Climatic forcing of erosion, landscape, and tectonics in the Bhutan Himalayas

Djordje Grujic Department of Earth Sciences, Dalhousie University, Halifax B3H 4J1, Canada
Isabelle Coutand Université de Lille I, UMR 8110, 59655 Villeneuve d'Ascq Cedex, France
Bodo Bookhagen Institute for Crustal Studies, University of California–Santa Barbara, Santa Barbara, California 93106, USA
Stéphane Bonnet Université de Rennes 1, Géosciences Rennes, 35042 Rennes Cedex, France
Ann Blythe Department of Earth Sciences, University of Southern California, Los Angeles, California 90089, USA
Chris Duncan Department of Geosciences, University of Massachusetts, Amherst, Massachusetts 01003, USA

ABSTRACT

A fundamental objective in studies of climate-erosion-tectonics coupling is to document convincing correlation between observable indicators of these processes on the scale of a mountain range. The eastern Himalayas are a unique range to quantify the contribution of tectonics and climate to long-term erosion rates, because uniform and steady tectonics have persisted for several million years, while monsoonal precipitation patterns have varied in space and time. Specifically, the rise of the Shillong plateau, the only orographic barrier in the Himalayan foreland, has reduced the mean annual precipitation downwind in the eastern Bhutan Himalaya at the Miocene-Pliocene transition. Apatite fission-track (AFT) analyses of 45 bedrock samples from an E-W transect along Bhutan indicate faster long-term erosion rates outside of the rain shadow in the west (1.0–1.8 mm/yr) than inside of it in the east (0.55–0.85 mm/yr). Furthermore, an AFT vertical profile in the latter segment reveals a deceleration in erosion rates sometime after 5.9 Ma. In this drier segment of Bhutan, there are remnants of a relict landscape formed under a wetter climate that has not yet equilibrated to the present climatic conditions. Uplift and preservation of the paleolandscape are a result of a climate-induced decrease in erosion rates, rather than of an increase in rock uplift rate. This study documents not only a compelling spatial correlation between long-term erosion and precipitation rates, but also a climatically driven erosion-rate change on the scale of the eastern Himalayas, a change that, in turn, likely influences that region's recent tectonic evolution.

Keywords: tectonics, climate, erosion, paleolandscape, Himalaya, apatite fission-track.

INTRODUCTION

In active mountain ranges, climate influences strain partitioning and landscape evolution through erosional focusing, as suggested by numerical (Avouac and Burov, 1996; Willett, 1999; Beaumont et al., 2004) and analogue (Bonnet and Crave, 2003) modeling of interactions between surface processes and tectonics. However, when deconvolving tectonic and climatic controls on orogenic evolution, it is inherently difficult to go from observing a correlation between, for example, spatial patterns of precipitation and erosion rate to demonstrating feedbacks. Consequently, observational studies of active orogens reveal divergent opinions regarding the relative contribution of tectonics and climate to erosional efficiency and to landscape evolution (Molnar, 2003, and references therein).

We approached this problem by comparing two adjacent segments of an active orogen that, on a million-year time scale, had nearly identical tectonic evolution but dissimilar climates. The Himalayas have structurally and lithologically little variance, and they have a nearly uniform plate convergence rate. There are, however, significant precipitation gradients along strike. Assuming that climate is important in the geomorphic and kinematic behavior of an active orogen, then there should be observable changes in deformation, erosion rates, and, by inference, uplift and landscape patterns wherever lasting climate changes have occurred.

Apatite fission-track (AFT) cooling ages from 45 samples collected along a broad E-W transect through the Bhutan Himalayas (Fig. 1; Table DR1[1]) indicate that significantly varying long-term ($\geq$1 m.y.) erosion rates closely track modern mean annual precipitation rates. Wetter areas, west of 90°E, have eroded faster than drier, eastern areas. Through geomorphic analysis, remnants of an ancient landscape were identified in the areas of lower erosion rates. Its geomorphic characteristics suggest that the paleolandscape in Bhutan developed under wetter conditions than those of the modern climate. Since tectonic conditions have not changed significantly during the last few million years, the relict landscape appears to have been uplifted probably as a result of climate-induced variations in erosion. We conclude that the long-term erosion rate pattern along the Bhutan Himalayas is primarily controlled by spatiotemporal variations of precipitation.

[1]GSA Data Repository item 2006177, Appendix DR1 (methodology), Table DR1 (apatite fission-track data), and Figures DR1 and DR2 (precipitation map), is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

GEOLOGICAL SETTING

From south to north and extending along the entire orogen, the main structures of the Himalayas are: the Main Frontal thrust (MFT), the Main Boundary thrust (MBT), the Main Central thrust (MCT), and the South Tibetan detachment (STD) (Gansser, 1983; Hodges, 2000). Between the MBT and MCT lies the Lesser Himalayan Sequence (LHS), which is dominated by low-grade metasediments. Flanked by the MCT and STD is the Greater Himalayan Sequence (GHS), which is composed of schist, gneisses, and migmatites that were deformed, metamorphosed, and intruded by granites during the Miocene. The hanging wall of the STD is made up of the less-deformed, low-grade to unmetamorphosed Tethyan Sedimentary Sequence (TSS). Although the first-order structures (MBT, MCT, STD) vary little along the Himalayan arc, second-order structures, such as windows, gneiss domes, klippen, and out-of-sequence thrusts, are restricted to certain parts of the orogen (e.g., Hodges, 2000). Gneiss domes in the TSS and windows through the GHS are common west of 90°E longitude, while klippen of TSS atop the GHS occur only east of that line (Fig. 1). In addition, 90°E is the approximate western boundary of the Shillong plateau, which is the only raised ground in the foreland of the Himalayas. Thus 90°E is a fundamental boundary between eastern and western areas of Bhutan that are characterized by different precipitation, erosion, landscape, and deformation.

An Uplifted Relict Landscape in Bhutan

In contrast to central Nepal, where the N-S topographic profile has a markedly concave shape, the Bhutan Himalayas rise more abruptly from the foreland and have topographic profiles that are straight to slightly

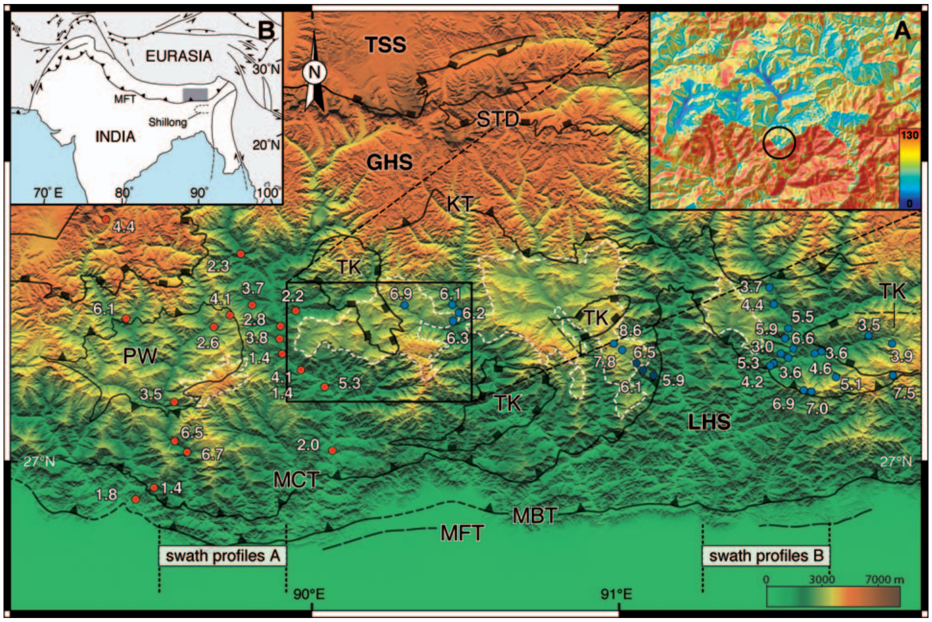


Figure 1. Digital elevation model (DEM) of Bhutan Himalayas with main shear zones and tectonic units (Grujic et al., 2002): MFT—Main Frontal thrust, MBT—Main Boundary thrust, MCT—Main Central thrust, KT—Kakhtang thrust, STD—South Tibetan detachment, LHS—Lesser Himalayan Sequence, GHS—Greater Himalayan Sequence, TK—Tethyan Klippen, PW—Paro window, TSS—Tethyan Sedimentary Sequence. Locations of the apatite fission-track (AFT) ages: red—western Bhutan, blue—eastern Bhutan. Dark blue indicates group of data from vertical profile at ~91°E (Fig. 3). Positions of topographic and precipitation profiles (Fig. 2) are indicated at bottom. Swaths are 500 km long and thus extend to south of map. Patches of low-relief relict landscape are contoured by white dashed lines, to be interpreted as erosional boundaries. A shaded local-relief map (inset A) was used to draw contours of relict landscape. Linear scale is for standard deviation of elevations within a 375 m radius (Appendix DR1, see text footnote 1). Small orphan remnants (see example within diagram circle) separated from main remnant by drainage divide strongly support concept of relict landscape. Gray box in inset B indicates geographic area of map.

convex (Duncan et al., 2003; Fig. 2). The topographic profile of Bhutan is characterized by a step of low slope at ~3000 m (Gansser, 1983; Duncan et al., 2003), which is formed by an E-W–trending belt of perched patches of low-relief topography (Fig. 1). Unlike the surrounding and steeply incised topography, the patches are wide, alluvium-filled valleys (Fig. 1) with deeply weathered bedrock, and, along their borders, longitudinal river profiles show pronounced knickpoints (Duncan et al., 2003; Baillie and Norbu, 2004). The patches do not follow lithological boundaries or faults, suggesting that they are remnants of an ancient landscape that has not yet been incised by headward-cutting bedrock rivers. The high elevation of the landscape remnants relative to the beds of surrounding rivers and the occurrence of knickpoints suggest that the remnants formed at a lower elevation and have been subsequently uplifted to their present position.

Two distinct scenarios may account for the formation of the relict landscape. First, a sudden increase in rock uplift rate relative to erosion rate may have led to a transient period of a nonequilibrium landscape characterized by the propagation of knickpoints into upstream areas undergoing surface uplift (Whipple and Tucker, 1999; Clark et al., 2005). In such cases, the low-relief areas would be relicts of a landscape that was equilibrated with a lower rate of rock uplift in the past. Alternatively, climate change combined with a constant rock uplift rate may have caused surface uplift. Apart from lithology, the main parameters that control erosivity are related to climate (Whipple and Tucker, 1999). The landscape may therefore have been modified by climate change while the rock uplift rate remained constant (Whipple et al., 1999). It has been demonstrated that landscape relief increases with decreasing precipitation (Bonnet and Crave, 2003; Gabet et al., 2004), so that, given a constant rock uplift rate, a decrease in precipitation reduces the erosion rate and consequently leads to increased surface elevation. If formed by such climatically induced surface uplift, the low-relief patches found in Bhutan represent relicts of a landscape that was equilibrated with a wetter climate in the past, without involving any variation in the rock uplift rate. Paleolandscape preserves information about erosional and geomorphic processes related to past tectonic and climatic conditions (e.g., Clark et al., 2005), and thus, in conjunction with climatic and thermochronological data, it can help to separate tectonic from climate-induced changes in surface uplift and incision rate of the modern landscape.

OROGRAPHIC BARRIER IN THE FORELAND OF THE BHUTAN HIMALAYAS

Along the southern flank of the Himalayas, the Indian summer monsoon plays an essential role in erosion (Bookhagen et al., 2005). The onset of the Indian summer monsoon is believed to have taken place by 12.0–10.7 Ma (Dettman et al., 2001, 2003). In eastern Bhutan, the Indian summer monsoon's precipitation is influenced by the Shillong plateau, the only elevated terrain outboard of the deformation front along the entire orogen. The Shillong plateau forms an ~1600-m-high barrier to the prevailing winds transporting moisture from the Bay of Bengal toward the Himalayan front (Bookhagen et al., 2005; Fig. DR1 [see footnote 1]). The plateau thus concentrates rainfall on its southern slope (>6 m/yr) and creates a rain shadow on its lee. Consequently, eastern Bhutan receives about half the precipitation delivered to the Himalayas outside the rain shadow (Fig. 2). The modern precipitation pattern closely mimics the shape of the Shillong plateau (Bookhagen et al., 2005; Fig. DR1), indicating that once the plateau had attained sufficient elevation, an orographic effect resulted, inducing condensation and precipitation on its windward side, and consequently decreasing precipitation on the lee (Bookhagen et al., 2005).

Sedimentary data indicate that the Shillong plateau was submerged until the Miocene-Pliocene transition, and that it emerged during the Pliocene as an outcrop of Precambrian basement rocks (Johnson and Nur Alam, 1991; Uddin and Lundberg, 1999, 2004). Therefore, the reorganization of precipitation distribution due to the uplift of the Shillong plateau occurred after the Indian summer monsoon was established along the Himalayas. Accordingly, it is reasonable to assume that, until the end of the Miocene, the eastern Himalayas currently located in the lee of the Shillong plateau received much higher rainfall than they do today.

Apatite Fission-Track Analysis

The study transect covers two longitudinal regions with different climatic histories, since the eastern part is located on the lee of the Shillong plateau. Apatite fission-track (AFT) ages indicate the time elapsed since cooling below the effective closure temperature of the system, estimated here at 130 ± 10 °C (Appendix DR1, see footnote 1).

Across western Bhutan, AFT ages range between 1.4 ± 0.6 Ma and 6.7 ± 0.8 Ma. However, most of the ages are Pliocene (ca. 1.5–4 Ma), except for four samples older than 6 Ma (Fig. 3; Table DR1 [see footnote 1]). Three of the latter samples were taken from the periphery of the Paro window where the distribution of cooling ages is likely disrupted across the boundary shear zone (see following). The Pli-

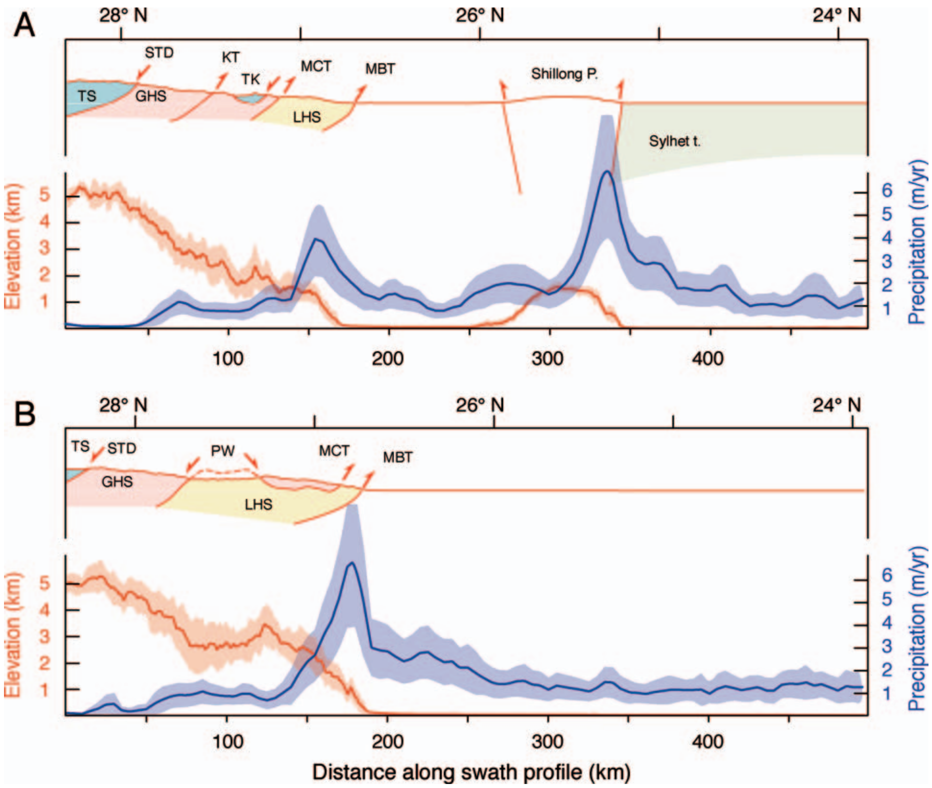
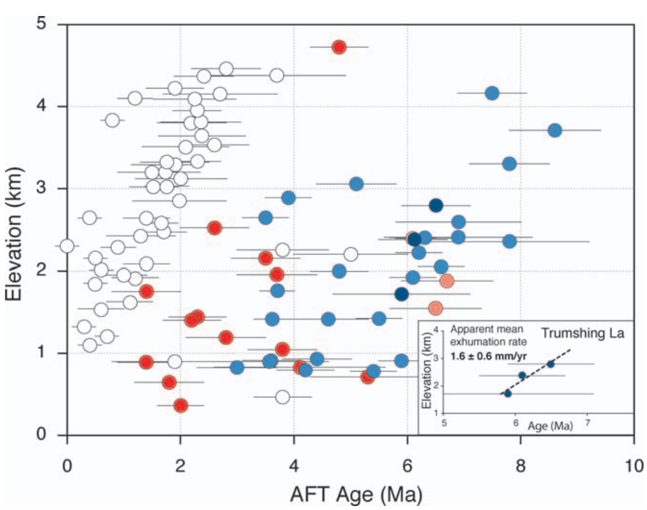


Figure 2. Topographic and precipitation profiles, in 40-km-wide swaths, across Bhutan Himalayas and Shillong plateau show that an orographic barrier of 1.5–2 km is sufficient to hinder moisture transport. A—eastern Bhutan; B—western Bhutan. Topography (orange) has been derived from Shuttle Radar Topography Mission data; precipitation (blue) is taken from the calibrated Tropical Rainfall Measuring Mission data (Appendix DR1, see text footnote 1). There is a strong E-W precipitation gradient: at ~1–1.5 km elevation in the east it is ~4 m/yr, while in the west it is ~6 m/yr. The orographic effect is also strongly pronounced with only Indian summer monsoon (ISM) precipitation (i.e., 0.5 versus 3.5 m/yr, respectively; Bookhagen et al., 2005). Geographic locations are shown on Figure DR1 (see text footnote 1). MFT—Main Frontal thrust, MBT—Main Boundary thrust, MCT—Main Central thrust, KT—Kakhtang thrust, STD—South Tibetan detachment, LHS—Lesser Himalayan Sequence, GHS—Greater Himalayan Sequence, TK—Tethyan Klippen, PW—Paro window, TSS—Tethyan Sedimentary Sequence.

ocene AFT ages show no correlation with elevation (Fig. 3). The weighted mean AFT age of 2.55 ± 0.15 Ma (excluding the 3 anomalous samples) provides a long-term exhumation rate (i.e., erosion rate; Appendix DR1 [see footnote 1]) on the order of 1.0–1.8 mm/yr.

Across eastern Bhutan, AFT ages vary between 3.0 ± 0.7 Ma and 8.6 ± 0.8 Ma, with late Miocene ages clearly dominant in this area (Fig. 3; Table DR1). The weighted mean AFT age of 5.08 ± 0.09 Ma yields a long-term exhumation rate of 0.55–0.85 mm/yr, assuming a steady exhumation rate until the present. However, a vertical profile at ~91°E (Figs. 1 and 3; Table DR1) reveals a positive correlation between age and elevation, with a slope (equivalent to exhumation rate) of 1.6 ± 0.6 mm/yr for the period between 6.5 and 5.9 Ma. This apparent late Miocene erosion rate is similar to the late Pliocene erosion rate in western Bhutan. If such a rapid erosion rate had continued until the present day across eastern Bhutan, younger AFT ages would dominate across the modern landscape. This is not the case, which leads us to conclude that across eastern Bhutan, the erosion rate must have slowed sometime after 5.9 Ma.

Figure 3. Age-elevation diagram of apatite fission-track (AFT) data. Data from western Bhutan are in bright red; data from periphery of Paro window are in pale red; data from eastern Bhutan are in pale blue. Dark blue indicates data from vertical profile at ~91°E (inset). In white are published AFT ages from western Himalayas (Sorkhabi et al., 1996; Thiede et al., 2004; Vannay et al., 2004) and central Nepal (Burbank et al., 2003).



DISCUSSION

The uplift of the Shillong plateau may account for up to one-third of the India-Eurasia convergence (Bilham and England, 2001), which would consequently lower the fault slip rate and thus the rock uplift rate in eastern Bhutan when compared with other frontal parts of the Himalayas. However, the degree of convergence partitioning between the plateau and eastern Bhutan is poorly constrained because neither the kinematics nor the attitude of the faults bounding the Shillong plateau are well known (Bilham and England, 2001; Biswas and Grasemann, 2005). Although the plateau emerged only in the early Pliocene, the sedimentary record of the more southerly Sylhet Trough (Johnson and Nur Alam, 1991) indicates sustained displacements along the southern boundary fault since the Eocene. Thus, the convergence partitioning started much earlier than the plateau's subareal uplift at the Miocene-Pliocene transition. The surface uplift of the Shillong plateau is likely due to a change of rock erodibility at a constant rock uplift rate, similar to mechanisms of surface uplift proposed elsewhere (Sobel and Strecker, 2003). The basement of the plateau was covered by ~3000 m of Tertiary sediments (Johnson and Nur Alam, 1991). When these sediments were eroded and more resistant bedrock was exposed, the erosion rate may have slowed, resulting in surface uplift.

Rock uplift rate in a critical taper wedge appears more sensitive to erosional efficiency than to the tectonic accretionary flux (Whipple and Meade, 2004). Therefore, convergence partitioning into the Shillong plateau, which would reduce the shortening rate in eastern Bhutan, would produce a lesser effect than reducing the erosion rate. The relict landscape argues against a significantly reduced shortening rate across the Bhutan Himalaya. In particular, rock uplift in the mountain chain could not have decreased considerably or there would have been no fast surface uplift of a paleolandscape. Assuming nearly constant fault-slip rate, a recent decrease in erosion rate in eastern Bhutan would cause rock uplift to become less compensated by erosion, resulting in surface uplift. The relict landscape is reminiscent of a wetter climate landscape that is characterized by smoother topography (Bonnet and Crave, 2003; Gabet et al., 2004). Accordingly, we propose that the Shillong plateau uplift decreased precipitation in eastern Bhutan. This allowed the nearly steady tectonic uplift along the Main Boundary thrust to enhance the surface uplift of the antecedent landscape and its incision through upstream propagation of knickpoints. Since the base of the range (the Brahmaputra Valley) could not be lowered, the present-day elevation of the lower erosional boundary of relict landscape (~2 km) indicates the maximum amount of its uplift.

In the central (Burbank et al., 2003) and western Himalayas (Sorkhabi et al., 1996; Thiede et al., 2004; Vannay et al., 2004), most of the AFT ages are Pliocene to Quaternary (Fig. 3), yielding rapid exhumation rates of 1–3 mm/yr. Although there are differences in AFT ages between eastern and western Bhutan, the latter, located at the western edge of the rain shadow, is probably a transition zone between eastern Bhutan and the central and western Himalayas in the sense of recent exhumation history and landscape evolution.

Segments of the Bhutan Himalayas that have different erosion histories are characterized by different second-order structures. In eastern Bhutan, outliers of Tethyan Sedimentary Sequence indicate that the South Tibetan detachment may once have extended farther south throughout the Himalayas but, apart from eastern Bhutan, has now been completely eroded back to the Himalayan crest (Grujic et al., 2002). In western Bhutan, the Paro window exhibits Lesser Himalayan Sequence in its core, surrounded by Greater Himalayan Sequence and bounded by a normal-sense shear zone (Figs. 1 and 2). Younger cooling ages in the core of the window relative to the ages of surrounding rocks support the hypothesis of focused core exhumation. The Paro window (like the similar Rampur window in the western Himalayas; Thiede et al., 2004; Vannay et al., 2004) possibly results from a local high erosion rate coupled with higher tectonic accretion in its core relative to its margins.

CONCLUSIONS

In the Bhutan Himalayas, spatiotemporal changes in climate are expressed through along-strike differences in erosion rates, landscape morphology, and tectonic features. Decreased precipitation along the Himalayan front in eastern Bhutan was caused by the rapid surface uplift of the Shillong plateau and its orographic effect on the Indian summer monsoon; the kinematic effect of the rising plateau on the tectonic uplift of the Himalayan front seems to have been minor. Therefore, recent changes in landscape and erosion of the Bhutan Himalayas are climate induced.

AFT ages document a decrease of erosion rates along the front of the eastern Bhutan Himalayas at the Miocene-Pliocene transition. In the same area, a relict landscape has been identified that was formed under wetter conditions and was uplifted to its current elevation in response to a decrease in erosion rate, which was caused by a decrease in precipitation rate rather than by an increase in tectonic uplift rate. Our study documents not only a compelling spatial correlation between long-term erosion and precipitation rates, but also a climatically driven erosion rate change on the scale of the eastern Himalayas. It is likely that this change in erosion rate is responsible for the development of second-order tectonic structures in Bhutan.

ACKNOWLEDGMENTS

Field work in the Kingdom of Bhutan was facilitated by the invaluable help provided by the people and the Royal Government of Bhutan, and by the Hoch family. The first author acknowledges motivating discussions with the members of the Canadian Institute for Advanced Research. We also thank M. Clark, P. Reiners, M. Strecker, P. van der Beek, and K. Whipple for their constructive reviews. The project was supported by the Natural Sciences and Engineering Research Council of Canada, the University of Lille 1 (Unité Mixte de Recherche 8110), the Deutsche Forschungsgemeinschaft (Germany), and the National Science Foundation (USA).

REFERENCES CITED

Avouac, J.P., and Burov, E.B., 1996, Erosion as a driving mechanism of intracontinental mountain growth: Journal of Geophysical Research, ser. B, Solid Earth and Planets, v. 101, p. 17,747–17,769.

Baillie, I.C., and Norbu, C., 2004, Climate and other factors in the development of river and interfluve profiles in Bhutan, eastern Himalayas: Journal of Asian Earth Sciences, v. 22, p. 539–553.

Beaumont, C., Jamieson, R.A., Nguyen, M.H., and Medvedev, S., 2004, Crustal channel flows: 1. Numerical models with applications to the tectonics of the Himalayan-Tibetan orogen: Journal of Geophysical Research, v.109, doi: 10.1029/2003JB002809.

Bilham, R., and England, P., 2001, Plateau ''pop-up'' in the great 1897 Assam earthquake: Nature, v. 410, p. 806–809.

Biswas, S., and Grasemann, B., 2005, Quantitative morphotectonics of the southern Shillong plateau (Bangladesh/India): Austrian Journal of Earth Sciences, v. 97, p. 82–93.

Bonnet, S., and Crave, A., 2003, Landscape response to climate change: Insights from experimental modeling and implications for tectonic versus climate uplift of topography: Geology, v. 31, p. 123–126.

Bookhagen, B., Thiede, R.C., and Strecker, M.R., 2005, Abnormal monsoon years (AMYs) and their control on erosion and sediment flux in the high, arid northwest Himalaya: Earth and Planetary Science Letters, v. 231, p. 131–146.

Burbank, D.W., Blythe, A.E., Putkonen, J., Pratt-Sitaula, B., Gabet, E., Oskin, M., Barros, A., and Ojha, T.P., 2003, Decoupling of erosion and precipitation in the Himalayas: Nature, v. 426, p. 652–655.

Clark, M.K., Maheo, G., Saleeby, J., and Farley, K.A., 2005, The non-equilibrium landscape of the southern Sierra Nevada, California: GSA Today, v. 15, p. 4–10.

Dettman, D.L., Kohn, M.J., Quade, J., Ryerson, F.J., Ojha, T.P., and Hamidullah, S., 2001, Seasonal stable isotope evidence for a strong Asian monsoon throughout the past 10.7 m.y.: Geology, v. 29, p. 31–34.

Dettman, D.L., Fang, X.M., Garzione, C.N., and Li, J.J., 2003, Uplift-driven climate change at 12 Ma: A long delta O^{18} record from the NE margin of the Tibetan Plateau: Earth and Planetary Science Letters, v. 214, p. 267–277.

Duncan, C., Masek, J., and Fielding, E., 2003, How steep are the Himalaya? Characteristics and implications of along-strike topographic variations: Geology, v. 31, p. 75–78.

Gabet, E., Pratt-Sitaula, B., and Burbank, D.W., 2004, Climatic controls on hillslope angle and relief in the Himalayas: Geology, v. 32, p. 629–632.

Gansser, A., 1983, Geology of the Bhutan Himalaya: Stuttgart, Birkhäuser Verlag, 181 p.

Grujic, D., Hollister, L., and Parrish, R., 2002, Himalayan metamorphic sequence as an orogenic channel: Insight from Bhutan: Earth and Planetary Science Letters, v. 198, p. 177–191.

Hodges, K.V., 2000, Tectonics of the Himalaya and southern Tibet from two perspectives: Geological Society of America Bulletin, v. 112, p. 324–350.

Johnson, S.Y., and Nur Alam, A., 1991, Sedimentation and tectonics of the Sylhet Trough, Bangladesh: Geological Society of America Bulletin, v. 103, p. 1513–1527.

Molnar, P., 2003, Nature, nurture and landscape: Nature, v. 426, p. 612–614.

Sobel, E.R., and Strecker, M.R., 2003, Uplift, exhumation and precipitation: Tectonic and climatic control of Late Cenozoic landscape evolution in the northern Sierras Pampeanas, Argentina: Basin Research, v. 15, p. 431–451, doi: 10.1046/j.1365-2117.2003.00214.x.

Sorkhabi, R.B., Stump, E., Foland, K.A., and Jain, A.K., 1996, Fission-track and $^{40}Ar/^{39}Ar$ evidence for episodic denudation of the Gangotri granites in the Garhwal Higher Himalaya, India: Tectonophysics, v. 260, p. 187–199.

Thiede, R.C., Bookhagen, B., Arrowsmith, J.R., Sobel, E., and Strecker, M., 2004, Climatic control on rapid exhumation along the Southern Himalayan Front: Earth and Planetary Science Letters, v. 222, p. 791–806.

Uddin, A., and Lundberg, N., 1999, A paleo-Brahmaputra? Subsurface lithofacies analysis of Miocene deltaic sediments in the Himalayan-Bengal system, Bangladesh: Sedimentary Geology, v. 123, p. 239–254.

Uddin, A., and Lundberg, N., 2004, Miocene sedimentation and subsidence during continent-continent collision, Bengal basin, Bangladesh: Sedimentary Geology, v. 164, p. 131–146.

Vannay, J.-C., Grasemann, B., Rahn, M., Frank, W., Carter, A., Baudraz, V., and Cosca, M., 2004, Miocene to Holocene exhumation of metamorphic crustal wedges in the NW Himalaya: Evidence for tectonic extrusion coupled to fluvial erosion: Tectonics, v. 23, p. TC1014, doi: 10.1029/2002TC001429.

Whipple, K.X, and Meade, B.J., 2004, Controls on the strength of coupling among climate, erosion, and deformation in two-sided, frictional orogenic wedges at steady state: Journal of Geophysical Research, v.109, doi: 10.1029/2003JF000019.

Whipple, K.X, and Tucker, G.E., 1999, Dynamics of the stream-power river incision model: Implications for the height limits of mountain ranges, landscape response timescales, and research needs: Journal of Geophysical Research, v. 104, p. 17,661–17,674.

Whipple, K.X, Kirby, E., and Brocklehurst, S.H., 1999, Geomorphic limits to climate-induced increases in topographic relief: Nature, v. 401, p. 39–43.

Willett, S.D., 1999, The effects of erosion on the structure of mountain belts: Journal of Geophysical Research, v. 104, p. 28,957–28,981.

Manuscript received 5 January 2006
Revised manuscript received 25 April 2006
Manuscript accepted 1 May 2006

Printed in USA