Has focused denudation sustained active thrusting at the Himalayan topographic front?

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ABSTRACT
The geomorphic character of major river drainages in the Himalayan foothills of central Nepal suggests the existence of a discrete, west-northwest–trending break in rock uplift rates that does not correspond to previously mapped faults. The 40Ar/39Ar thermochronologic data from detrital muscovites with provenance from both sides of the discontinuity indicate that this geomorphic break also corresponds to a major discontinuity in cooling ages: samples to the south are Proterozoic to Paleozoic, whereas those to the north are Miocene and younger. Combined, these observations virtually require recent (Pliocene–Holocene) motion on a thrust-sense shear zone in the central Nepal Himalaya, ~20–30 km south of the Main Central thrust. Field observations are consistent with motion on a broad shear zone subparallel to the fabric of the Lesser Himalayan lithotectonic sequence. The results suggest that motion on thrusts in the toe of the Himalayan wedge may be synchronous with deeper exhumation on more hinterland structures in central Nepal. We speculate that this continued exhumation in the hinterland may be related to intense, sustained erosion driven by focused orographic precipitation at the foot of the High Himalaya.

Keywords: tectonics, Himalayas, Nepal, geomorphology, argon-argon, Main Central thrust.

INTRODUCTION
Recent geodynamic modeling of orogenic growth has led to the provocative hypothesis that erosion may exert first-order control on orogen-scale tectonics (e.g., Beaumont et al., 2001). However, direct field evidence of this feedback is not easily obtained. Here we present evidence for recent thrusting in the Himalayan hinterland at the position of the major topographic break between the physiographic lesser and higher Himalaya. Combined with evidence for Pliocene activity on the Main Central thrust (e.g., Harrison et al., 1997; Catlos et al., 2001; Robinson et al., 2003), our data imply sustained out-of-sequence thrusting that is suggestive of a direct link between tectonics and the monsoon-driven erosion of the High Himalaya.

We utilize the geomorphology of the Burhi Gandaki and Trisuli watersheds in central Nepal—derived from a 90 m digital elevation model (DEM) and observations on the ground—to identify breaks in hillslope, valley, and channel morphologies that may reflect unmapped, active structures in this area. All of the geomorphic observations suggest a narrowly distributed decrease in rock uplift rates from north to south, centered ~20–30 km south of the Main Central thrust zone. The 40Ar/39Ar thermochronologic data from detrital muscovites also indicate a major break in cooling ages at this location, implying a significant change in exhumation rates across a 10-km-wide zone. The simplest explanation for all of the data is a tectonic model including Pliocene–Holocene thrusting on a surface-breaking shear zone near the base of the High Himalaya.

GEOLoGIC SETTING
The Burhi Gandaki and Trisuli Rivers carve through the High Himalaya ~80 km northwest of Kathmandu, Nepal (Fig. 1). Their upper reaches traverse primarily Neoproterozoic rocks of the Tibetan Sedimentary Sequence, which are bounded at their base by predominantly normal-sense structures of the South Tibetan fault system. Downstream (south) of the South Tibetan fault system, and for most of their courses, the rivers carve steep-walled gorges through the high-grade metamorphic core of the range, represented by the Greater Himalayan Sequence. The Greater Himalayan Sequence is bounded at its base by the Main Central thrust zone, a crustal-scale feature that can be traced nearly the entire length of the Himalayan orogen (e.g., Hodges, 2000). In the footwall of the Main Central thrust zone, the rivers traverse the Lesser Himalayan Sequence, which is dominated in central Nepal by phyllites, quartzites, psammites, and metacarbonates of the Kuncha Formation (e.g., Stöcklin, 1980). Recent studies suggest that there may be significant repetition of the Kuncha section along foliation-parallel thrusts (e.g., DeCelles et al., 2001).

The steep-walled gorges typical of the Greater Himalayan Sequence persist within the Lesser Himalayan Sequence for ~20–30 km south of the Main Central thrust zone. Both rivers then cross a prominent physiographic transition, uncorrelated with any mapped structures or change in rock type, referred to as physiographic transition 2 (PT2) by Hodges et al. (2001). PT2 is characterized by a number of changes in landscape morphology, including (1) a change from narrow, steep-walled gorges in the north to wide, alluviated valleys in the south; (2) an abrupt decrease in hillside gradient from north to south (Fig. 1); (3) an abrupt transition from fresh, landslide-covered hillslopes in the north to deeply weathered, red soils on hillslopes and channel banks; (4) an abrupt appearance from north to south of thick (to 200 m) fluvial fill terraces in both drainages; and (5) an abrupt decrease in channel gradient from north to south, discussed in more detail herein. All of these observations suggest a profound and narrowly distributed decrease in the rates of denudation from north to south.

Noting the existence and position of this physiographic transition throughout the Him-
alaya, Seeber and Gornitz (1983) suggested that it may be indicative of recent movement on the Main Central thrust system. However, this interpretation runs counter to the generally agreed upon developmental sequence for major thrust fault systems in the Himalaya. For example, the Main Central thrust system is thought to have been active ca. 30–23 Ma, with shortening progressing southward to the Main Boundary thrust system in late Miocene–Pliocene time and to the Main Frontal thrust system in Pliocene–Holocene time (e.g., Hodges, 2000). Implicit in this model is the assumption that the Main Central thrust became inactive as deformation stepped southward.

With this assumption, tectonic models of the Nepal Himalaya typically invoke a ramp-flat geometry on the basal décollement, or Himalayan sole thrust, to explain the prominent physiographic transition (e.g., Cattin and Avouac, 2000) (Fig. 2A). Alternatively, PT₂ may be an expression of recent motion on the Main Central thrust through much of Nepal (e.g., Seeber and Gornitz, 1983), or on unmapped structures farther to the south in the Burhi Gandaki and Trisuli watersheds (Fig. 2B). Such out-of-sequence thrusting is relatively common in fold-and-thrust belts, and is predicted by many kinematic models as a way of preserving the critical taper of accretionary wedges with strong erosion gradients between the foreland and the hinterland (e.g., Dahlen and Suppe, 1988). Data from microseismicity and geodetics have been invoked as evidence for the ramp-flat model (e.g., Pandey et al., 1999; Bilham et al., 1997); however, these data are equally consistent with surface-breaking structures at PT₂. Thermochronologic and thermobarometric data suggest varied types of activity on the Main Central thrust as recently as the early Pliocene, lending additional support to the hypothesis of reactivated hinterland structures (e.g., Macfarlane et al., 1992; Harrison et al., 1997; Catlos et al., 2001).

If PT₂ marks the locus of out-of-sequence thrusting rather than the position of a buried ramp in the Himalayan sole thrust, PT₂ would be expected to correspond with an abrupt change in rock uplift rates. In the following, a combination of stream-profile analysis and \(^{40}\text{Ar}^{39}\text{Ar}\) thermochronology is used to test this prediction.

**METHODS AND RESULTS**

**Stream Profiles**

In a variety of natural settings, empirical data from river channels exhibit a scaling in which local channel slope can be expressed as a power-law function of contributing drainage...
area (e.g., Howard and Kerby, 1983). Previous work suggests that the pre-exponential factor in this function—referred to as the steepness coefficient ($k_s$)—is positively correlated with the rock uplift rate $U$ (e.g., Snyder et al., 2000). The exponent on drainage area—referred to as the concavity index ($\theta$)—typically falls in a narrow range between 0.3 and 0.6, but may approach much higher values in zones of distributed uplift (e.g., Snyder et al., 2000; Kirby and Whipple, 2001). We stress that our quantitative understanding of feedbacks related to changes in channel width, hydraulic roughness, the quantity and caliber of abrasive tools, and the relative importance of various erosive processes remains limited (e.g., Lave and Avouac, 2001; Sklar and Dietrich, 1998; Whipple et al., 2000). Moreover, we note that $k_s$ also depends on many factors, including rock strength and climate, limiting our ability to derive quantitative estimates of uplift rates from slope versus area data. However, where rock erodibility is nearly invariant and climatic variability is smooth, abrupt changes in $k_s$ may be confidently interpreted as reflecting a change in rock uplift rate.

Channel slope and drainage area data were extracted for 56 tributaries in the study area from a 90 m DEM of central Nepal. Using a reference concavity of 0.45 (e.g., Snyder et al., 2000), steepness coefficients derived from logarithmic plots of slope versus area range from 84 to 560 m$^{-0.9}$. Channels having a source below PT$_2$ typically have uniformly low steepness values. Channels crossing PT$_2$ typically have low steepness values in the lowest reaches and approach the upper envelope of $k_s$ values above PT$_2$. The trans-Himalayan trunk streams, including the Burhi Gandaki and Trisuli main stems, have high steepness values in their middle reaches, bounded above and below by sections having lower steepness (see Fig. DR-1'). In plan view, the boundary between high and low $k_s$ values is nearly coincident with the break in hillslope gradients illustrated in Figure 1, suggesting that hillslopes and river channels may each be responding to a decrease in rock uplift rates from north to south (Fig. 3A). Although the Lesser Himalayan Sequence in the field area varies locally among phyllites, psammites, and metacarbonate, no systematic changes in rock character were observed at PT$_2$ in any of the drainages, suggesting that the transition from high to low steepness values is not a result of a change in rock erodibility (e.g., Snyder et al., 2000).

40Ar/39Ar Thermochronology

Eight detrital samples were collected from small tributaries to the Burhi Gandaki for muscovite 40Ar/39Ar thermochronology (Fig. 3A). Selected tributary basins were oriented subparallel to PT$_2$ and the overall structural grain, ensuring that the sediment from each sample was derived from a similar tectonostratigraphic position. Basins were typically 20–25 km$^2$, with maximum across-strike basin widths ranging from 2 to 5 km. The northernmost sample was collected from the Burhi Gandaki trunk stream, to provide a view of cooling histories upstream of the Main Central thrust. Sampling locations span a distance of 47 km, as projected onto a line oriented at 19° east of north (approximately parallel to section A–A’ in Fig. 1).

Muscovites were separated by standard mineral-separation techniques prior to irradiation at the McMaster University nuclear reactor in Ontario, Canada. For each sample, 20–80 aliquots of muscovite were analyzed by laser microprobe, each consisting of between 1 and 20 grains. Many of the smaller aliquots had low radiogenic yields and therefore high uncertainties. Analyses reported here are limited to those with >50% radiogenic yield, reducing the total number of reported analyses to between 18 and 68. Complete data are available in the Data Repository (see footnote 1).

Figure 3B shows the normalized probability-density functions of sample ages plotted against distance from PT$_2$. South of PT$_2$, dates range from Mesoproterozoic to Paleozoic, with an apparent trend toward older ages from north to south. This trend may reflect partial loss of radiogenic 40Ar from samples near PT$_2$ due to footwall heating beneath a thin thrust sheet in the early stages of Main Central thrust development (e.g., Arita et al., 1997). Argon release spectra from bedrock samples south of PT$_2$ and in the Kathmandu nappe are consistent with this hypothesis (e.g., Copeland et al., 1991, personal commun.). North of PT$_2$, nearly all dates are Miocene or younger. The ~400 m.y. break in cooling ages at PT$_2$ suggests a major discontinuity in rock uplift rates across the physiographic transition. Furthermore, the

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*GSA Data Repository item 2003131, stream profiles and thermochronologic data, is available online at [www.geosociety.org/pubs/ft2003.htm](http://www.geosociety.org/pubs/ft2003.htm), or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.*
age distributions south of PT2 require that none of the samples below PT2 have undergone prolonged heating above ~350 °C during Himalayan orogenesis. This result seems inconsistent with tectonic models that require prolonged transport of the Main Central thrust hanging wall over a ramp on the Himalayan sole thrust, with a geometry as envisioned by Pandey et al. (1999) or Cattin and Avouac (2000).

Field Observations

Limited outcrop in the field area and a lack of marker beds in the Kuncha Formation phyllites limit our ability to constrain unequivocally the position of a thrust at PT2. Any new thrusts in this setting are also likely to be parallel to—and thus difficult to deconvolve from—the more pervasive Himalayan fabric (nominally west-northwest trending and dipping north at 30°–50°). Despite these limitations, however, a number of structural observations are consistent with the presence of a surface-breaking thrust at PT2, including (1) numerous small-scale shear zones subparallel to and crosscutting the structural grain within the Kuncha Formation phyllites, (2) hydrothermal activity in tributary valleys along PT2, and (3) large-scale changes in bedrock attitudes in outcrop at the scale of tens of hundreds of meters.

DISCUSSION AND CONCLUSIONS

All of the data indicate a major change in rock uplift rates and thermal history in central Nepal, centered ~20–30 km south of the Main Central thrust. The tectonic picture that emerges for central Nepal is therefore one in which activity at the frontal thrusts today (e.g., Main Boundary thrust and Main Frontal thrust) may be synchronous with motion on structures farther hinterland (e.g., Main Central thrust and at PT2). Previous work has suggested that modern activity on or near the Main Central thrust may be favored by extreme topographic gradients between the Tibetan Plateau and the Indian foreland (e.g., Hodges et al., 2001; Grujic et al., 2002). In central Nepal, the Main Central thrust forms a major reentrant to the north, in contrast to its more linear trend farther to the west (see Fig. 1). This geometric relationship may have favored the initiation of a new shear zone at PT2, parallel to the regional trend of the Main Central thrust and the pervasive structural grain.

Intense precipitation at the southern front of the High Himalaya is also likely to play a role in the kinematics of the Himalayan fold-and-thrust belt, and may have been important in maintaining a locus of active thrusting at PT2 (e.g., Dahlen and Suppe, 1988). As the summer monsoons approach the Tibetan Plateau, orographic focusing of precipitation results in strong north-south gradients in rainfall, which increases surface denudation rates on the windward side of the range. Coupled with extreme topographic gradients and continued convergence between India and Eurasia, this strong precipitation may have resulted in sustained focusing of exhumation along the metamorphic core of the Himalaya (e.g., Beaumont et al., 2001), rather than a complete transfer of shortening to the Main Boundary thrust and Main Frontal thrust. The combined geomorphic, thermochronologic, and field evidence for an active shear zone at the foot of the Himalaya may therefore provide evidence for erosionally driven rock uplift at the orogen scale.

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