1996); (**c**) channel flow from the middle crust (generalized for model HT1 at 12 Ma, Jamieson et al. 2004) where the flowing channel is indicated in red (800 °C isograd is shown as dashed line that is internal to, and so hotter than, the channel boundary, which lies at a temperature between 650 and 750 °C); (**d**) schematic section based on INDEPTH profile (Nelson et al. 1996) modified to accommodate the essential elements of mid-crustal channel flow predicted by Beaumont et al. (2004). Abbreviations as for Figure 1.

lowering the shear stress along the base of the wedge, which resulted in extrusion of the wedge by extension along the South Tibetan Detachment System.

One problem with wedge tectonics, as applied to the Himalaya, is that the continuous post-collisional shortening across the orogen implies that extrusion of a wedge will lead to crustal thinning, unless there is some means of accreting new material into the wedge. Some form of channel flow would obviate the need for such thinning, as such models require that the crust thickens continuously until it weakens at depth, whereupon continued convergence leads to outward plateau growth. Grujic *et al.* (1996) modified flow models previously used to describe subduction zone processes to explain microfabrics observed in quartz tectonites from the High Himalayan Crystalline Series in Bhutan (eastern Himalaya); the resulting model required ductile extrusion of a wedge-shaped body (Fig. 2b). The velocity field within the wedge was modelled as a hybrid between two end-members: (1) induced shear at the boundaries, which generates a uniform vorticity across the channel (Couette flow); (2) induced pressure gradients, which generate highest velocities in the centre of the channel and opposite vorticity at the top and bottom of the channel (Poiseuille flow). This approach was extended to the High Himalayan Crystalline Series of the western Himalaya by Grasemann *et al.* (1999).

The relationship between extrusion of the wedge and drop of shear stress along the basal thrust induced by partial melting, as evidenced by anatectic granites and migmatites in the High Himalayan Crystalline Series, was seen as an important aspect of the Coulomb wedge model as applied to the Himalaya (Harris & Massey 1994). Hence topography, a function of the angle of taper, was related to crustal anatexis in the mid-crust. To develop tectonic models that incorporated changing lithological viscosities it was necessary to obtain empirical evidence for the distribution of melt within the crust. The INDEPTH seismic survey of southern Tibet revealed a zone of bright reflection spots, low seismic velocities and low resistivities at depths of about 15–20 km, as described by Brown *et al.* (1996) and Nelson *et al.* (1996). Nelson *et al.* interpreted their findings as evidence for a zone of partial melting in the crust, and argued that 'the HHC (High Himalayan crystallines) can be viewed as an ongoing extrusion of the fluid middle crust'. However, the presence of a widespread melt fraction was disputed by Makovsky *et al.* (1996), who argued that the low seismic velocities might equally represent a zone of saline aqueous fluid percolation. A subsequent study of crustal xenoliths found in shoshonitic lavas from central Tibet suggested that sufficiently high temperatures had been maintained in at least part of the Tibetan lower crust to generate melting, particularly if an aqueous fluid was present (Hacker *et al.* 2000). This indicates that although a widespread melt may not be proven, the presence of an aqueous fluid under the prevailing conditions in the middle or lower crust will inevitably induce melting. Harrison (2006) noted that the INDEPTH and subsequent resistivity surveys (Unsworth *et al.* 2005) were run along north–south-trending graben or along crustal-scale strike-slip faults (where the roads have been constructed) and suggested that the distribution of melts in the middle crust may be controlled by upper crustal structures. A recent conductivity study of experimental melts obtained from samples of Miocene leucogranites exposed in the Himalaya closely matched the electrical conductivity bright spots obtained from the INDEPTH traverse (Gaillard *et al.* 2004), and thus supported the linkage between possible melting in the contemporary middle crust of southern Tibet and the emplacements of anatectic granites at *c.* 20 Ma in the Himalaya.

The studies described in this section so far have largely focused on the mechanical behaviour of the continental crust during convergence rather than exploring the behaviour of entire lithosphere. In contrast, Chemenda *et al.* (2000) published a 2D thermomechanical model of continental subduction that encompassed the subcontinental lithospheric mantle. Citing tomographic evidence for the subduction of continental lithospheric mantle down to depths of 1700 km (Van der Voo *et al.* 1999) and seismic data for the subduction of Indian crust to a depth of 80 km (Owens & Zandt 1997), they investigated, *inter alia*, the effects of considerably reducing the strength of the crust as it heated at depth. Their experiments involved the detachment of continental crust that was extruded upward and southward as a wedge, facilitated by crustal melting. However, interpretation of the tomographic evidence for the extent of underthrusting of the Indian plate beneath Tibetan lithosphere was, and remains, contentious; Replumaz *et al.* (2004) concluded that the subducted Indian crust overrides its own sinking mantle, and does not extend significantly further north than the Indus–Tsangpo suture; they inferred that the Indian lithosphere plays no part in lithospheric thickening beneath Tibet. In contrast, Zhou & Murphy (2005) identified wholesale subduction beneath southern and central Tibet, which, they argued, precludes deformation of a thin viscous sheet as a model for thickening and uplift, at least beneath the southern plateau.

The quantitative thermomechanical channel-flow model for the tectonic evolution of the Himalaya and southern Tibet that was published by Beaumont *et al.* (2001, 2004), sparked the current interest in the consequences of a weak middle crust for Himalayan tectonics. The model, which provided a 2D, north–south section through the region, sought to address a series of first-order observations of the Himalayan–Tibetan orogenic belt, set out in the review by Hodges (2000). Several versions of the model were run by varying critical input parameters, particularly surface erosion rates and relative strengths of crustal layers, to reproduce these observations successfully. Although no single set of input parameters could reproduce all the observations, the experiments demonstrated that each observation was compatible with the model for selected inputs. All models incorporated the bivergent tectonics of Willett *et al.* (1993) to generate rapid initial crustal thickening, and then invoked an 'effective viscosity model' to induce crustal flow. In effect, the experiments examine the consequences of the viscosity of crustal material decreasing linearly at temperatures above 700 °C to a value of 10^{19} Pa s at 750 °C. A small amount of *in situ* partial melt was proposed as the cause of such a reduction in viscosity (although appropriately located layers of graphite or evaporites could, theoretically, but implausibly, provide a similar result).

Recent steady-state fluid-mechanical studies suggest that effective viscosities can be reduced by about 50% by low-degree partial melting, with a melt fraction of *c.* 0.4 (Holtzman *et al.* 2005); even at much lower melt fractions ($F = 0.07$) a dramatic loss in aggregate strength is observed (Rosenberg & Handy 2005). This compares well with the observed velocity structure within the low-velocity zone beneath southern Tibet, which is consistent with a melt fraction *c.* 0.07–0.12 (Yang *et al.* 2003), and with magnetotelluric data, which suggest a melt fraction of 0.05–0.14 to account for the low-resistivity layer (Unsworth *et al.* 2005). However, it should be noted that similar magnetotelluric anomalies from the central Himalaya are also indicative of crustal fluids where prevailing temperatures are clearly subsolidus (<400 °C); in this case, aqueous fluids derived from dehydration reactions are the likely cause (Lemonnier *et al.* 1999).

The results of incorporating both the temperature and viscosity changes into a model of thickened lithosphere are shown in a generalized form in Figure 2c. Assuming the inputs for the first Himalaya–Tibet model, termed HT1 (one of several thermo-mechanical continuum models that vary in their input parameters as formulated by Beaumont *et al.* (2001)), a low-viscosity channel is created *c.* 21 Ma after collision by partial melting of the Indian crust at temperatures above *c.* 700 °C. By 33 Ma after collision the low-viscosity channel migrates southward, driven by the differential pressure between the thickened Tibetan crust to the north and the Indian crust of normal thickness to the south. The channel does not reach the surface unless the topographic rise of the southern Himalaya is actively eroded. The parameters selected for model HT1, the basis for model–data comparisons, and some key tests of the models have been discussed in detail by Beaumont *et al.* (2006). The possible significance of focused orographic precipitation on middle to lower crustal flow has been discussed by numerous workers (e.g. Jamieson & Beaumont 1989; Beaumont *et al.* 1992; Avouac & Burov 1996) and was first applied to the extrusion of the high-grade rocks of the Himalaya by Wu *et al.* (1998). For model HT1, the low-viscosity channel is predicted to break the surface *c.* 42 Ma after collision (Fig. 2c). Thus the channel-flow model explains the southward extrusion of rocks brought up from the middle crust and predicts that these will be extruded along the southern topographic front of the Himalaya where precipitation, from the summer monsoon, is most intense. The low-viscosity channel extruding southward, as originally described for the eastern Himalaya by Grujic *et al.* (2002), is identified as the High Himalayan Crystalline Series, bounded by the South Tibetan Detachment System above and the Main Central Thrust below (Fig. 2d). In contrast, eastern Tibet has been cited as an example of 'channel tunnelling', where the weak crustal layer does not reach the surface because of the absence of focused orographic precipitation (Beaumont *et al.* 2001).

Assessing the significance of channel flow in the Himalaya

The concept of channel flow as a mechanism for large-scale tectonics in mature collision zones has received considerable, but not unanimous, recent favour amongst geoscientists. The two essential requirements for Himalayan style (gravitationally driven) channel flow are the formation of a low-viscosity layer in the middle–lower crust and a lateral pressure gradient linked to the contrasting topographic elevation between the plateau and the foreland.

Although a mechanically strong upper mantle is not an essential requirement for the model, the scale and style of flow are likely to evolve differently given a persistently weak upper mantle (Beaumont *et al.* 2006). Hence it is useful to summarize current knowledge concerning the strength of the upper layers of the continental lithosphere. Earthquake focal depths from the Himalaya and the Tibetan Plateau suggest a strong upper crust to depths of *c.* 15 km (Maggi *et al.* 2000). There is evidence from seismic anisotropy of Rayleigh and Love wave propagation in western Tibet (Shapiro *et al.* 2004) of a weak lower to middle crust (25–50 km) that lies at deeper levels than the low-velocity zone identified by the INDEPTH traverse (15–20 km) across southern Tibet. Whereas the paucity of mantle-sourced earthquakes in continental regions has been interpreted as evidence for a weak upper mantle (Maggi *et al.* 2000; Jackson 2002), the persistence of mountain ranges over millions of years has been cited as evidence for a strong mantle lithosphere with viscosities

of 10^{22}–10^{24} Pa s as opposed to a weak mantle (10^{19}–10^{20} Pa s) implied by competing models (Burov & Watts 2006). Further evidence for a strong underlying lithospheric mantle is inferred from the analysis of intracontinental earthquakes beneath Tibet (Chen & Yang 2004). Some of the apparent conflict between models for the mechanical behaviour of the lower crust and upper mantle can be resolved by recognizing that the behaviour of Earth materials will change according to their tectonic environment; from the analysis of 1700 Himalayan earthquakes detected by an array of 29 broadband seismometers, Shulte-Pelkum *et al.* (2005) identified many deep crustal earthquakes beneath the foreland basin, south of the Himalaya, indicative of a strong lower crust, but beneath the High Himalaya and Tibet a 'jelly sandwich' structure was indicated by the concentration of earthquakes in the upper crust and upper mantle layers. Shulte-Pelkum *et al.* concluded that the middle or lower crust is weakened by metamorphism as it is drawn into the orogenic belt. In a comprehensive review of geophysical evidence for channel flow, Klemperer (2006) concluded, from what has been established about present-day crustal temperatures and rheologies, that crustal flow of some kind is inevitable. Further, the depth of the viscosity minima within the crust increases northward, from the upper to middle crust beneath southern Tibet, to the middle to lower crust beneath central and northern Tibet, consistent with proposed flow in the middle crust beneath southern Tibet and in the lower crust further north on the plateau. Klemperer assigned Poiseuille flow to the channel beneath southern Tibet; in northern Tibet, the relative weakness of the lithospheric mantle suggests a larger component of Couette flow.

Given the prevailing uncertainties in interpreting the geophysical data, it is important to assess the geological evidence that has been collected, or could be collected, to test the hypothesis that the high-grade rocks of the Himalaya are extruding southward as a low-viscosity channel derived from the middle crust, by a process linked at depth to partial melting within the channel and on the surface to erosional intensity (Grujic *et al.* 2002; Jamieson *et al.* 2004). This can be addressed by identifying specific questions posed by the model.

Is the timing and distribution of movement and melting of the High Himalayan Crystalline Series consistent with the requirements of channel flow?

If the rocks now exposed as the High Himalayan Crystalline Series represent a crustal sheet whose extrusion towards the surface was effected by the flow of a low-viscosity channel, a fundamental requirement is that both the faults or shear zones that define the boundaries of this sheet, the Main Central Thrust and the South Tibetan Detachment System, were active during the period of flow. Although evidence suggests that both faults were initially active at *c.* 24 Ma and the Main Central Thrust has been active intermittently since this time, there is no evidence that either strand of the detachment system has been active more recently than 12 Ma (Godin *et al.* 2006). Moreover, unlike the thrust zones to the south the detachment is no longer seismically active. Thus, although the hypothesis that the High Himalayan Crystalline Series has been exhumed during the Early to Mid-Miocene by channel flow is supported by available geochronological evidence, there is no evidence that exhumation has been a continuous process since that time.

The channel-flow model, for parameters specified for model HT1 (Beaumont *et al.* 2001), predicts that melting will be initiated in the channel at *c.* 35 Ma (assuming collision at 54 Ma) when transport directions reverse from progressive burial to

lateral return flow. Thereafter melting is possible by decompression as the channel is extruded towards the surface (Fig. 2c). Crust-derived granites are found across the Himalaya, intruding and derived from the High Himalayan Crystalline Series from 23 Ma to 12 Ma (see Fig. 4 caption for references). However, these granites, together with associated migmatites, are found almost exclusively in the upper part of the High Himalayan Crystalline Series, often located along its northern margin (Le Fort *et al*. 1987; Hodges 2000). Indeed, evidence for *in situ*, incipient melting (as inferred from migmatites or grain-boundary melts) near the postulated lower boundary, although not entirely lacking (see Harris *et al*. 2004), is scant; the hanging wall of the Main Central Thrust is usually characterized by sub-solidus, garnet- or kyanite-grade schists (Formation 1 of Colchen *et al*. 1986). Although the physical argument for channel flow requires a critical reduction in viscosity, the margins of the extruding channel may not necessarily coincide with the onset of *in situ* melting, as strain-softened material could become part of the channel at temperatures of $<700\,^{\circ}C$ (Beaumont *et al*. 2004). Moreover, cooler material will be accreted to the footwall during channel exhumation, thereby separating the lower boundary of channel flow from the spatial distribution of melt weakening.

The Main Central Thrust was originally defined as the thrust zone that emplaces gneisses, migmatites and schists of the 'Main Central thrust mass' (now termed the High Himalayan Crystalline Series) over lower-grade metacarbonates and quartzite formations of the 'Lower Himalaya' (Heim & Gansser 1939). Decoupling zones of *in situ* melting from the channel boundaries allows the Main Central Thrust to be generally equated with the 'model Main Central Thrust', defined as the protolith boundary between outflowing (High Himalayan Crystalline Series) and inflowing (Lesser Himalayan Series) material, as conceived in HT1 and similar models (Jamieson *et al*. 2006). Because the extruding channel will thicken with time, lithologies in the footwall of the thrust zone early in the process will become entrained into the hanging wall in time, thus requiring the lower boundary of the model Main Central Thrust to migrate southward through time. This accounts for much of the dispute between geologists over the precise location of the Main Central Thrust in some Himalayan sections. However, because the putative channel cannot reach the surface by purely ductile processes, it is probable that the margins of the sheet now exposed at the surface may be related to late-stage brittle thrusting rather than represent the original mid-crustal channel (Grujic 2006; Hodges 2006). This is particularly true at the base

of the sheet. For example, penetrative deformation associated with shearing along the top of the slab in the Everest region of the eastern Himalaya seems to have occurred at close to peak metamorphic conditions (Law *et al*. 2004; Jessup *et al*. 2006). In contrast, there is abundant evidence at the base of the slab for late-stage brittle deformation in the central Himalaya (Hodges *et al*. 2004; Robinson & Pearson 2006), and in the eastern Himalaya penetrative deformation features preserved within the Main Central Thrust zone can be related to shearing that post-dates peak metamorphic conditions (Jessup *et al*. 2006). Indeed, the Main Central Thrust does not appear to define the base of continuing or recent extrusion in the central Himalaya, where a marked physiographic transition, bounded by brittle faults, is located *c*. 30 km south of the Main Central Thrust (Fig. 3). These faults define a Late Pliocene–Quaternary thrust zone as indicated by contrasting $^{40}Ar/^{39}Ar$ cooling ages from detrital muscovites derived from either side of the transition (Wobus *et al*. 2003; Hodges *et al*. 2004), thus providing the most likely lower boundary of recent or continuing extrusion. If the Miocene channel were bounded below by the Main Central Thrust, then the locus of extrusion had migrated southward by the Late Pliocene to expel the uppermost lithologies of the Lesser Himalaya (Fig. 3).

The apparent scarcity of evidence for the Oligocene melting that is predicted by the model may be a characteristic of the current erosion front on the southern flanks of the Himalaya, where granites of *c*. 20 Ma or less are commonly exposed; older granites are assumed to have been eroded away (Jamieson *et al*. 2004). There is sporadic evidence for pre-Miocene crustal melting (Coleman 1998; Godin *et al*. 2001; Prince *et al*. 2001). Recently, both Zhang *et al*. (2004) and Lee & Whitehouse (2007) have identified crustal melts of Oligocene age (35–23 Ma) from a North Himalayan gneiss dome exhumed by the North Himalayan antiform (Figs 1 and 2d) that lies south of the Indus–Tsangpo suture marking the boundary between the Indian and Asian plates (Watts *et al*. 2005). The North Himalayan intrusive rocks are unusual for Himalayan granites in that some are kyanite bearing, indicative of a greater depth of origin than that for the Early to Mid-Miocene leucogranites from the High Himalaya. They provide the first evidence for melting of the deeper crust at this early stage of orogenic evolution. Both experimental constraints (Patiño Douce & Harris 1998) and pseudosection analysis (Harris *et al*. 2004) suggest much lower melt fractions for high-pressure melts than those produced during uplift, a contributory explanation of their scarcity.
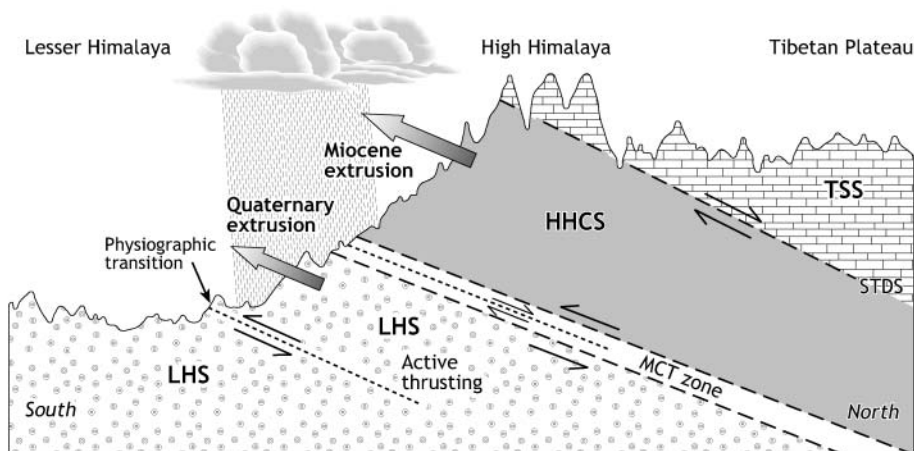

Fig. 3. Schematic north–south geological section through the central Himalaya showing (1) Miocene extrusion bounded by Main Central Thrust zone and South Tibetan Detachment System (dashed lines) and (2) Quaternary extrusion bounded by brittle reactivation of the Main Central Thrust and thrusting along the physiographic transition (dotted lines). Modified from Hodges *et al*. (2004), Thiede *et al*. (2004), Burbank (2005) and Wobus *et al*. (2005). Abbreviations and legend as for Figure 1.

Is there any linkage between surface erosion and extrusion rates?

The possible linkage between climatically driven erosion and tectonic deformation has been the subject of considerable debate (e.g. Burbank *et al.* 2003; Burbank 2005; Wobus *et al.* 2005; Huntington *et al.* 2006). Both the time scales and length scales of climatic variation and of tectonic processes need to be considered in assessing the possible feedbacks involved. Although the geological record often allows erosion and exhumation rates across a range of time scales to be assessed quantitatively, deconvolving the implications for a possible linkage between tectonic extrusion and climate is hazardous.

Linkage between precipitation and tectonics may be evident from comparing changing erosion rates through time with variations in extrusion rates over the same period. Apatite fission-track and muscovite ^{40}Ar/^{39}Ar dating of bedrock from the central Himalaya (Huntington *et al.* 2006) indicates that temporal variations in erosion rates over a *c.* 1 Ma time scale correlate more closely with changes in global climate than with tectonic extrusion. On a longer time scale, there is abundant geological evidence that extrusion of the High Himalayan Crystalline Series was particularly vigorous during the Early Miocene (Hodges 2006). The channel-flow model would require an intense period of precipitation and erosion at this time, which could be assessed by analysis of sedimentation patterns in the foreland basin and the submarine fans of the Indus and Bay of Bengal. Available data from the Indus Fan do support rapid erosion during the Early to Mid-Miocene (Clift 2006) consistent with climate–tectonic interactions.

The proposition that focused precipitation is a driving force for exhuming a low-viscosity channel implies that the locations of channel boundaries will be determined by the distribution of precipitation patterns at the time of active extrusion. In the Himalaya, this could be revealed as a correlation between summer monsoon precipitation patterns and neotectonics (Hodges 2006). Monsoon precipitation is focused on the topographic front of the central Himalaya, increasing in intensity southward (Hodges *et al.* 2004). Maximum rainfall is recorded in a zone of 30 km width, immediately south of the Main Central Thrust, bounded below by a sharp physiographic transition that is recognized from geomorphological and thermochronological studies to be an active brittle thrust zone of Pliocene–Quaternary age (Wobus *et al.* 2003, 2005). To the west, along the Sutlej Valley in NW India, precise satellite-based meteorological data reveal that the highest rainfall is precipitated across a zone of *c.* 60 km width, south of the Main Central Thrust, that is bounded by Quaternary thrusts (Thiede *et al.* 2004). Apatite fission-track ages are positively correlated with monsoon precipitation rates. Because both exhumation rates, derived from the fission-track data, and precipitation patterns are spatially associated with active faulting, these results provide evidence for linkage between extrusion and precipitation over a length scale of tens of kilometres and a time scale of *c.* 1 Ma.

A recent apatite fission-track study across the eastern Himalaya compared exhumation rates over the past 2 Ma from two regions of the eastern Himalaya that receive contrasting rainfall (Grujic *et al.* 2006). The results demonstrated that climate and erosion rates are demonstrably linked over a time scale of 1 Ma and a length scale of tens of kilometres. However, the study also confirmed that exhumation rates, inferred from thermochronology in the absence of tectonic or geomorphological constraints, may reflect climate forcing, independent of changes in extrusion rates.

On a larger length scale (10^3 km), present-day monsoon intensity along the strike of the Himalayan orogen increases strongly eastward between 75° and 92°E, producing stronger erosion rates (Fig. 4a). Although there are strong regional variations in present-day rainfall patterns, precipitation along the Main Central Thrust in NW India is 500–1000 mm a^{-1}, which generally rises (with significant perturbations) to over 4500 mm a^{-1} in western Bhutan (Fig. 4a). At the far east of this region, and eastward of Figure 4, rainfall decreases sharply as a result of the Shillong rain shadow (Grujic *et al.* 2006). Thus, if the overall eastward increase in precipitation on the topographic front has been maintained over geological time scales, one expected consequence of channel flow might be a more rapid extrusion of the channel eastward in response to the increased erosion rates. The underlying assumptions of the following discussion are that (1) precipitation has remained focused on the topographic front beneath which the channel is extruding and (2) the present-day eastward intensification of the monsoon has been maintained over geological time scales. It is not assumed that precipitation rates have remained unchanged over millions of years. If both assumptions hold true, evidence of an eastward intensification in tectonic activity across the orogen over geological time scales would be indicative of long-term climate–tectonic
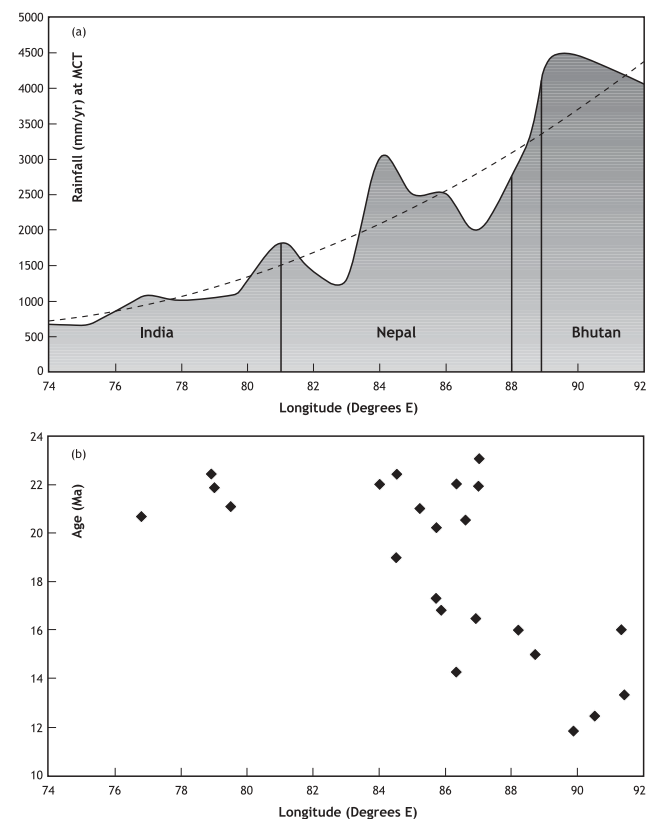

Fig. 4. (**a**) Annual precipitation rates along the Main Central Thrust integrated at degree intervals of longitude between 74°E and 92°E; dashed line indicates second-order polynomial trend-line through point sources taken from Das (1981) and Chalise *et al.* (1996). (**b**) Distribution of ages (vertical axis in Ma) for High Himalayan leucogranites exposed along the strike of the central Himalaya. Data from Schärer *et al.* (1986), Harrison *et al.* (1997), Searle *et al.* (1997, 2003), Simpson *et al.* (2000), Daniel *et al.* (2003) and sources therein.

linkage in the Himalayan system. There are several observations that support such a conjecture, as follows.

(1) A comparative geomorphological study by Duncan *et al*. (2003) of Bhutan (eastern Himalaya) and Nepal (central Himalaya) has identified contrasts that have been linked to a more active tectonic regime in Bhutan. In comparing a concave north–south profile in the central Himalaya with a convex profile in the eastern Himalaya, those workers inferred a more rapid rate of uplift, relative to erosion, in the east. As the precipitation rate, and therefore the current erosion rate, is much higher in the east (Fig. 4a), this observation implies an eastward increase in exhumation rate over the time scales of landscape formation (*c*. $10^4–10^5$ years.

(2) Across the Himalaya from Zanskar eastward to Bhutan (a distance of 1500 km) there is a regional decrease in $^{40}Ar/^{39}Ar$ mica cooling ages in the High Himalayan crystalline Series from 22–18 Ma to 13–11 Ma, as noted by Guillot *et al*. (1999). Those workers interpreted this trend as evidence for oblique collision. However, such an interpretation is contentious; a study of detrital zircons from clastic sediments of the southern Himalaya limits any such diachroneity between Zanskar (NW India) and western Nepal to less than 2 Ma (DeCelles *et al*. 2004). The alternative explanation for the trend is that the along-strike, eastward-younging trend for cooling rates reflects an eastward increase in exhumation rates over a time scale of 10–20 Ma.

(3) Supporting evidence for the rate of exhumation increasing eastward along the orogen since the Early Miocene can also be inferred from the age distribution of leucogranites now exposed in the High Himalayan Crystalline Series (Fig. 4b). The granites considered here all lie between longitudes 75° and 92°E (Fig. 1). These geographical limits include all the major leucogranite bodies of the High Himalaya and exclude the Nanga Parbat and Namche Barwa syntaxes, where localized effects of accelerated uplift rates and juvenile melt formation associated with the syntaxial geometries dominate (Zeitler *et al*. 1993; Booth *et al*. 2004). Whereas leucogranites from the main body of the orogen range in age from 23 Ma to 19 Ma across the western and central Himalaya, east of 85°E (eastern Nepal) the youngest ages of granites decrease markedly to <12 Ma. According to the channel-flow model, the ages of exposed granites will be youngest where the active channel is most recently exposed (Jamieson *et al*. 2004). Given the tectonic geometry where the extrusion vector (southward from Tibet) is approximately orthogonal to the exposed surface of the channel along its leading edge (striking roughly east–west as the High Himalayan Crystalline Series; see Fig. 1), younger ages will be exposed where extrusion is most rapid. The model also predicts that younger granites will be exhumed where additional exhumation mechanisms have operated, as in the gneiss domes exposed by the North Himalayan antiform (Fig. 2d). Young anatectic leucogranites, emplaced at 10–15 Ma, have been recognized from this tectonic setting (Zhang *et al*. 2004).

Are either fabrics or mineral assemblages observed in rocks within the High Himalayan Crystalline Series indicative of channel flow?

Many of the complex fabrics found in the rocks of the High Himalayan Crystalline Series are indicative of ductility during their exhumation and of the distribution of simple and pure shear during their deformation (Law *et al*. 2004), but are not, *per se*, evidence of channel flow from the lower or middle crust. However, transport-parallel stretching associated with the pure shear component could make an important contribution to

driving extrusion (Jessup *et al*. 2006). Current extrusion models lack the resolution to predict specific microstructures from within the channel (Jamieson *et al*. 2002) although multiple reversals of the direction of flow are likely to generate complex overprinting within the channel, contrasting with simpler patterns outside it (see Grujic *et al*. 1996; Grasemann *et al*. 1999). For example, structural evidence for reversals of shear from the high-grade terranes of the Canadian Cordillera has been cited as evidence for lower crustal flow (Williams & Jiang 2005). However, quantitative evidence for the depth and timing of extrusion is more likely to be recovered from analysis of pressure–temperature–time ($P–T–t$) paths than from microstructures preserved at the surface, although both approaches may be affected by overprinting during near-surface recrystallization.

Although individual $P–T–t$ paths are not diagnostic of a particular metamorphic style, a systematic relationship in the shape and precise timing of the $P–T–t$ paths across the channel is an expected consequence of channel flow (Jamieson *et al*. 2002, 2004). In general, channel flow requires that there should be strong decompression in the clockwise paths of particles exhumed from within the channel (Fig. 5a, bounded by lines C_L, C_U); particles from the lower parts of the channel (C_L) reach greater depths and achieve higher temperatures. Lithologies from the initial footwall of the bounding thrust zone that forms the lower boundary of the channel are later underthrust and then experience reverse flow as they are expelled southward with the channel, resulting in a 'hairpin' $P–T–t$ path (Fig. 5a, line L). Timing of peak metamorphism near the lower channel boundary (t_1) will be younger than for the path described by particles from the centre of the channel ($t_0 > t_1$). The precise form and timing of a given particle path depends critically on its position within the channel, but for selected paths t_0 is *c*. 18 Ma, compared with *c*. 9 Ma for t_1 (Jamieson *et al*. 2004).

These predictions have not been systematically tested across a north–south Himalayan transect, not least because of the difficulty of obtaining precise $P–T–t$ data, particularly along the prograde path, as a result of (1) mineral chronometers recording cooling temperatures if heated above their closure temperatures and (2) overprinting by near-surface recrystallization. Paths for three studies from the High Himalayan Crystalline Series (within the channel) are shown schematically in Figure 5b. The prograde burial path, from 35 to 25 Ma, is best defined by Sm–Nd dating of garnet from kyanite schists in Zanskar (Vance & Harris 1999). Data from the upper part of the channel in the western Himalaya (line V, Fig. 5b) and from the lower part of the channel in the eastern Himalaya (line M, Fig. 5b) are also plotted. All samples from these parts of the channel experienced a clockwise path and reached maximum depths at *c*. 24 Ma, followed by rapid decompression. In contrast, a sample from the lower margin of the channel, which originated in the footwall of the lower bounding thrust (line J, Fig. 5b), was taken down to shallower levels before experiencing a sharp 'hairpin' bend and returning to the surface (Caddick *et al*. 2006). This sample reached peak temperatures at *c*. 11 Ma, close to the prediction of channel-flow models.

Although arrays so far published are broadly consistent with channel flow, the paths could also be explained by burial beneath active thrusts followed by extrusion beneath shear zones with normal displacement (Vance & Harris 1999), without recourse to flow models. The predicted variation in peak temperature and pressure with position within the channel, as seen by comparing C_U and C_L (Fig. 5a), cannot yet be assessed, as $P–T–t$ paths from the upper and lower parts of the same Himalayan section have not been recovered. A further test would be to model the
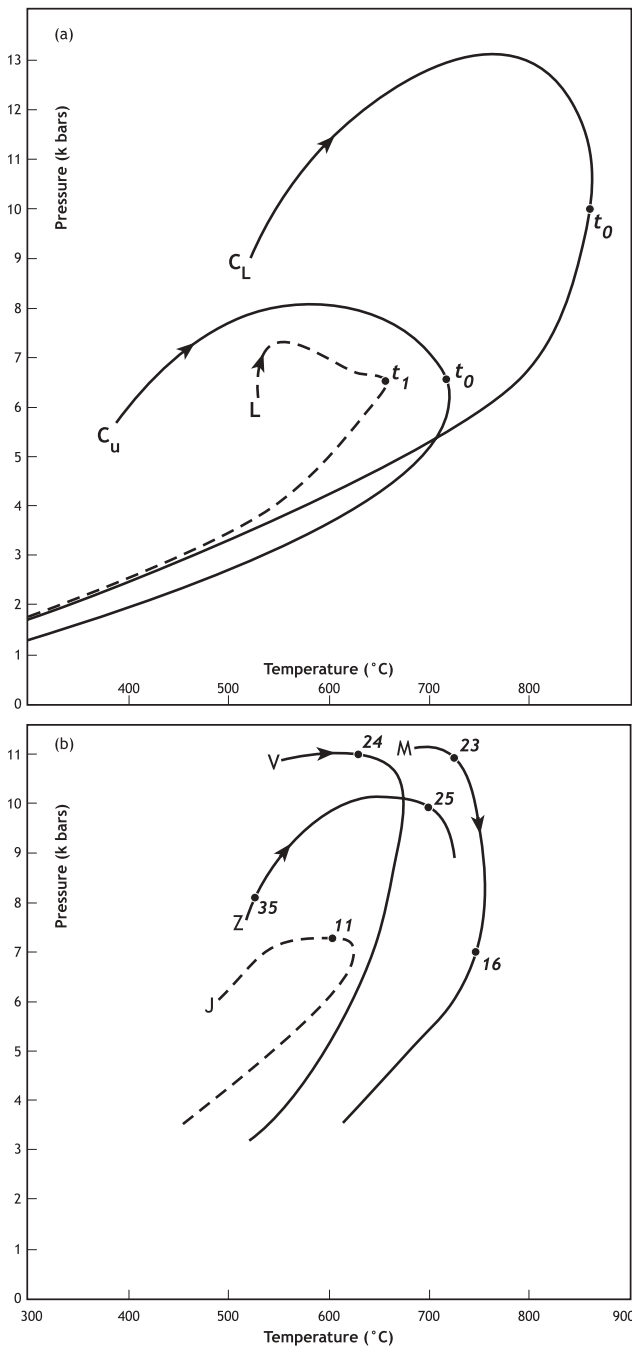
Fig. 5. (**a**) *P–T–t* paths predicted from channel-flow models (after Jamieson *et al*. 2002, 2004); C_L and C_U (continuous lines) indicate paths of particles extruded within lower and upper parts of the channel, respectively, reaching peak metamorphism at time t_0; L (dashed line) indicates path of particle initially below, and now extruded at lower margin of the channel, reaching peak temperatures at t_1. (**b**) Empirical data obtained from the High Himalayan Crystalline Series; Z (Zanskar, Vance & Harris 1999), V (Vaikrita Formation, Sutlej valley, from Caddick *et al*. 2006) and M (Sikkim migmatite, Harris *et al*. 2004) represent samples extruded within the main channel; path J (dashed) represents a sample now extruded beneath the lower margin of the original channel (Jutogh Formation, Sutlej valley, from Caddick *et al*. 2006).

P–T–t path of a particle now located just above the channel and to compare this with empirical data from rocks recovered from the base of the Tethyan Sedimentary Series, now exposed in the hanging wall of the South Tibetan Detachment System.

Is the evidence for the timing of uplift of the plateau consistent with channel flow?

An important prediction of models for mid-crustal flow beneath southern Tibet is that the topographic rise of Tibet will develop initially by elevation of the surface proximal to the Indus–Tsangpo suture, and this steep and narrow topographic rise will propagate outward, both northward across Tibet and southward towards the Himalaya, as the middle crust becomes hot and weak (Beaumont *et al*. 2004; Medvedev & Beaumont 2006). In practice the evolving topography of the plateau will be complex, and also will be affected by pre-collision topography as envisaged by England & Searle (1986) and modified by the east–west growth of the plateau from lower crustal flow in response to crustal thickening beneath central Tibet (Royden *et al*. 1997; Clark & Royden 2000). Evidence for the time scale of the latter process, based on geomorphological observations on river incisions coupled with isotopic and fission-track dating of river gorges from the margins of eastern Tibet, suggests that *c*. 1.5 km of uplift has occurred since Pliocene times (Schoenbohm *et al*. 2004, 2006). For crustal flow on all scales, the post-collision increase in elevation must be rapid to thicken the crust sufficiently for internal heating to allow melting in the middle crust at about 20 Ma following collision. In contrast, time–elevation paths derived from thin viscous sheet deformation of the lithosphere, which predicts that the elevation of the plateau will propagate from south to north (England *et al*. 1988), imply that the rate of increase in elevation will be relatively slow because of the shortening between the Indian plate and Eurasia being accommodated by thickening of the entire lithosphere, not just the crust, following collision.

The contrasting elevation paths between these two groups of models are shown most clearly in the period 40–30 Ma (Fig. 6) at which time the channel-flow model requires elevation of
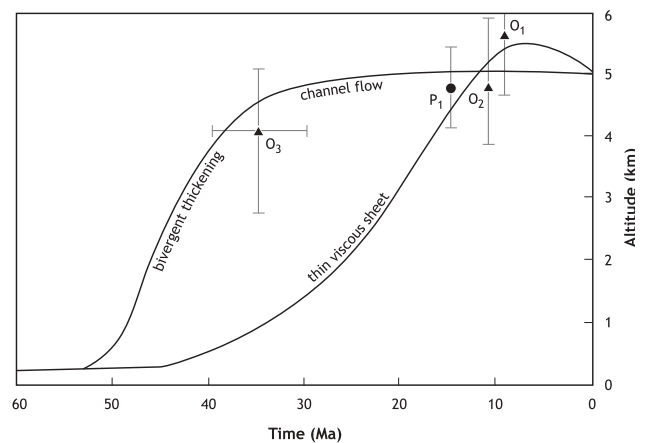

Fig. 6. Estimates of the altitude of the surface of the southern Tibetan Plateau deduced from (1) oxygen isotope studies (O_1, Rowley *et al*. 2001; O_2, Garzione *et al*. 2000; O_3, Rowley & Currie 2006); (2) palaeobotany sites (P_1, Spicer *et al*. 2003). Time–elevation paths for southern Tibet are indicated for behaviour as a thin viscous sheet (Fielding 1996), and assuming bivergent thickening followed by channel flow (Willett *et al*. 1993; Beaumont *et al*. 2004).

southern Tibet to be close to its present height, whereas the thin viscous sheet model suggests elevation no higher than about 1 km (Fielding 1996), although this would be increased by pre-collision topography. It should be noted that, because the current 2D models for channel flow cannot consider movement out of the section, it remains unclear whether the process is consistent with east–west spreading, as the plateau altitude exceeds the maximum elevation that can be supported by marginal stress, thus allowing the timing of Neogene north–south graben and dyke formation to provide proxies for the timing of maximum elevation (Williams *et al*. 2001). Palaeoelevation estimates that are independent of assumed tectonic models are scarce, as has been reviewed by Harris (2006). There is reasonable unanimity between diverse techniques applied that southern Tibet was elevated to close to its present height certainly by 15 Ma (Spicer *et al*. 2003). However, critical to the present discussion is the estimate by Rowley & Currie (2006) that clearly places southern Tibet at an altitude of *c*. 4 km as early as 35 Ma (Fig. 6). Thus one can argue either that increase in surface uplift was rapid following collision, consistent with the requirements of mid-crustal channel flow, or that significant pre-collision topography was already established prior to collision, as might be expected beneath an active continental margin.

Is there evidence for the southward flow of crustal material at depth from the Tibetan lithosphere to the Indian lithosphere?

Published channel-flow models predict southward transport of Asian middle to lower crust beneath the surface position of the suture, although this process is mitigated by the southward transport of the suture, along with the Indian and Asian upper crust within which it is embedded (Beaumont *et al*. 2004). Harrison (2006) noted the absence of zircons of Late Cretaceous to Eocene age, representative of the arc that forms much of the southern Tibetan crust, from the numerous geochronological studies of the supracrustal rocks and associated granites of the High Himalayan Crystalline Series. However, if the channel were restricted to the return flow of the downgoing Himalayan crust, material from the Tibetan lithosphere would not be incorporated during either subduction or extrusion. None the less, the observation is inconsistent with regional melting of Asian lithosphere that is mobilized within the extruding channel. Interestingly, Nd isotope values that are characteristic of the middle or lower crust beneath southern Tibet, and distinct from lithologies that constitute the Indian plate, have been recorded in Miocene dykes (12–9 Ma) intruding Tethyan sediments south of the Tsangpo suture; the dykes are identical in trace element and isotopic composition to mid-Miocene magmatic rocks north of the suture, as noted by King *et al*. (2007). Those workers suggested southward flow of source material, identified as the gneisses of the Tibetan middle or lower crust, which provided a source for the dyke swarm south of the surface suture. Such southward movement of the Tibetan middle crust is predicted by modelling, provided a weakened layer is embedded into the model crust (Jamieson *et al*. 2006). However, it should be emphasized that there is currently no isotopic evidence of melts derived from the Tibetan lithosphere being entrained into a channel now exposed as the High Himalayan Crystalline Series.

Conclusions

There can be little doubt that the high-grade rocks of the Himalaya were extruded southward, bounded by thrusting below

and normal faults and shear zones above. Arguments persist regarding the chronology of movement, the geometry of the extruding sheet and the driving forces responsible for its extrusion. The channel-flow model, as currently formulated for the Himalayan orogen, explores the consequences of a mechanically weak crustal layer on the evolution of a continent–continent collision zone, where precipitation is focused on the topographic front. It makes a range of predictions regarding the evolution of the topography, the timing and shape of P–T–t paths for rocks now exposed at the surface, the style of deformation across the channel and the along-strike variations in both the timing of melting in the channel and the extrusion rate. For each of these areas, evidence is emerging that is largely consistent with the hypothesis that southward extrusion during the Early to Mid-Miocene was facilitated by channel flow.

The evidence that mid-crustal flow has persisted since that time is much weaker. Pliocene–Quaternary brittle thrusts south of the Main Central Thrust along the central Himalaya appear to facilitate extrusion of lower-grade lithologies of the Lesser Himalaya that correlates spatially with current precipitation patterns. However, the relationship between these upper crustal neotectonic structures and apparent melt weakening in the present-day middle crust, inferred from geophysical traverses in South Tibet, is unknown. Climate–tectonic feedbacks can be incorporated both by crustal channel-flow models and by wedge-extrusion models, and it is possible that the active, brittle extrusion of Lesser Himalayan lithologies is not connected to the melt-weakened layer at deeper levels in the middle crust. On the other hand, over the same, 1 Ma, time scale, there is strong geomorphological and geophysical evidence for the outward growth of the eastern margin of the Tibetan Plateau, which can be readily explained by eastward flow of the lower crust.

Despite the success of models for flow in both the lower and middle crust in accounting for many geological and geophysical observations, most of the tectonic features of the Himalayan orogen can also be explained by an orogenic wedge, characterized by brittle deformation towards the foreland and by ductile deformation of high-grade metamorphic rocks towards the hinterland, that has been thickened by underplating at the brittle–ductile transition (Toussaint *et al*. 2004; Bollinger *et al*. 2006). Rapid extrusion of the High Himalayan Crystalline Series can be explained by a crustal ramp under the lower margin of the wedge, without recourse to channel flow (Avouac 2003).

The task of critically assessing any model is made particularly difficult by *a posteriori* tuning to fit emerging geological and geophysical observations; an example of this refining process can be seen by comparing a recent Himalaya–Tibet model, termed HT111 (Jamieson *et al*. 2006) with earlier versions such as model HT1 (Beaumont *et al*. 2004). The embedding of a 2.5 km weak layer within the upper crust allowed the model to reproduce several geological observations (e.g. the changing provenance of detrital material through time), but there is no independent evidence for the existence of such a layer. Although this model outcome may be taken as an indication that such a layer might exist and should therefore be investigated, it remains unclear what critical observations could emerge that would serve to falsify, or indeed confirm, the model's ultimate validity.

Importantly, because current crustal-flow models are 2D they cannot evaluate east–west deformation, and so linkages with 2D geophysical surveys that run along active rifts remain problematic, as deep crustal and mantle processes are unlikely to be representative of processes outside the line of section. This may explain the apparent mismatch between models that require channel flow to have been continuous since the Early Miocene

and the paucity of geological evidence for the process being extant. It may be speculated that following channel flow during the Early Miocene, the plateau reached a critical elevation, which induced east–west extension in the hitherto southward extruding mid-crustal channel and the formation of neotectonic graben in the uppermost crust. For as long as there remain fundamental uncertainties regarding the extent of subduction of Indian lithosphere beneath the Tibetan Plateau and the mechanical strength of the lower and middle crust, it is unlikely that any unified model for orogenic evolution will become universally accepted.

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