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Southward extrusion of Tibetan crust and its effect on Himalayan tectonics

K.V. Hodges, J.M. Hurtado, and K.X. Whipple

Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology Cambridge, Massachusetts USA

Abstract. The Tibetan Plateau is a storehouse of excess gravitational potential energy accumulated through crustal thickening during India-Asia collision, and the contrast in potential energy between the Plateau and its surroundings strongly influences the modern tectonics of south Asia. The distribution of potential energy anomalies across the region, derived from geopotential models, indicates that the Himalayan front is the optimal location for focused dissipation of excess energy stored in the Plateau. The modern pattern of deformation and erosion in the Himalaya provides an efficient mechanism for such dissipation, and a review of the Neogene geological evolution of southern Tibet and the Himalaya shows that this mechanism has been operational for at least the past 20 million years. This persistence of deformational and erosional style suggests to us that orogens, like other complex systems, can evolve toward "steady state" configurations maintained by the continuous flow of energy. The capacity of orogenic systems to self-organize into temporally persistent structural and erosional patterns suggests that the tectonic history of a mountain range may depend on local energetics as much as it does on far-field plate interactions.

1. Introduction

From the perspective of thermodynamics the development and evolution of orogenic systems involves three kinds of processes: those that serve to accumulate energy, those that transfer energy from one part of the system to another, and those that help dissipate excess energy. Crustal thickening and other forms of energy accumulation in orogenic settings are predominantly caused by lithospheric plate interactions; as a consequence, the rates at which they occur and the geometries of the structures they produce are at least broadly related to plate motions. On the other hand, processes responsible for the transferal or dissipation of energy are more dependent on the abundance and distribution of matter within an orogenic system, making their spatial and temporal evolution impossible to predict from plate tectonic principles alone. If we aspire to a comprehensive understanding of orogenesis, we must look more closely at the distribution of energy in orogenic systems because, at least in theory, gradients in that distribution should drive the processes of energy transfer and dissipation.

In this paper, we show that the distribution of gravitational potential energy in the Himalayan-Tibetan orogenic system favors the localization of high-efficiency dissipation processes along the Himalayan orogenic front. A closer look at the geology and physiography of this margin of the Tibetan Plateau reveals that large amounts of energy are dissipated through coordinated deformational and erosional activity that accommodate southward extrusion of the middle crust from beneath the Tibetan Plateau. These processes are not just modern phenomena; evidence that they have been active in the Himalaya for at least the past 20 million years suggests that the southern margin of the orogenic system may have achieved a dynamical steady state reflecting a rough balance between the accumulation of energy and its dissipation.

2. Potential Energy Gradients Around the Tibetan Plateau

Of all the energy accumulative processes that operate during orogeny the increase of gravitational potential energy in the system due to crustal thickening is among the most important. The gravitational potential energy (U) per unit area of a column of isostatically compensated lithosphere is equivalent to the integral of the body force over the vertical distance between the surface and the compensation horizon:

$$U = \int_{z=0}^{S} \rho(z) g z dz, \qquad (1)$$

where the spatial coordinate (z) ranges from zero at the compensation horizon to S at the Earth's surface, $\rho(z)$ is density as a function of depth through the column, and g is gravitational acceleration [*Molnar and Lyon-Caen*, 1988]. Since the variation in U from one column of lithosphere to another is a measure of the contribution made by buoyancy forces to the deformation of the lithosphere, it is convenient to compare the gravitational potential energy for a specific lithospheric column of interest (U_i) to that of a reference potential energy, for example, the mean value for the Earth's lithosphere (U_r) [*Cobblentz et al.*, 1994], through the potential energy anomaly (ε_U):

$$\varepsilon_U = U_i - U_r. \qquad (2)$$

The calculation of ε_U requires some means of estimating density structures for both the column of interest and the reference column. Perhaps the most effective approach is to invert seismic velocity data through empirical relationships [e.g., *Jones et al*, 1996], but such data are unavailable for most of the Himalaya and Tibet We instead follow the approach of *Coblentz et al* [1994], who noted that ε_U is approximately related to the more familiar geoid anomaly (ε_N) through the relationship:

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$$\mathcal{E}_U \approx \frac{-g^2 \mathcal{E}_N}{2\pi G} \qquad (3)$$

where G is the gravitational constant. Because we are interested only in variations in the potential energy field that are related to lithospheric density and thickness variations, we have filtered out long-wavelength contributions to the geoid height, which might be related to sublithospheric heterogeneities, by removing terms below degree and order seven (cosine-tapered to degree and order 11) from the geoid prior to applying equation (3), as advocated by *Jones et al.* [1996].

Plate 1a is a map of $\mathcal{E}_U$ for the Tibetan Plateau region derived in this way from the NASA-National Mapping and Imagery Agency joint geopotential model EGM96 [*Lemoine et al.*, 1998]. In general, positive values of $\mathcal{E}_U$ imply that deviatoric stresses arising from horizontal variations in the lithospheric density structure are tensile, whereas negative values imply that they are contractile. The Himalayan-Tibetan orogenic system is well defined in Plate 1a as a band of high gravitational potential separating the low-$\mathcal{E}_U$ regions of the Indian subcontinent on the south and the Tarim and Qiadam Basins on the north. As has been noted elsewhere [e.g., *Molnar and Tapponnier*, 1978; *Molnar*, 1988; *England and Houseman*, 1989], $\mathcal{E}_U$ contrasts between Tibet and its surroundings provide strong motivation for lateral redistribution of the Tibetan crust in order to dissipate excess gravitational potential energy. Indeed, the nature of seismic activity in Tibet over the 1977-1998 interval implies that the plateau region is actively losing potential energy [*Tanimoto and Okamoto*, 2000].

The distribution of $\mathcal{E}_U$ across the plateau provides some insights regarding the probable direction, magnitude, and rate of crustal flow related to spatially variable buoyancy forces. (In this paper, we use the term "crustal flow" to refer to the spatial transfer of crustal material without regard to mechanism. For example, the viscous transport of lower crustal material [*Bird*, 1991; *Kruse et al.*, 1991] and the fluvial transport of eroded sediments are both mechanisms of flow in the context of our working definition.) Imagine, for a moment, that the orogenic system is not subject to lateral forces related to lithospheric plate interactions. In that case, Plate 1a is a map of a potential field through which gradients in $\mathcal{E}_U$ drive the flow of material. This situation is analogous to the influence of gradients in temperature, hydraulic pressure, or chemical concentration on heat flux, fluid transport, or chemical diffusion. Structural homologies are notorious among equations governing such transport processes. For example, Fourier's law for heat flow, Darcy's law for groundwater flow, and Fick's law for chemical diffusion all have the same basic form in one dimension:

$$q = -K\frac{\partial b}{\partial x}, \qquad (4)$$

where q is a flux per unit cross-sectional area, $\delta b/\delta x$ is the change in potential over some spatial dimension x, and K is a proportionality term [*Carslaw and Jaeger*, 1986; *Furbish*, 1997, *Crank*, 1975]. For many problems in diffusive flow, K is assumed to be constant, but this need not be the case in general.

By analogy with these more familiar examples a general law for crustal flow driven by gravitational potential energy gradients is

$$v = -\kappa\frac{\partial \mathcal{E}_U}{\partial x} = -\kappa\left(\Delta\mathcal{E}_U\right), \qquad (5)$$

where v is the flow velocity, κ is a transport coefficient, and $\delta\mathcal{E}_U/\delta x$ (or $\Delta\mathcal{E}_U$, for simplicity) is the spatial gradient in $\mathcal{E}_U$. The nature of κ reflects the mechanism assumed for crustal flow, and it is likely to be dependent on factors that vary in time and space. For the special case of channelized flow of a viscous lower crust under the influence of crustal thickness variations [*Kruse et al.*, 1991; *Clark and Royden*, 2000; *McQuarrie and Chase*, 2000],

$$\kappa \propto \left(\frac{D^3}{12\mu}\right), \qquad (6)$$

where D is the channel thickness and μ is the viscosity of material flowing in the channel. (This relationship involves a proportionality rather than an equality because $\Delta\mathcal{E}_U$ is proportional to, but not equivalent to, the lateral pressure gradients invoked by *Kruse et al.* [1991] and subsequent authors as the impetus for channelized flow.) For the special case of erosion and fluvial transport of eroded sediments out of the orogenic system, κ is strongly dependent on factors such as lithologic resistance to erosion, erosional mechanism, stream network geometry, climate, and the exact relationship between stream gradient and $\Delta\mathcal{E}_U$ [*Howard et al.*, 1994; *Tucker and Slingerland*, 1997; *Sklar and Dietrich*, 1998; *Whipple and Tucker*, 1999]. In reality, these and many other processes combine to accommodate energy transfer in orogenic systems, such that κ is very complicated, but equation 5 nevertheless captures the essential physics of how potential energy gradients influence material fluxes in orogenic systems. It clearly does not provide a comprehensive depiction of material fluxes, however, because externally imposed, "far-field" tectonic forces, basal tractions, and the like also play important roles.

The negative sign is equation (5) implies that crustal flow proceeds down gradients in gravitational potential energy. In Plate 1a, values of $\mathcal{E}_U$ are highest ($\geq 5.9 \times 10^{12}$ N/m) in the Karakoram Range and along the Himalayan arc. North of the Himalaya, on the physiographic Tibetan Plateau, $\mathcal{E}_U$ drops smoothly eastward from the Karakoram to ~95°E longitude before rising again slightly toward the Longmenshan mountains, immediately west of the Sichuan Basin. This "saddle" in the $\mathcal{E}_U$ field is related to a region of relatively low gravitational potential energy extending southward from the Qiadam Basin. High positive $\mathcal{E}_U$ across the plateau and the broad negative gradient in $\mathcal{E}_U$ from west to east is consistent with geological evidence of Neogene E-W surface extension [*Molnar and Tapponnier*, 1978; *Armijo et al.*, 1986] and interpretive models of eastward lower-crustal flow [*Royden et al.*, 1997, *Clark and Royden*, 2000].

Equation (5) also implies that the rate of crustal flow is proportional to spatial gradients in $\mathcal{E}_U$ [see also *England and Molnar*, 1997] For the Himalayan-Tibetan system we can evaluate, in a general way, where the most efficient dissipation of excess gravitational potential energy might occur by studying a map of the spatial derivative of the potential energy anomaly ($\Delta\mathcal{E}_U$) over the region (Plate 1b). This exercise shows that the steepest gradients (up to ~3.3×10^7 N/m^2) are concentrated along the southern plateau boundary, between ~80°E and 95°E longitudes. A few discontinuous zones of high $\Delta\mathcal{E}_U$ also exist along the western Kunlun mountain front. Slightly less dramatic

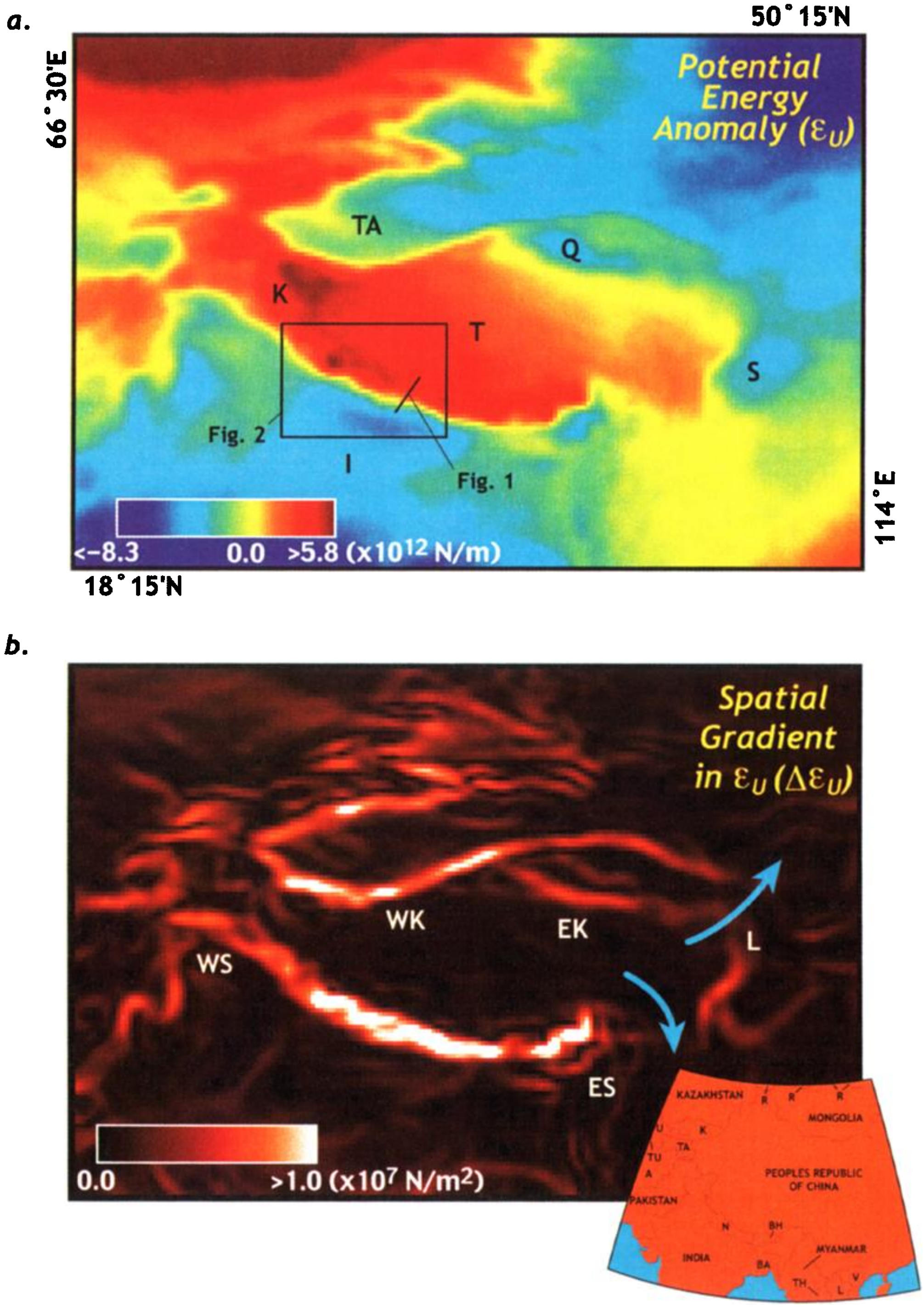

Plate 1. (a). Distribution of the gravitational potential energy anomaly (ε_U) in the Himalayan-Tibetan system and surrounding regions of south Asia. Areas of special interest include northern India (I), the Karakoram Range (K), the central Tibetan Plateau (T), and the Sichuan (S), Tarim (TA), and Qiadam (Q) Basins. The rectangular box shows the area covered by Figure 2. Within that box the oblique line indicates an approximate profile for which the generalized cross section in Figure 1 is appropriate. (b) A map of the same area as Plate 1a, showing the spatial derivative of the potential energy anomaly ($\Delta\varepsilon_U$). The highest gradients occur along the range front between the western (WS) and eastern (ES) syntaxes of the Himalaya. Gradients are nearly as high along the western Kunlun Mountains (WK) but are more subdued along the eastern Kunlun Mountains (EK) and the Longmenshan (L). Low-gradient gaps to the north and south of the Longmenshan, designated by blue arrows, have been postulated as pathways for the flow of lower crust outward from beneath the central plateau region [*Clark and Royden*, 2000]. Inset shows the political geography of the region of Plates 1a and 1b: A, Afghanistan; BA, Bangladesh; BH, Bhutan; K, Kyrgyzstan; L, Laos; N, Nepal; R, Russia; TA, Tajikistan; TU, Turkmenistan; TH, Thailand; U, Uzbekistan; and V, Vietnam. Plates 1a and 1b are in unprojected geographic coordinates and the inset is an Albers conical projection.

gradients (2 to 3 x 10^7 N/m^2) characterize the eastern Kunlun and Longmenshan fronts.

It is unlikely that all high-$\Delta\mathcal{E}_U$ margins in Plate 1b are zones of very rapid energy dissipation by crustal flow for three reasons: (1) the lithosphere is not mechanically isotropic, (2) the mechanisms available for transfer of matter out of the system vary from place to place along the margins, and (3) the system is subject to anisotropic forces related to plate convergence. *Clark and Royden* [2000] have described how rheological variability might be important if, for example, the low-$\mathcal{E}_U$ region adjacent to a high-$\Delta\mathcal{E}_U$ margin is strong enough to act as a barrier to the lateral flow of lower crust. In particular, they suggested that the Longmenshan front may have developed because the crust was anomalously strong in the region of the Sichuan Basin, diverting eastward lower crustal flow through weaker channels to the north and south (Plate 1b).

It might be argued that one of the most important agents of energy dissipation, the erosion and transport of material out of the orogenic system through sedimentary processes, is most effective along the margins receiving the heaviest precipitation. Thus we might expect the Himalayan margin, which receives extremely high monsoonal precipitation, to support a higher rate of $\mathcal{E}_U$ dissipation than the western Kunlun margin which receives far less precipitation, even though the two margins have comparable $\Delta\mathcal{E}_U$ in some areas. However it also might be argued that the high-$\mathcal{E}_U$ gradient along the Himalayan margin is dynamically supported by India-Eurasia convergence, and that this convergence effectively counteracts the horizontal components of buoyancy forces that might drive the southward flow of material from the Tibetan Plateau toward India. In order to evaluate the actual significance of dissipation along a particular high-$\Delta\mathcal{E}_U$ margin it is important to investigate the dissipative capacity of deformational and erosional processes that occur now along those margins and to ask whether or not the geological record suggests a history of efficient material transport out of the system. In the next section we review geomorphologic

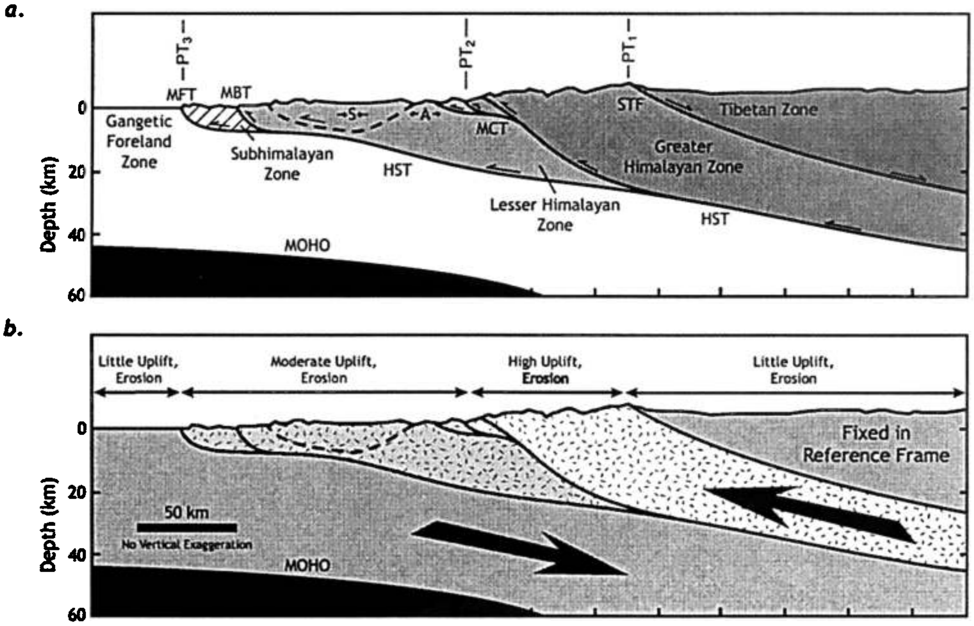

Figure 1. (a) Generalized cross section of the Himalayan margin of the Tibetan Plateau showing principal tectonostratigraphic zones separated by the South Tibetan fault (STF), Main Central thrust (MCT), Main Boundary thrust (MBT), and Main Frontal thrust (MFT) systems. The subsurface structural configuration shown here, slightly modified from *Pandey et al.* [1995] and *Cattin and Avouac* [2000], presumes that all major thrust systems in the Himalaya root into a common basal décollement: the Himalayan Sole thrust (HST). The dashed line designates a now-inactive thrust fault that lies beneath klippen of metamorphic rocks within the Lesser Himalayan Zone; it has been interpreted alternatively as an erosional remnant of the MCT system or as a separate thrust system [*Hodges*, 2000]. Vertical lines indicate the principal physiographic transitions of the Himalaya (PT_1-PT_3) as discussed in the text. The approximate positions of the axial planes of a major anticlinorium (A)-synclinorium(S) pair in the Lesser Himalaya are labeled as well. (b) Interpretive model of the extrusion-erosion mechanism for excess energy dissipation along the southern Tibetan Plateau margin. A channel of middle to lower crustal material (designated by the random-dash pattern) extrudes southward from the central Tibetan Plateau between the STF and HST. Relief and geodetically determined uplift rates are relatively high in the regions between the surface traces of these structures, implying high erosion rates compared to the Gangetic Foreland and Tibetan Plateau. Much of the shortening between India and Tibet during the Holocene epoch has been accommodated by slip on the MFT system [*Lavé and Avouac*, 2000], and it may be that all of the region between PT_1 and PT_3 represents the free boundary of the extruding wedge over that timescale. However, the highest rates of erosion and uplift today occur north of the MCT trace, which may indicate instead that extrusion is presently concentrated in a channel that surfaces between STF and MCT traces (the unshaded zone marked with the random-dash pattern), and that relatively little extrusion occurs to the south today.

and geological evidence that the active tectonics of the Himalaya are strongly influenced by the southward flow of Tibetan middle and lower crust to the Himalayan topographic front, where it is removed from the system by orographically focused erosion. These processes act together as an efficient engine for energy dissipation along the southern margin of the Tibetan Plateau, even as continued India-Eurasia convergence adds energy to the system as a whole.

3. Physiography and Neotectonics of the Himalaya

The southern margin of the Tibetan Plateau is marked by a series of sharp physiographic transitions (Figure 1a). The northernmost of these (PT_1) separates the rugged, high peaks of the main Himalayan ranges and the more subdued topography of the Tibetan Plateau. A second (PT_2) occurs south of the range crest and represents the main topographic front of the central Himalaya, where the southern slopes of the high peaks give way to a foothills region with much lower relief and mean elevation. A less significant front (PT_3) separates the foothills region from the Gangetic Plains.

Physiographic transitions PT_1-PT_3 are related to neotectonic activity at or below the surface. The PT_3 front coincides roughly with the trace of the north dipping Main Frontal thrust (MFT) system (Figure 1a), a feature which was first established in

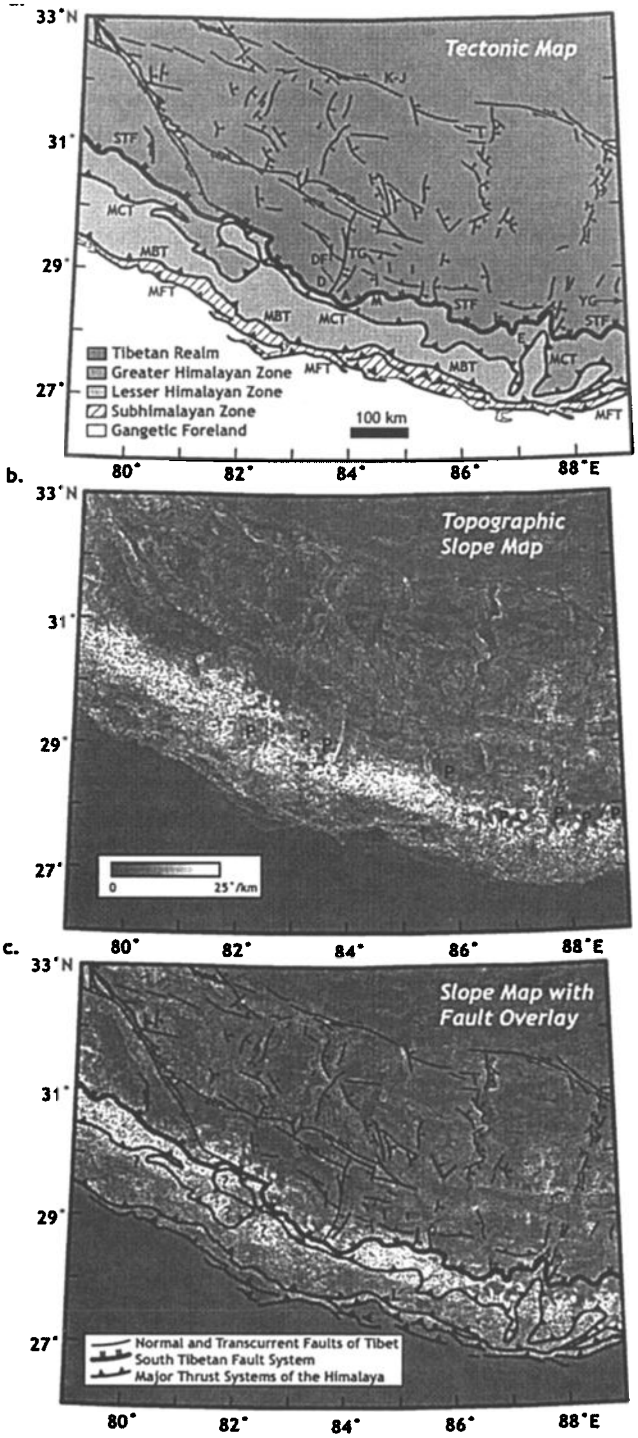

Figure 2. (a) Simplified tectonic map (Albers conical projection) of the central region of southern Tibet and the Himalaya, after *Hodges* [2000]. Half-arrows and ball-and-bar symbols adorn Quaternary transcurrent and normal faults (respectively) in southern Tibet. The double-tick symbols indicate the dip direction of the basal detachment of the South Tibetan fault (STF) system, whereas the barbs indicate the dip directions of reverse faults of the Main Central (MCT), Main Boundary (MBT), and Main Frontal (MFT) thrust systems. The MCT system is geometrically complex and includes numerous splays with different movement histories; only the roof fault of the system is shown here for the sake of clarity. Lithologic descriptions of units in the Greater Himalayan, Lesser Himalayan, and Subhimalayan Zones are given by *Hodges* [2000]. The hanging wall of the STF system corresponds to the Tibetan Zone in that paper, but the field shown as "Tibetan Realm" in Figure 2a also includes other tectonostratigraphic packages, such as the Indus-Tsangpo and Transhimalayan Zones of *Hodges* [2000]. Landmarks include the Annapurna Range (A), the Dangardzong fault (DF), the Dhaulagiri Range (D), Mount Manaslu (M), the Thakkhola graben (TG), and the Yadong-Gulu rift (YG; just east of the map margin at ~89°-90°E longitude). (b) Slope map of the same area derived from GTOPO 30 digital elevation data. White-shaded regions indicate the steepest topography. Note the region of poor slope resolution (designated with "P") near the southeastern corner due to poor GTOPO 30 data coverage. The highest relief in the Himalaya occurs in a zone bound by abrupt physiographic transitions referred to as PT_1 and PT_2 in the text. (c) Equivalent to Figure 2b with fault systems from Figure 2a superimposed. The trace of the STF system (corresponding with PT_1) separates the east-west extensional strain field of southern Tibet from the north-south contractional strain field of the Himalayan realm. Divergence of the southern margin of the high-relief zone (PT_2) and the MCT trace often occurs in regions where the MCT is poorly mapped (designated here with question marks). However, there are some areas where the divergence is well documented; note, for example, the linear segment of PT_2 (marked with an L in Figure 2c) that lies tens of kilometers south of a segment of the MCT zone mapped by *Stöcklin et al.* [1980], *Macfarlane et al.* [1992], and *Upreti and Le Fort* [1999].

Pliocene time but has experienced episodes of slip in the more recent past [*Nakata*, 1989; *Yeats et al.*, 1992, *Lavé and Avouac*, 2000]. Marking the southern outcrop boundary of Neogene-Quaternary foreland basin sedimentary rocks of the "Subhimalayan Zone" (Figure 2a), the MFT system projects northward into a shallowly dipping thrust surface that marks the principal horizon along which the Indian plate is subducted [e.g., *Seeber et al*, 1981; *Yeats and Lillie,* 1991]. This Himalayan Sole thrust (HST; Figure 1a) is typically drawn as extending northward, with a dip of no more than a few degrees, beyond the surface trace of the Main Boundary thrust (MBT) system [e.g., *Baranowski et al*, 1984; *Ni and Barazangi*, 1984]. Developing in late Miocene-Pliocene time, the MBT system separates the Subhimalayan Zone from overlying greenschist- to lower amphibolite-facies metamorphic rocks of the "Lesser Himalayan Zone" (Figure 2a). In the central Himalaya of Nepal and adjacent regions of India and Bhutan the internal structure of the Lesser Himalayan zone is characterized by a long-wavelength synclinorium-anticlinorium pair (Figure 1a). Stratal dips in Lesser Himalayan rocks decrease progressively from south to north, toward the core of the synclinorium, suggesting that the MBT system roots smoothly into the HST as shown in Figure 1a [*Gansser*, 1964; *Le Fort*, 1975; *Schelling and Arita*, 1991].

In the eastern and central Himalaya the complementary anticlinorium to the north has been interpreted as a fault bend fold structure developed above a ramp in the HST with a structural relief of more than 5 km [*Brunel*, 1986; *Schelling and Arita*, 1991; *Schelling*, 1992]. Although a somewhat more complex geometry has been proposed for the Himalaya west of central Nepal [*Srivastava and Mitra*, 1994; *DeCelles et al.*, 1998], generalized cross sections drawn across the Himalayan front almost always show some form of "crustal-scale" ramp in the HST [e.g., *Gansser*, 1964; *Le Fort*, 1975; *Hauck et al.*, 1998; *Harrison et al.*, 1998]. While such a feature is not required by the surface geology, it nevertheless provides a convenient explanation for several geophysical observations, including patterns of seismicity within the orogenic wedge [*Molnar*, 1990; *Pandey et al.*, 1995, 1999], the depth to seismic reflectors interpreted as the HST beneath southern Tibet [*Zhao et al.*, 1993; *Hauck et al.*, 1998], and evidence that much of the estimated India-Tibet convergence rate has been accommodated on the MFT system during the Holocene [*Lavé and Avouac*, 2000].

Because the position of the postulated ramp is generally drawn below PT_2, many authors have attributed the topographic front to block uplift of the Greater Himalayan zone due to strain accumulation over the ramp [*Jackson et al.*, 1992; *Jackson and Bilham*, 1994, *Bilham et al.*, 1997; *Bürgmann et al*, 1999; *Jouanne et al*, 1999; *Larson et al.*, 1999; *Pandey et al.*, 1995; *Cattin and Avouac*, 2000]. However, the mountain front also lies near and sometimes coincident with the 1- to 5-km-thick shear zone that marks the trace of the MCT system, a third important structure that divides the Lesser Himalayan rocks from middle to upper amphibolite-facies metamorphic rocks of the Greater Himalayan zone (Figures 1a and 2a). Although slip on the MCT commenced at 20-23 Ma (see review by Hodges [2000]), the structure has been active episodically since that time [*Macfarlane et al*, 1992; *Harrison et al*, 1997], and some researchers [e g , *Seeber and Gornitz*, 1983] have attributed PT_2 to active deformation on the system. A somewhat modified interpretation is that a newly emergent, out-of-sequence thrust system, partly reactivating strands of the MCT system, partly breaking along new fault traces, might be responsible for PT_2. Regardless of the exact relationship between this physiographic transition and specific structures, there seems little doubt that it is a manifestation of recent faulting in the Himalayan realm and is not a passive erosional front, as has been suggested elsewhere [*Masek et al*, 1994].

The topographic break at PT_1 marks a boundary between two regions of the lithosphere that are responding in distinctive ways to continental collision South of PT_1, deformation over the past 23 million years has produced contractional structures such as the MCT, MBT, and MFT systems. Seismologic and geodetic studies show that the current rate of shortening across the range is 17-18 mm/yr [*Bilham et al*, 1997]. Farther north, on the plateau itself, the modern strain field is much different. Landsat imagery, field maps, and seismic data suggest that active deformation in Tibet includes roughly E-W extension on numerous north striking rift systems, right-lateral displacements on NW striking transcurrent faults, and left-lateral displacements on NE striking transcurrent faults [*Molnar and Tapponier*, 1975; *Armijo et al.*, 1986] Collectively, these fault systems are compatible with an extensional regime in the southern plateau and eastward extrusion of Tibetan crust as India converges with the rest of Eurasia [*Tapponier and Molnar*, 1976]. Geodetic measurements are not yet adequate to document modern strain rates for the plateau region, but neotectonic studies suggest Holocene E-W extension at an integrated rate of ~10 mm/yr [*Armijo et al*, 1986], or roughly half the rate of N-S shortening across the Himalayan ranges to the south.

The abrupt surface transition between "Himalayan" and "Tibetan" strain fields should be manifested by a major, active structural system Indeed, an important family of faults has been mapped at this position, the South Tibetan fault (STF) system (Figures 1a and 2a). The STF system typically separates the high-grade Greater Himalayan Zone to the south from lower amphibolite facies to unmetamorphosed, Cambrian-Eocene sedimentary rocks of the Tibetan Zone to the north. It consists principally of regionally extensive, low-angle normal faults (detachments) that dip shallowly northward beneath the Tibetan Zone, although some faults and ductile shear zones at the boundary also have accommodated N-S shortening and right-lateral transcurrent displacement [*Pêcher*, 1991; *Coleman*, 1996, *Hodges et al.*, 1996]. Where it has been extensively studied in the Annapurna Range of north central Nepal (Figure 2a), the STF system displays evidence of a complex slip history that includes cycling between N-S extension and N-S shortening over a period of several million years [*Hodges et al*, 1996; *Vannay and Hodges*, 1996].

Structural and geochronologic data indicate that the STF system was established in early Miocene time [*Hodges*, 2000], but the duration of STF activity is not well constrained for most regions in the Himalaya. In at least two areas (Figure 2a), near the 8000 m peaks of Annapurna [*Hodges et al.*, 1996] and Manaslu [*Guillot et al*, 1994], major detachments of the STF system were intruded by middle to early Miocene (16-22 Ma) granites and cannot have moved subsequently. In most areas, however, the system includes multiple faults with complicated movement histories, and the ages of many of these structures are constrained only to be younger than middle to early Miocene [e.g., *Hodges et al.*, 1996; Searle et al., 1997].

Recent mapping at the southern terminus of the Thakkhola graben, one of the most conspicuous N-S rift systems in southern Tibet (Figure 2a), provides important constraint on just how young STF activity might be [*Hurtado et al*, 2001]. The main growth structure of this graben, the Dangardzong fault, has had a history of episodic displacement stretching from circa 11 Ma to as late as the Quaternary [*Fort et al*, 1982; *Garzione et al.*, 2000]. As the Dangardzong fault is traced southward toward the Tibetan Zone - Greater Himalayan Zone contact, it can be shown to offset an early strand of the STF system but to be cut by the latest strand of the system. This relationship, documented and described in detail elsewhere [*Hurtado et al*, 2001], requires that low-angle normal faulting along STF system persisted into the Quaternary period at the longitude of the Thakkhola graben. Here, at least, the surface strain discontinuity between the Himalayan realm and the Tibetan Plateau has been accommodated by slip on the STF system.

Whether or not the STF system experienced Quaternary displacement along the entire length of the Himalayan chain remains unknown, but several lines of evidence are consistent with such a scenario for the central and eastern Himalaya. *Nakata* [1989] documented the existence of an important WNW-ESE striking, NE dipping normal fault which offsets glacial moraines near the western end of the Dhaulagiri Range (Figure 2a). Recent field mapping and satellite image analysis have shown that this structure is the probable westward extension of the detachment that truncates the Dangardzong fault, extending the strike length of the STF structure with documented post-Pleistocene slip to at least 100 km west of the Thakkhola graben (J.M. Hurtado and K V. Hodges, manuscript in preparation, 2001). Much farther east, at roughly 89°E longitude, a reflection seismic profile collected across the STF west of the Yadong-Gulu rift of southern Tibet (Figure 2a) shows a Pliocene-Pleistocene extensional basin developed in the hanging wall of the Zherger La detachment, a relationship which requires relatively recent slip on the basal STF detachment in the region [*Hauck et al*, 1998].

Additional evidence for neotectonic activity on the STF system comes from the nature of PT_1. This transition is manifested in the field by a combination of drainage divides and major knickpoints on large, trans-Himalayan rivers, and it marks a particularly obvious discontinuity in slope maps of the southern Tibetan Plateau region (Figure 2b). PT_1 probably is not related to a change in precipitation rate (because it lies entirely within the rain shadow of the Himalaya) or the erosional susceptibility of the bedrock. It is also unlikely to be associated with a fundamental change in erosional mechanism, since the transition is not spatially related to the limit of glacial activity in the region [*Duncan et al.*, 1998] We interpret the sharpness of PT_1 as an indication of recent tectonic activity. Indeed, the discontinuity itself corresponds almost exactly to the youngest strand of the STF system in those regions where the fault system has been mapped in detail and where digital elevation data of sufficiently high quality are available to constrain the position of PT_1 and knickpoints on major drainages (Figure 2c).

4. Effect of Coordinated Deformation and Erosion on the Southern Plateau Margin

Close scrutiny of the topographic slope map in Figures 2b and 2c shows that the highest relief along the southern margin of the Tibetan Plateau lies in a well-defined zone generally bound to the north and south by the surface traces of the STF and MCT systems. This implies a direct relationship between coordinated displacement on extensional and contractional fault systems and high erosion rates. We interpret the neotectonic and physiographic characteristics of the southern plateau margin as indicating the southward extrusion of a crustal wedge which is bound above by the STF system and below by the Himalayan sole thrust (Figure 1b) The current geometry of contractional structures in the Himalaya is such that the rate of extrusion is accelerated between the surface trace of the STF and MCT systems, producing a relatively narrow zone of rapid uplift that corresponds to the high-relief band in Figures 2b and 2c. The coincidence of high relief and high rock uplift rate implies that this is also a zone of unusually rapid erosion, an interpretation that is consistent with thermochronologic and isotopic data for detrital mineral suites from modern Himalayan rivers and the Bengal Fan, which indicate that the Greater Himalayan Zone has been the principle source for sediments removed from the southern flank of the orogenic system since Miocene time [*France-Lanord et al.*, 1993, *Brewer et al*, 2000].

Numerical experiments such as those of *Beaumont et al.* [1992] and Willett [1999] suggest a strong feedback relationship between deformational and erosional processes in orogenic systems In the case of the Himalaya the processes illustrated in Figure 1b together provide a remarkably efficient mechanism for the dissipation of excess potential energy. While southward extrusion reduces the crustal thickness of the Himalayan-Tibetan system (and thus its gravitational potential energy per unit area), accelerated erosion at the margin of the system leads to the removal of mass (and therefore energy) from the system altogether. In our view, it is no accident that this "extrusion-erosion" mechanism has developed along the southern plateau margin, where its dissipative efficiency is magnified by the highest potential energy gradients in the Himalayan-Tibetan system .

One of the most interesting characteristics of the extrusion-erosion mechanism is that it accomplishes the dissipation of energy along a front of active N-S shortening without interfering with concurrent processes of energy accumulation related to India-Eurasia convergence. Unlike the dissipative extensional processes that accommodate the "collapse" of orogenic systems after convergence has ceased [*Dewey*, 1988], the processes illustrated in Figure 1b may persist over a significant part of the constructional history of an orogen. Indeed, coupled thermal-mechanical models of large orogens with orographically focused erosion, such as that taking place along the southern margin of the Tibetan Plateau, naturally evolve toward channeled flow of the middle crust toward the erosion front [*Jamieson et al.*, 2001].

Students of the earlier history of the Himalayan orogen will note that the extrusion-erosion mechanism illustrated in Figure 1b bears strong similarity to previously published interpretations of the deformational processes operative in Miocene time, just after the STF had been established and when the MCT probably served as the Himalayan sole thrust. *Burchfiel and Royden* [1985] first suggested that the STF may have developed during gravitational collapse of the Miocene topographic front between India and Eurasia and may have accommodated the southward extrusion of a wedge of material between the MCT and STF systems at that time. Additional geological, petrologic, and geochronological evidence for a dynamical coupling of Miocene movement on the two fault systems was published subsequently [*Searle*, 1986; *Searle and Rex*, 1989; *Burchfiel et al.*, 1992; *Hodges et al.*, 1992, 1993, 1996], and Miocene wedge extrusion along the Himalayan front was articulated as a channel flow process by *Grujic et al.* [1996] and *Grasemann and Vannay*. [1999]. A key question regarding the long-term efficiency of this set of processes is how energy is transferred from other parts of the system to the dissipative margin. In our view this process requires the development of one or more channels of middle or lower crustal flow that feeds material to the southern margin, a notion suggested earlier by *Nelson et al.* [1996] and *Wu et al.* [1998] on the basis of geophysical data interpreted as favoring a partially molten middle crust beneath Tibet. The rocks currently exposed in the Greater Himalayan Zone, which display abundant evidence of Miocene in situ anatexis at middle crustal levels, represent the modern leading edge of this feeder channel but also preserve a record of the kinematic evolution of the channel in their deformational fabrics. Studies of these features by *Grujic et al* [1996], *Hodges et al.* [1996], and *Grasemann and Vannay* [1999] suggest that the extrusion-erosion mechanism had been established along the southern plateau margin by early Miocene time, and the neotectonic evidence reviewed in this paper argues that it is still active today.

5. Implications

From a thermodynamic perspective an orogen is an open system whose behavior is dictated largely by how energy flows through it. The relative rates of energy accumulation and dissipation help define three stages of orogenesis. In the first stage newly established mountain ranges stockpile energy because the rate of accumulation through crustal thickening greatly exceeds the rate of dissipation. In the second stage a fully developed mountain range reaches its maximum elevation as energy accumulative and dissipative processes compete for prominence. In the third and final stage, as plate convergence wanes, energy dissipation mechanisms predominate and the mountain range is eventually destroyed.

Between the time of initial India-Eurasia collision and the end of the Oligocene epoch the Himalayan-Tibetan system was a first-stage orogen, with crustal shortening and thickening outpacing erosion and other modes of energy dissipation. Near the Oligocene-Miocene boundary, there was a dramatic increase in the rate of energy dissipation as evidenced by an increased erosional input to the Himalayan foreland and Bengal Fan [*Galy et al.*, 1996], the earliest documented continental extrusion at the southeastern edge of the Tibetan plateau [*Chung et al.*, 1997], and coeval development of the STF and MCT systems [*Hodges et al*, 1996] We interpret such changes as evidence of a transition to the second stage of orogenesis Along the southern margin of the Tibetan Plateau, linked displacement on the STF and MCT systems permitted southward extrusion of the middle crust (represented by the Greater Himalayan Zone) toward the Indian foreland in early Miocene time However, this energy dissipative process has persisted episodically throughout much of the Neogene, as has the energy accumulative process of crustal accretion along the southern flank of the orogen, suggesting the spontaneous development of a near steady state condition that fluctuates around a balance between energy influx and efflux.

Exactly how the Himalayan-Tibetan system has responded to natural perturbations from the steady state condition over the past 20 million years has depended on three parameters that change over time and from place to place: the rheology of the lithosphere, the rate of crustal shortening, and the rate of erosion along the Himalayan range front A strong lithosphere is capable of achieving a much greater thickness than a weak lithosphere before collapsing under its own weight. At several times during the early to middle Miocene, rocks of the Greater Himalayan Zone underwent partial melting, resulting in a dramatic drop in crustal strength. We might expect such episodes to coincide with major episodes of movement on the STF and MCT systems. Indeed, a close relationship has been demonstrated between crustal anatexis and STF and MCT displacement [*Hodges et al.*, 1996] The specific kinematics of movement on structures bounding the wedge during any phase of activity depends on whether the orogenic system needs to gain or lose energy in response to a perturbation from the steady state If energy accumulation is favored, the upper and lower bounding fault systems may accommodate shortening. This may explain, for example, evidence for some episodes of early Miocene thrust-sense displacement on the STF system in central Nepal [*Hodges et al.*, 1996; *Vannay and Hodges*, 1996]. If energy dissipation is favored, extrusion of the wedge by normal slip on the upper fault system and reverse slip on the lower bounding fault system increases structural relief and enhances the orographic effect on precipitation, thus increasing the efficiency of erosion along the Himalayan front.

Some deformation related to the redistribution of energy along the southern margin of the Tibetan Plateau may be more complicated than simple southward extrusion. Figure 1a reveals significant variations in gravitational potential energy along strike in the Himalaya. Evidence in the geological record for transcurrent movement on the STF and MCF systems, as well as for range-parallel shortening and extension in the Greater Himalayan zone [Burg et al , 1984; Pêcher, 1991; Coleman, 1996], might indicate the lateral flow of material down such gradients in ε_U.

Many mechanisms began to work in concert to dissipate large amounts of gravitational potential energy from the Himalayan-Tibetan system in middle to late Miocene time. In addition to the extrusion-erosion engine featured in this paper these include process sets that accommodate E-W extension of the upper crust in southern Tibet [*Armijo et al.*, 1986], eastward extrusion of the lower crust in eastern Tibet [*Royden et al.*, 1997], and eastward extrusion, clockwise rotation, and ~N-S extension of the upper crust along the eastern margin of the Tibetan Plateau [*Burchfiel et al.*, 1995]. The vigorous collaboration of these processes in the relatively recent past may simply be coincidental, but it might also suggest that some unusual and abrupt energy accumulation mechanism may have driven the system far from its steady state configuration in middle Miocene time. One possibility is that convective removal of dense lower lithosphere beneath Tibet, and its subsequent replacement by less dense asthenosphere, catastrophically increased the gravitational potential energy of the region [*England and Houseman*, 1989], but this hypothesis remains untestable by geologic means.

As reviewed by *Molnar et al.* [1993], there have been major changes in climate in the Himalayan-Tibetan region over the past 20 million years, most notably an abrupt intensification of the Asian monsoon in late Miocene time and an increase in glacial activity in the Quaternary The most likely impact of these events would be to increase erosion rates along the Himalayan front, with possible feedbacks to other dissipative mechanisms as well [*Willett*, 1999; *Beaumont et al*, 1992], although there is no unequivocal geologic evidence for a strong geodynamic response of the Himalayan-Tibetan system to climatic forcing [*Burbank et al.*, 1993; *Derry and France-Lanord*, 1997] The persistence of the extrusion-erosion engine described here, despite such events, implies that the effect of secular climate change is to increase or decrease the efficiency of energy dissipation and to alter the relative importance of specific dissipative mechanisms, but not to affect a major change in the overall process or to switch off the engine altogether.

Evidence that the STF system is an active feature has important implications for the modern geodynamics of Tibet Termination of the principle growth fault of the Thakkhola graben at the shallowly north dipping STF system [*Hurtado et al.*, 2001] implies that the rift systems of southern Tibet are rootless, kinematically decoupled from the remaining Tibetan lithosphere. This observation, consistent with geophysical data from southern Tibet [*Nelson et al*, 1996], is at odds with tectonic models that require strong mechanical coupling between the Tibetan and Himalayan realms [*McCaffrey and Nabelek,* 1998]. More generally, it suggests caution in the use of surface faulting patterns to infer a single style of deformation for the entire lithosphere; for example, the lower crust of southern Tibet appears to extrude southward over the downgoing Indian plate while the upper crust extends east-west. To make matters even more complicated, the fault plane solutions of great earthquakes beneath the southern plateau suggest that E-W extension, kinematically similar to deformation in the upper crust but fundamentally dissimilar to that in the lower crust, occurs in the mantle lithosphere of Tibet [*Chen and Kao*, 1997; *Holt*, 2000]. Thus the kinematic response of the lithosphere to continental collision is variable in three spatial dimensions and the additional dimension of time.

If a steady state condition such as the one described here can develop in orogenic systems and persist over long timescales, it follows that the structural history of an orogen does not place unique constraints on the history of plate interactions responsible for their development, limiting the value of simple kinematic models For example, evidence for extensional deformation or lateral extrusion in a convergent orogen at a particular time does not necessarily mean that wholesale gravitational collapse of the system had begun by that time. Instead, such processes may simply accommodate energy dissipation at a rate comparable to that of energy accumulation through other processes operating at the same time elsewhere in the system. A deeper understanding of orogenic systems requires that we concentrate research on more than just the temporal evolution of geological structures and landforms We must also examine the geologic record for evidence of persistent process sets that might imply dynamical steady state conditions, and we must determine whether or not the forcing factors responsible for the initial development of major structural features continue to dictate their evolution over periods that may last tens of millions of years. Expanding our perspective to view the patterns of deformation and erosion in the context of energy flow may be an important part of rising to one of the great challenges before continental tectonics today: to define the process relationships that link the simple physics of mountain building to the rich complexity of mountain ranges.

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References

Armijo, R , P Tapponier, J Mercier, and T Han, Quaternary extension in Southern Tibet. Field observations and tectonic implications, *J Geophys Res* , *91*, 13803-13872, 1986

Baranowski, J , J Armbruster, L Seeber, and P Molnar, Focal depths and fault plane solutions of earthquakes and active tectonics of the Himalaya, *J Geophys Res* , *89*, 6918-6928, 1984

Beaumont, C , P Fullsack, and J Hamilton, Erosional control of active compressional orogens, in *Thrust Tectonics*, edited by K R McClay, pp 1-18, Chapman and Hall, New York, 1992

Bilham, R , K Larson, J Freymuller, and P I Members, GPS measurements of present-day convergence across the Nepal Himalaya, *Nature*, 386, 61-64, 1997

Bird, P , Lateral extrusion of lower crust from under high topography, in the isostatic limit, *J Geophys Res* , *96*, 10,275-10,286, 1991

Brewer, I D , D.W Burbank, and K V Hodges, The downstream evolution of detrital mineral cooling ages - Insights from the Marsyandi Valley of central Nepal, *EOS Trans AGU, 81* (48), Fall Meet. Suppl , Abstract T51C-04, 2000

Brunel, M , Ductile thrusting in the Himalayas Shear sense criteria and stretching lineations, *Tectonics*, *5*, 247-265, 1986

Burbank, D.W , L Derry, and C France-Lanord, Lower Himalayan detrital sediment delivery despite an intensified monsoon at 8 Ma, *Nature*, *364*, 48-50, 1993

Burchfiel, B C , and L H. Royden, North-south extension within the convergent Himalayan region, *Geology*, *13*, 679-682, 1985

Burchfiel, B C , Z Chen, K V Hodges, Y Liu, L H Royden, C Deng, and J Xu, *The South Tibetan Detachment System, Himalayan Orogen Extension Contemporaneous With and Parallel to Shortening in a Collisional Mountain Belt*, 41 pp , *Geol Soc Am , Spec Pap , 269*, 1992

Burchfiel, B C , Z Chen, Y. Liu, and L H Royden, Tectonics of the Longmen Shan and adjacent regions, central China, *Int Geol Rev* , *37*, 661-735, 1995

Burg, J P , M Brunel, D Gapais, G M Chen, and G H Liu, Deformation of leucogranites of the crystalline Main Central Sheet in southern Tibet (China), *J Struct Geol* , *6*, 535-542, 1984

Burgmann, R , K.M Larson, and R Bilham, Model inversion of GPS and leveling measurements across the Himalaya· Implications for earthquake hazards and future geodetic networks, *Himalayan Geol* , *20*, 59-72, 1999

Carslaw, H S , and J C. Jaeger, *Conduction of Heat in Solids*, 510 pp., Clarendon, Oxford, England, 1986.

Cattin, R , and J P Avouac, Modeling mountain building and the seismic cycle in the Himalaya of Nepal, *J Geophys Res* , *105*, 13,389-13,407, 2000.

Chen, W -P , and H. Kao, Seismotectonics of Asia. some recent progress, in *The Tectonic Evolution of Asia*, edited by A Yin and M. Harrison, pp 37-62, Cambridge Univ Press, New York, 1997.

Chung, S.-L , T -Y Lee, C -H Lo, P -L Wang, C -Y Chen, N T Yem, T T Hoa, and G Wu, Intraplate extension prior to continental extrusion along the Ailao Shan-Red River shear zone, *Geology*, 25, 311-314, 1997

Clark, M K , and L H. Royden, Topographic ooze Building the eastern margin of Tibet by lower crustal flow, *Geology*, 28, 703-706, 2000

Cobblentz, D D , R M Richardson, and M. Sandiford, On the gravitational potential of the Earth's lithosphere, *Tectonics*, 13, 929-945, 1994

Coleman, M.E , Orogen-parallel and orogen-perpendicular extension in the central Nepalese Himalayas, *Geol Soc Am Bull* , *108*, 1594-1607, 1996.

Crank, J , *The Mathematics of Diffusion*, 414 pp , Oxford Univ Press, New York, 1975

DeCelles, P G , G.E Gehrels, J Quade, and T P Ojha, Eocene-early Miocene foreland basin development and the history of Himalayan thrusting, western and central Nepal, *Tectonics*, *17*, 741-765, 1998

Derry, L A , and C France-Lanord, Himalayan weathering and erosion fluxes· Climate and tectonic controls, in *Tectonic Uplift and Climate Change*, edited by W F. Ruddiman, pp 289-312, Plenum, New York, 1997

Dewey, J.F , Extensional collapse of orogens, *Tectonics, 7*, 1123-1139, 1988

Duncan. C , A Klein, J. Masek, and B. Isacks, Comparison of late Pleistocene and modern glacier extents in central Nepal based on digital elevation data and satellite imagery, *Quat Res* , *49*, 241-254, 1998

England, P , and G Houseman, Extension during continental convergence, with application to the Tibetan Plateau, *J Geophys Res , 94,* 17561-17579, 1989.

England, P , and P Molnar, Active deformation of Asia From kinematics to dynamics, *Science,* 278, 647-650, 1997

Fort, M , P Freytet, and M Colchen, Structural and sedimentological evolution of the Thakkhola-Mustang graben (Nepal Himalayas), *Z Geomorphol , 42,* 75-98, 1982

France-Lanord, C., L Derry, and A. Michard, Evolution of the Himalaya since Miocene time. Isotopic and sedimentologic evidence from the Bengal Fan, in *Himalayan Tectonics,* edited by P J Treloar, and M Searle, *Geol Soc Spec Publ 74,* 605-621, 1993

Furbish, D J , *Fluid Physics in Geology,* 476 pp , Oxford Univ Press, New York, 1997.

Galy, A , C France-Lanord, and L A Derry, The late Oligocene-early Miocene Himalayan belt Constraints deduced from isotopic compositions of early Miocene turbidites in the Bengal Fan, *Tectonophysics, 260,* 109-118, 1996

Gansser, A , *Geology of the Himalayas,* 289 pp , Wiley-Interscience, New York, 1964

Garzione, C.N , D.L Dettman, J Quade, P G DeCelles, and R F Butler, High times on the Tibetan Plateau. Paleoelevation of the Thakkhola Graben, Nepal, *Geology, 28,* 339-342, 2000

Grasemann, B , and J.-C Vannay, Flow controlled inverted metamorphism in shear zones, *J Struct. Geol , 21,* 743-750, 1999.

Grujic, D , M Casey, C. Davidson, L.S Hollister, R Kundig, T Pavlis, and S. Schmid, Ductile extrusion of the Higher Himalayan crystalline in Bhutan Evidence from quartz microfabrics, *Tectonophysics, 260,* 21-43, 1996

Guillot, S., K V Hodges, P. Le Fort, and A. Pêcher, New constraints on the age of the Manaslu leucogranite Evidence for episodic tectonic denudation in the central Himalayas, *Geology, 22,* 559-562, 1994.

Harrison, T.M , F.J. Ryerson, P. Le Fort, A. Yin, O. Lovera, and E.J Catlos, A late Miocene-Pliocene origin for the central Himalayan inverted metamorphism, *Earth and Planetary Science Letters, 146,* E1-E7, 1997

Harrison, T M , M. Grove, O M Lovera, and E J. Catlos, A model for the origin of Himalayan anatexis and inverted metamorphism, *J. Geophys Res , 103,* 27,017-27,032, 1998.

Hauck, M.L., K.D. Nelson, L D. Brown, W Zhao, and A R Ross, Crustal structure of the Himalayan orogen at ~90° east longitude from Project INDEPTH deep reflection profiles, *Tectonics, 17,* 481-500, 1998.

Hodges, K V., Tectonics of the Himalaya and southern Tibet from two perspectives, *Geol Soc Am Bull , 112,* 324-350, 2000.

Hodges, K V , R Parrish, T Housh, D Lux, B C. Burchfiel, L. Royden, and Z Chen, Simultaneous Miocene extension and shortening in the Himalayan orogen, *Science, 258,* 1466-1470, 1992

Hodges, K V , B C. Burchfiel, L H Royden, Z Chen, and Y Liu, The metamorphic signature of contemporaneous extension and shortening in the central Himalayan orogen Data from the Nyalam transect, southern Tibet, *J Metamorph Geol , 11,* 721-737, 1993

Hodges, K V , R R Parrish, and M P Searle, Tectonic evolution of the central Annapurna Range, Nepalese Himalayas, *Tectonics, 15,* 1264-1291, 1996

Holt, W E., Correlated crust and mantle strain fields in Tibet, *Geology, 28,* 67-70, 2000.

Howard, A D , M A Seidl, and W E Dietrich, Modeling fluvial erosion on regional to continental scales, *J Geophys Res , 99,* 13,971-13,986, 1994

Hurtado, J M , K V Hodges, and K.X. Whipple, Neotectonics of the Thakkhola Graben and implications for recent activity on the South Tibetan Fault System in the central Nepalese Himalaya, *Geol Soc Am Bull , 113,* 222-240, 2001

Jackson, M E , and R Bilham, 1991-1992 GPS measurements across the Nepal Himalaya, *Geophys Res Lett , 21,* 1169-1172, 1994

Jackson, M , S Barrientos, R Bilham, D. Kyestha, and B Shrestha, Uplift in the Nepal Himalaya revealed by spirit leveling, *Geophys Res Lett , 19,* 1539-1542, 1992

Jamieson, R A , C Beaumont, M H Nguyen, and B Lee, Interaction of metamorphism, deformation, and exhumation in large convergent orogens, *J Metamorph Geol ,* in press, 2001

Jones, C H , J R Unruh, and L.J Sonder, The role of gravitational potential energy in active deformation in the southwestern United States, *Nature, 381,* 37-41, 1996.

Jouanne, F , J L. Mugnier, M.R Pandey, J F. Gamond, P Le Fort, L Serrurier, C Vigny, and J P. Avouac, Oblique convergence in the Himalayas of western Nepal deduced from preliminary results of GPS measurements, *Geophys Res Lett , 26,* 1933-1936, 1999

Kruse, S , M McNutt, J Phipps-Morgan, and L. Royden, Lithospheric extension near Lake Mead, Nevada: A model for ductile flow in the lower crust, *J Geophys Res , 96,* 4435-4456, 1991.

Larson, K , R Burgmann, R Bilham, and J Freymueller, Kinematics of the India-Eurasia collision zone from GPS measurements, *J Geophys Res , 104,* 1077-1093, 1999

Lavé, J , and J P Avouac, Active folding of fluvial terraces across the Siwalik Hills, Himalayas of central Nepal, *J Geophys Res , 105,* 5735-5770, 2000

Le Fort, P , Himalayas· The collided range. Present knowledge of the continental arc, *Am J Sci , 275-A,* 1-44, 1975

Lemoine, F.G , et al., *The development of the joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) geopotential model EGM96, NASA Tech Pap NASA/TP-1998-206861,* 600 pp , 1998

Macfarlane, A , K V Hodges, and D Lux, A structural analysis of the Main Central thrust zone, Langtang National Park, central Nepal Himalaya, *Geol Soc Am Bull , 104,* 1389-1402, 1992.

Masek, J G , B L Isacks, T L Gubbels, and E J Fielding, Erosion and tectonics at margins of continental plateaus, *J Geophys Res , 99,* 13,941-13,956, 1994

McCaffrey, R , and J. Nabelek, Role of oblique convergence in the active deformation of the Himalayas and southern Tibetan plateau, *Geology,* 26, 691-694, 1998.

McQuarrie, N , and C G Chase, Raising the Colorado Plateau, *Geology,* 28, 91-94, 2000

Molnar, P , A review of geophysical constraints on the deep structure of the Tibetan Plateau, the Himalaya and the Karakoram, and their tectonic implications, in *The Geological Evolution of Tibet,* vol 326 A, edited by C Chang, et al , *Philos Trans. R. Soc London, Ser A,* 33-88,1988.

Molnar, P , A review of the seismicity and rates of active underthrusting and deformation at the Himalaya, *J Himalayan Geol , 1,* 131-154, 1990

Molnar, P , and H Lyon-Caen, Some simple physical aspects of the support, structure, and evolution of mountain belts, in *Processes in Continental Lithospheric Deformation,* edited by S. Clark, B C Burchfiel and J Suppe, *Geol Soc Am Spec Pap , 218,* 179-207, 1988

Molnar, P , and P Tapponier, Cenozoic tectonics of Asia Effects of a continental collision, *Science, 189,* 419-426, 1975

Molnar, P , and P Tapponnier, Active tectonics of Tibet, J Geophys Res , 83, 5361-5375, 1978

Molnar, P , P England, and J Martinod, Mantle dynamics, uplift of the Tibetan Plateau, and the Indian monsoon, *Rev Geophys , 31,* 357-396, 1993

Nakata, T , Active faults of the Himalaya of India and Nepal, in *Tectonics of the Western Himalayas,* edited by L L Malinconico and R J Lillie, *Geol Soc Am Spec Pap , 232,* 243-264, 1989

Nelson, K D , et al , Partially molten middle crust beneath southern Tibet Synthesis of Project INDEPTH results, *Science, 274,* 1684-1688, 1996

Ni, J , and M Barazangi, Seismotectonics of the Himalayan collision zone Geometry of the underthrusting Indian Plate beneath the Himalaya, *J Geophys Res , 89,* 1147-1163, 1984

Pandey, M R , R P Tandukar, J P Avouac, J Lavé, and J P Massot, Interseismic strain accumulation on the Himalayan crustal ramp (Nepal), *Geophys Res Lett , 22,* 751-754, 1995

Pandey, M.R , R P Tandukar, J P Avouac, J Vergne, and T Héritier, Seismotectonics of the Nepal Himalaya from a local seismic network, *J Asian Earth Sci , 17,* 703-712, 1999.

Pêcher, A , The contact between the Higher Himalyan crystallines and the Tibetan sedimentary series Miocene large-scale dextral shearing, *Tectonics, 10,* 587-599, 1991

Royden, L H., B C Burchfiel, R W. King, E Wang, Z Chen, F Shen, and Y Liu, Surface deformation and lower crustal flow in eastern Tibet, *Science, 276,* 788-790, 1997

Schelling, D., The tectonostratigraphy and structure of the eastern Nepal Himalaya, *Tectonics, 11,* 925-943, 1992

Schelling, D , and K Arita, Thrust tectonics, crustal shortening, and the structure of the far-eastern Nepal Himalaya, *Tectonics, 10,* 851-862, 1991

Searle, M P , Structural evolution and sequence of thrusting in the High Himalayan, Tibetan-Tethys and Indus suture zones of Zanskar and Ladakh, Western Himalaya, *J Struct. Geol , 8,* 923-936, 1986

Searle, M P., and A.J. Rex, Thermal model for the Zanskar Himalaya, *J Metamorph Geol , 7,* 127-134, 1989.

Searle, M.P , R R. Parrish, K V Hodges, A Hurford, M W. Ayres, and M J Whitehouse, Shisha Pangma leucogranite, South Tibetan Himalaya. Field relations, geochemistry, age, origin, and emplacement, *J Geol , 105,* 295-317, 1997

Seeber, L., and V Gornitz, River profiles along the Himalayan arc as indicators of active tectonics, *Tectonophysics, 92,* 335-367, 1983

Seeber, L , J G. Armbruster, and R.C. Quittmeyer, Seismicity and continental subduction in the Himalayan arc, in *Zagros, Hindu Kush, Himalaya Geodynamic Evolution, Geodyn Ser ,* vol. 3, edited by H.K. Gupta and F M Delany, pp. 215-242, AGU, Washington, DC, 1981

Sklar, L., and W.E Dietrich, River longitudinal profiles and bedrock incision models: Stream power and the influence of sediment supply, in *Rivers Over Rock. Fluvial Processes in Bedrock Channels, Geophys Monogr Ser ,* vol 107, edited by K J Tinkler and E.E Wohl, pp 237-260, AGU, Washington, D C , 1998

Srivastava, P , and G Mitra, Thrust geometries and deep structure of the outer and lesser Himalaya, Kumaun and Garhwal (India) Implications for evolution of the Himalayan fold-and-thrust belt, *Tectonics,* 13, 89-109, 1994.

Stocklin, J , K D Bhattarai, V Singh-Chetri, and A N Bhandari, Geologic map of Kathmandu area and Central Maharabharat Range (1 250,000), Dep of Mines and Geol , Kathmandu, Nepal, 1980

Tanimoto, T , and T. Okamoto, Change of crustal potential energy by earthquakes. An indicator for extensional and compressional tectonics, *Geophys Res Lett , 27,* 2313-2316, 2000

Tapponier, P , and P Molnar, Slip-line field theory and large-scale continental tectonics, *Nature, 264,* 319-324, 1976

Tucker, G E , and R L Slingerland, Drainage basin response to climate change, *Water Resour Res , 33,* 2031-2047, 1997

Upreti, B N , and P Le Fort, Lesser Himalayan crystalline nappes of Nepal Problems of their origin, in Himalaya and Tibet, in *Mountain Roots to Mountain Tops*, edited by A Macfarlane, R B Sorkhabi and J Quade, *Geol Soc Am Spec Pap 328*, 225-238, 1999

Vannay, J -C , and K V Hodges, Tectonometamorphic evolution of the Himalayan metamorphic core between Annapurna and Dhaulagiri, central Nepal, *J Metamorph Geol*, *14*, 635-656, 1996

Whipple, K X , and G E Tucker, Dynamics of the stream-power river incision model Implications for height limits of mountain ranges, landscape response timescales, and research needs, *J Geophys Res*, *104*, 17,661-17,674, 1999

Willett, S D , Orogeny and orography The effects of erosion on the structure of mountain belts, *J Geophys Res*, *104*, 28957-28981, 1999

Wu, C , K D Nelson, G Wortman, S D Samson, Y Yue, J Li, W S F Kidd, and M A Edwards, Yadong cross structure and South Tibetan detachment in the east central Himalaya (89°-90°E), *Tectonics*, *17*, 28-45, 1998

Yeats, R S , and R J Lillie, Contemporary tectonics of the Himalayan Frontal Fault System Folds, blind thrusts and the 1905 Kangra earthquake, *J Struct Geol*, *13*, 215-225, 1991

Yeats, R S , T Nakata, A Farah, M Fort, M A Mirza, M R Pandey, and R S Stein, The Himalayan frontal fault system, *Ann Tecton*, *6*, 85-98, 1992

Zhao, W , K D Nelson, and P I Team, Deep seismic reflection evidence for continental underthrusting beneath southern Tibet, *Nature*, *366*, 557-559, 1993

K V Hodges, J M Hurtado, and K X Whipple, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA (kvhodges@mit edu, hurtado@mit edu, kxw@mit edu)

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