

Erosion, Himalayan Geodynamics, and the Geomorphology of Metamorphism

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ABSTRACT

Is erosion important to the structural and petrological evolution of mountain belts? The nature of active metamorphic massifs co-located with deep gorges in the syntaxes at each end of the Himalayan range, together with the magnitude of erosional fluxes that occur in these regions, leads us to concur with suggestions that erosion plays an integral role in collisional dynamics. At multiple scales, erosion exerts an influence on a par with such fundamental phenomena as crustal thickening and extensional collapse. Erosion can mediate the development and distribution of both deformation and metamorphic facies, accommodate crustal convergence, and

locally instigate high-grade metamorphism and melting.

INTRODUCTION

Geologists have long recognized the interplay between erosional unloading and passive isostatic response, but the past two decades have seen a new focus on the role of surface processes in active tectonic environments. Erosion's influence on structural evolution has been examined at a variety of spatial scales (e.g., Pavlis et al., 1997; Norris and Cooper, 1997; Hallet and Molnar, 2001). Thermal modeling yielded the fundamental result that variations in the timing and rate of erosion influence the thermal and hence metamorphic evolution of thickened crust (e.g., England and Thompson, 1984). Geodynamical models now link the mechanical and thermal evolution of orogens to lateral variations in erosion rate and magnitude and show how erosion can exert a strong control on particle paths through an orogen and thus on the surface expression of metamorphic facies (Koons, 1990; Beaumont et al., 1992; Willet

et al., 1993). To further explore interactions between surface and lithospheric processes during orogeny, three-dimensional geodynamic models have been developed to explain particular patterns of crustal deformation and metamorphic exposures (e.g., Koons, 1994; Royden et al., 1997; see below).

The general conclusion is that erosion can be a significant agent in active tectonic systems, particularly at larger spatial scales, and that interpretation of mountain belts past and present requires consideration of erosion (e.g., Hoffman and Grotzinger, 1993). The issue is complex, because, as pointed out by Molnar and England (1990), records of unroofing that have traditionally been viewed as evidence for tectonic activity, such as sedimentation or radiometric cooling ages, could in fact document erosion events driven by climate. Further, it can be argued that tectonics can force a climate response (e.g., Raymo and Ruddiman, 1992), and vice versa. Thus, to get beyond a "chicken and egg" controversy, we need to study specific processes, in specific settings, and look for feedback relationships between erosion and tectonism (e.g., Brozovic, et al., 1997). With their high elevations, great relief, and highly active surface and tectonic processes, the eastern and western syntaxial terminations of the Himalayan chain offer an opportunity to examine questions about the interplay between erosion and tectonics in the context of the India-Asia collision. In this article, we hope to stimulate debate by offering our conclusions and speculations about the role of erosion during collisional orogenesis, from a perspective grounded in the Himalayan syntaxes. In particular, we draw on results obtained from multidisciplinary study of the Nanga Parbat massif in the western syntaxis (Fig. 1), as well as preliminary work that has been done at the Namche Barwa massif in the eastern syntaxis.



Figure 1. View to south of Nanga Parbat and central Nanga Parbat massif. Indus River in foreground passes base of massif in middle distance, more than 7 km below summit of Nanga Parbat itself.

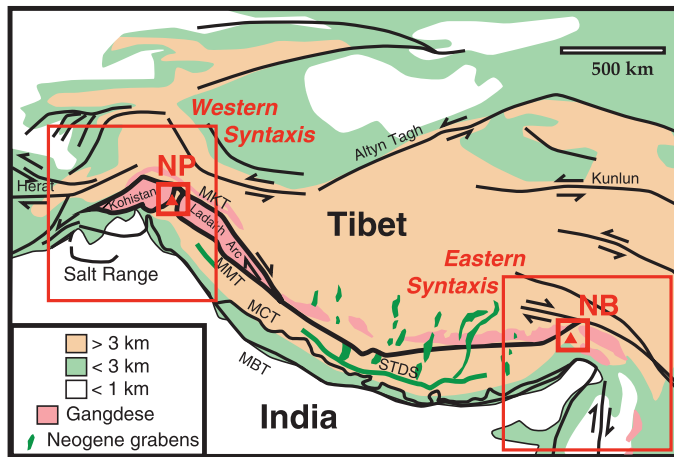


Figure 2. Tectonic sketch map of India-Asia collision (after Harrison et al., 1992). Approximate locations of western and eastern Himalayan syntaxes are shown, as are locations of Nanga Parbat (NP) and Namche Barwa (NB) metamorphic massifs. MKT—Main Karakoram thrust; MMT—Main Mantle thrust; MCT—Main Central thrust; MBT—Main Boundary thrust; STDS—Southern Tibetan detachment system.

CORNERS, SYNTAXES, AND SYNTAXIAL METAMORPHIC MASSIFS

Setting: Himalayan Syntaxes and Indenter Corners

The Himalayan syntaxes compose about one-third of the India-Asia collision zone and encompass a substantial part of the crustal deformation that occurs within the system (Fig. 2). Some of the most active orogenic processes on Earth occur within these syntaxes. For example, a broad zone of active strike-slip deformation throughout a large part of southeast Asia (Royden et al., 1997) is evident in a pronounced topographic grain dominated by the strong convergence and alignment of three of the great Asian rivers (Hallet and Molnar, 2001). Embedded within the syntaxes are unusual, highly active antiformal basement massifs (Nanga Parbat in the west [Fig. 1] and Namche Barwa in the east), where the deep gorges of the Indus and Tsangpo rivers expose, uniquely to our knowledge, ~7000 m of relief, actively deforming metamorphic rocks, and granites as young as Pleistocene (Burg et al., 1997).

The two Himalayan syntaxes are somewhat different in their regional tectonics. The eastern syntaxis spans a well-defined “indenter corner” generated at the eastern edge of the Indian plate (Koons, 1995). Intense deformation should start near the original corner of an indenting plate; through time, this deformation will evolve and propagate (e.g., Tapponnier et al., 1990; Royden et al., 1997; Enlow and Koons, 1998). As the indenter plows material into a two-sided orogen, material at the ends of the orogen slips around the indenter in a wake of strike-slip structures and mountains of diminishing elevation, generating a crustal syntaxis at shallow levels with well-defined structural and topographic trends. In contrast, the tectonics, geomorphic expression, and kinematics of the western Himalayan syntaxis are more diffuse, and regional strain patterns exhibit negligible vorticity (e.g., Bernard et al., 2001). The western syntaxis shows less influence of a lateral plate edge than does the eastern syntaxis, where large compressive and shear strains are clearly localized (Hallet and Molnar, 2001).

Despite significant differences in their tectonics, the eastern and western syntaxes each entrain one of the Himalaya's two major orogen-traversing rivers. Both the Indus in the west and Tsangpo in the east cut cross-strike gorges through the Himalaya as they turn sharply from the Tibetan Plateau to head south into the foreland, establishing extreme local relief, and facilitating efficient removal of detritus. The cutting of these gorges may be recent, perhaps due to river capture within the syntaxes that diverted these rivers within the

past 10 m.y. (e.g., Seeber and Gornitz, 1983; Brookfield, 1998; Royden et al., 2000); thus, the history of these rivers, and the tectonics of the syntaxes, may be closely linked.

Syntaxial Metamorphic Massifs

One additional feature common to the Himalayan syntaxes is an active metamorphic massif developed in basement rocks of the Indian crust.

Nanga Parbat. Structural mapping and cooling-age patterns show the Nanga Parbat massif to be a crustal-scale pop-up structure delineated by active brittle faults and older shear zones into which granitoids were emplaced (Fig. 3A; Schneider et al., 1999a, 1999b; Edwards et al., 2000). Rocks of the massif include Proterozoic metamorphic basement having high radiogenic heat production and Lesser Himalayan affinity (Whittington et al., 1999). Several episodes of Himalayan metamorphism are shown by the presence of an anatectic granite ~18 m.y. old (Schneider et al., 1999b), small granite bodies less than 10 m.y. old scattered across the massif, and metamorphic monazite ages of 13 Ma or less. Very young metamorphism is documented by widespread anatectic granite dikes 1–3 m.y. old confined to its topographically high core (Zeitler and Chamberlain, 1991; Schneider et al., 1999c; Gazis et al., 1998), where low-pressure–high-temperature cordierite–K-feldspar gneisses (Poage et al., 2000) with metamorphic ages of ~3 m.y. are also present (Zeitler et al., 1993). Pervasive upper-crustal fluid flow occurs in the core region, as do steep thermal gradients of 60 °C/km within the top 3 km of the crust (Craw et al., 1994, 1997; Poage et al., 2000).

At or near Nanga Parbat, mapping shows no evidence for significant extensional exhumation having an age less than 15–20 m.y. (Schneider et al., 1999a), and thus this mechanism cannot explain the 15–20 km of unroofing seen within the past 3 m.y. Studies of denudation around the massif (Burbank et al., 1996; Shroder et al., 1999; Shroder and Bishop, 2000) indicate that erosion rates and processes are sufficient to provide the rapid exhumation required by petrologic and other studies. Geomorphic, petrologic, and geochronologic data all suggest that long-term erosion rates have been some 5 mm/yr (Gardner and Jones, 1993; Winslow et al., 1994; Zeitler et al., 1993).

A sharp lower cutoff in microseismicity, bowed upward 3 km beneath the summit region, indicates that the brittle-ductile transition is shallow, at ~2–5 km bsl (Meltzer et al., 1998). This pattern, together with tomographic results showing very low seismic velocities and higher attenuation throughout the crust in the region below the core of the massif (Meltzer et al., 1998; Sarker et al., 1999), is consistent with the thermal consequences of rapid advection at 5 mm/yr. This also suggests that the primary flow path of crust into the massif is from depth rather than along a shallow detachment. Magnetotelluric and seismic data rule out large magma bodies as the cause of the very young high-temperature metamorphism. The magnetotelluric data, surprisingly, show the lower crust to be atypically resistive for an active orogen, indicating the virtual absence or lack of connection of an aqueous fluid phase (Park and Mackie, 2000). These structural, geophysical, and petrological anomalies occur in a bull's-eye pattern around the summit massif and are associated with focused exhumation, concentrated strain, and young igneous activity and metamorphism (Fig. 3A).

At a relatively low elevation of ~1000 m, the Indus River flows directly past the Nanga Parbat massif to its northwest, carving a deep, extensive valley parallel to the active massif-bounding thrust, creating extreme local relief, and efficiently removing detritus from the region. To the north, the Indus cuts across the massif and is generally accepted to be antecedent to it. Brookfield (1998) has argued that the ancestral Indus flowed northwestward from Ladakh to Afghanistan, where it deposited thick sedimentary sections during the interval ca. 30 to 10 Ma before being captured near Nanga Parbat and diverted south along its present course. At about 11 Ma, a change occurred in the Siwalik foreland with deposition of the Nagri Formation (Cervený et al., 1989). This unit contains abundant blue-green hornblende sourced from the Kohistan terrane, which currently abuts the Nanga Parbat massif and is widely assumed to have overlain Nanga Parbat

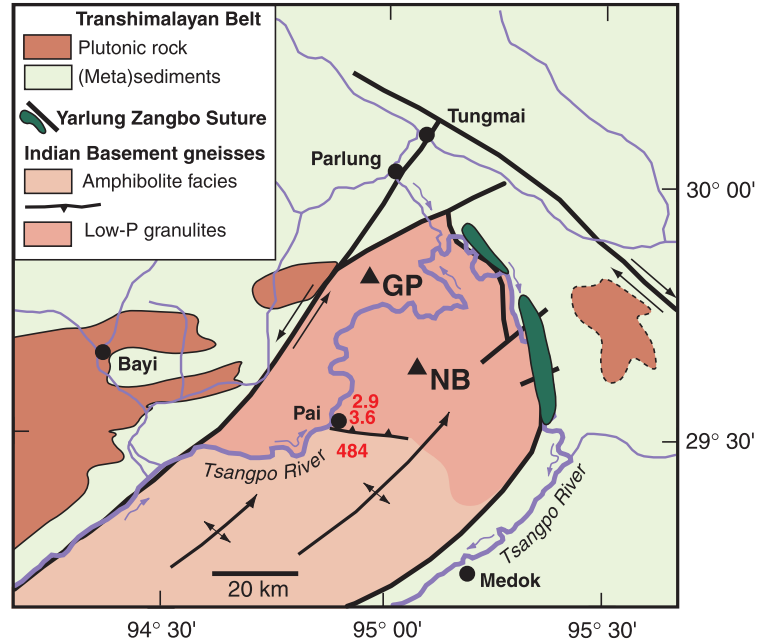
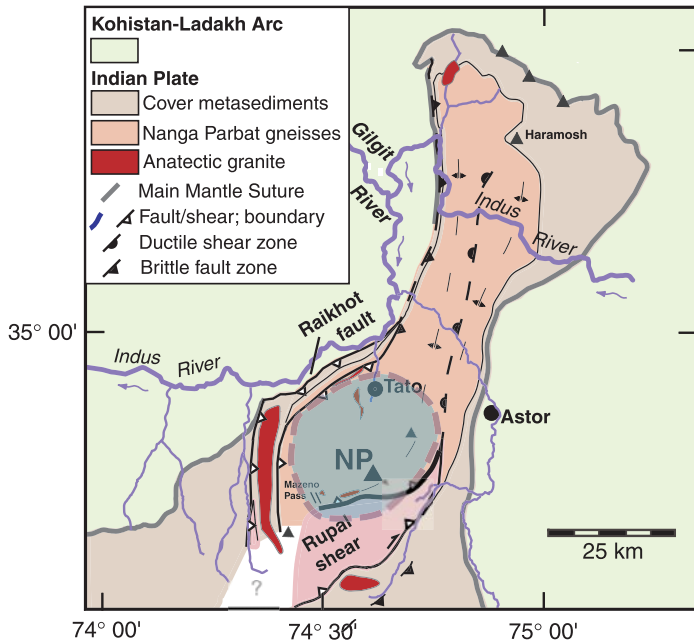


Figure 3. A: Geological sketch map of Nanga Parbat massif (after Schneider et al., 1999a). Colored region in core of massif (enclosed by heavy dashed lines) shows area characterized by young (<3 m.y.) granites, low-P cordierite-bearing granulites, low seismic velocities, resistive lower crust, shallow microearthquakes implying shallow brittle-ductile transition bowed upward by ~3 km, and other anomalies described in text. **B:** Geological sketch map of Namche Barwa metamorphic massif (after Burg et al., 1997; Liu and Zhong, 1997; see Fig. 2 for location). Metamorphic zonation within massif is only approximate; also, metamorphic grade decreases considerably toward southeast. Note remarkable 180° bend made by Tsangpo River, and stream capture that has occurred at apex of this bend. To west of Pai, river's grade is virtually nil, and sediments are accumulating; downcutting begins several kilometers downstream (northeast) of Pai.

before its emergence. In addition, in contrast to lower paleodischarges estimated for older units of the Siwalik molasse, values for the Nagri Formation suggest the arrival of a large Indus-sized river in the foreland at about 11 Ma (Zaleha, 1997a, 1997b).

Namche Barwa. The active Namche Barwa metamorphic massif in the eastern syntaxis shares several features with Nanga Parbat. These include rapid exhumation of an antiformal massif, which exhibits Pleistocene metamorphic and structural overprinting of Proterozoic Indian basement (Fig. 3B; Burg et al., 1997; Liu and Zhong, 1997). Where the Tsangpo River crosses the Namche Barwa antiform, a spectacular knickpoint is developed (Fig. 4), just at a point where local relief becomes greatest, suggesting that high rates of differential rock uplift are likely to occur around Namche Barwa. Just upstream of the knickpoint, considerable sediment is accumulating along some 30 km of the Tsangpo and also the Nyang Qu tributary, and just downstream of the knickpoint, the Tsangpo forms a great falls, dropping some 30 m across a bedrock lip. Regional drainage patterns suggest that an ancestral Tsangpo-Irrawaddy river was captured by the Brahmaputra network due to efficient headward cutting; this was likely caused by the river system's confinement within topography established by the tectonics of the eastern syntaxis (Koons, 1995). Brookfield (1998) suggested that this capture occurred a few million

years ago, on the basis of comparison of stream profiles of the current Tsangpo with those of other major Himalayan rivers.

MODEL: TECTONIC ANEURYSMS

To our knowledge, active metamorphic massifs like Nanga Parbat and Namche Barwa are unique to the Himalayan syntaxes. Even though the tectonics of each syntaxis are quite different, we think that

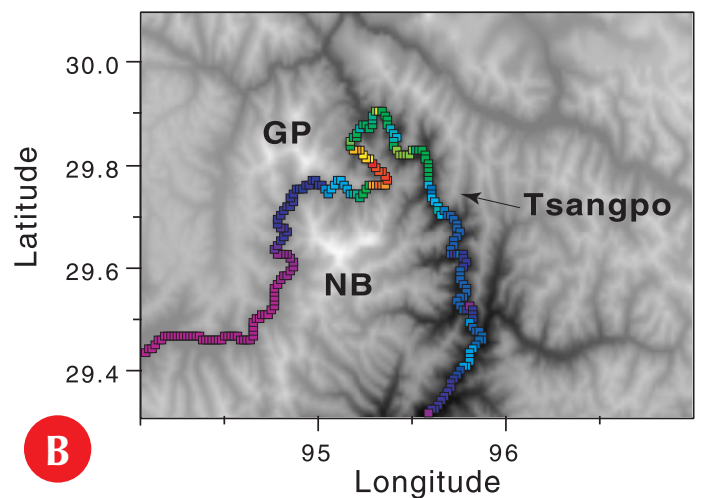
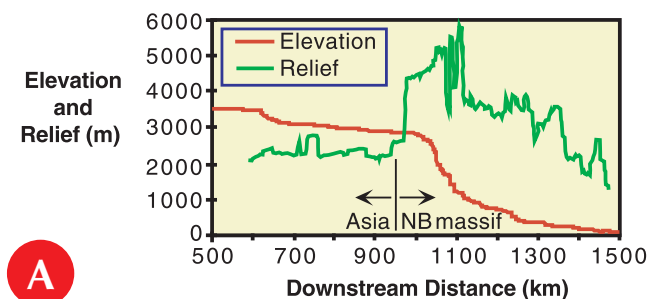


Figure 4. A: Elevation and relief profile along Tsangpo River as it traverses southeastern Tibet, Namche Barwa massif, and Big Bend gorge. Also shown is approximate position of massif's western boundary. Relief (maximum elevation difference within 20 km of river) jumps where river starts to slice its deep gorge through high peaks of easternmost Himalaya. **B:** Variation of river power along length of Tsangpo through Namche Barwa area showing local area of rapid energy expenditure (red) where river makes its steepest descent. Note how Tsangpo flows directly between >7000 m peaks Gyala Peri (GP) and Namche Barwa (NB).

it is no coincidence that the two massifs occur within the syntaxial interiors. Rather, we think they owe their origin to rapid exhumation by great orogen-scale rivers (Indus and Tsangpo) as the rivers turn south and slice across the Himalaya.

On the basis of the observations from Nanga Parbat summarized above, we suggest that local feedbacks between tectonic and surface processes created these massifs: large-magnitude river incision focuses deformation of weak crust, leading to lower crustal flow into the region and creating what amounts to a “tectonic aneurysm” (see below). Alternative models have been proposed that attribute the Nanga Parbat and Namche Barwa antiforms to crustal-scale buckling related to syntaxial tectonics (Treloar et al., 1991; Burg et al., 1997), the major rivers being passively antecedent to these structures. However, such models do not explain the observed very young metamorphism nor the geophysical data from Nanga Parbat which show the massif to be developed atop weak crust that is hot, dry, and thin by overthickened Himalayan standards (Meltzer et al., 1998; Park and Mackie, 2000).

Coupled thermal-mechanical-erosional modeling (Koons, 1998) shows that in a deforming orogen, local rheological variations will arise from deep and rapid incision. The crust will weaken as the strong upper crust is stripped from above by erosion and the local geotherm is steepened from below by rapid uplift of hot rock. If this weakening occurs where the crust is already close to failure, it will focus particle paths such that local movement of material will be concentrated into the weaker zone. Provided that efficient erosion continues, a positive feedback develops in which flow of material into this weakened zone maintains local elevation and relief, reinforcing the concentrated exhumation and bowing up isotherms, further weakening the upper crust (Fig. 5). This focusing of strain and rapid exhumation leads to metamorphic and structural overprinting of the crust as high-temperature lower crustal rocks are isothermally decompressed, and also leads to development of large mountains of limited spatial extent perched atop hot, weak crust. It is this concentration of exhumation and redirection of strain, with associated thermal, petrological, and geophysical anomalies, that we have dubbed a “tectonic aneurysm,” in the sense of self-sustained failure of a normally strong boundary. Inherent in this model is the notion that feedback can amplify rather local geomorphic processes to the point where they can exert profound influence on the metamorphic and structural evolution of rocks at considerable depth.

Applying this model, especially to Nanga Parbat but also to Namche Barwa, our view is that rapid erosion and excavation of a deep gorge by the Indus River focused strain and triggered development of a tectonic aneurysm in high-grade Proterozoic basement that was weakened by early Himalayan thickening and high radioactive heat production. The emplacement of vapor-absent anatectic melts during recent erosional exhumation, development, and exposure of young low-pressure granulites, development of structural relief via antiform growth and thrusting, formation of a vigorous metamorphic-meteoric hydrothermal system, upward advection of isotherms as evidenced by a shallow brittle to ductile transition, and generally hot resistive crust are all consistent with advection of deep crustal material into a relatively weak crustal zone.

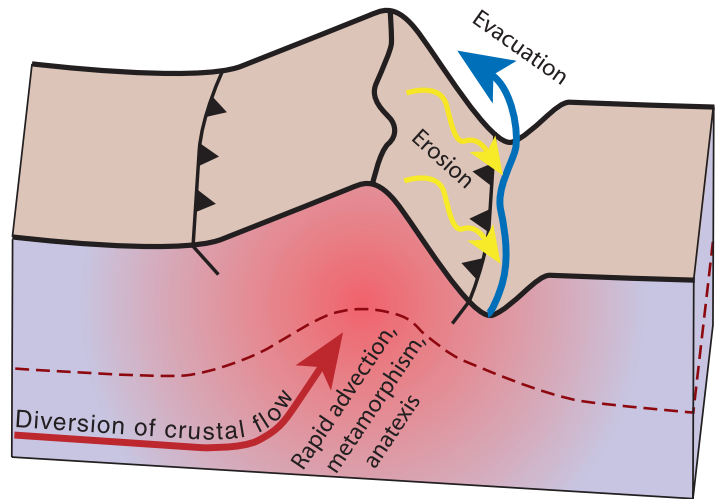


Figure 5. Cartoon illustrating dynamics of a tectonic aneurysm, shown at mature stage. Large river gorge weakens crust, encouraging failure and incising in advective flow toward topographic gap. This builds elevation and, together with incising river, builds relief, leading to rapid erosion rates. Result is steepened thermal gradient, raising of brittle-ductile transition, and further weakening of crust. Deep and mid-crustal material can experience decompression melting and low-*P*-high-*T* metamorphism as it is moved rapidly to the surface.

CONSEQUENCES OF EROSION IN INDENTER CORNERS Regional-Scale Control of Drainage Patterns and Mass Flux

The channeling of the two great Himalayan rivers through the eastern and western syntaxes is likely to be an inevitable consequence of orogenic evolution, because development of a syntaxis will bring focused erosion to bear within it. This will lead to enhanced headward cutting, which can efficiently capture any “outboard rivers” (Koons, 1995) that orogenic topography has compelled to run parallel to the orogen’s north side and off past its terminations. Thus, the localization of the great rivers within the syntaxes is linked to the tectonics of the crustal deformation field.

These are not one-way linkages. A large river provides a way to convey crustal material out of the orogenic system. In southeastern Tibet and in particular in the Three Rivers region directly east of the Himalaya, the rugged landscape traversed by large rivers flowing through deeply incised gorges strongly suggests that the area is undergoing significant erosion. Under these conditions, motion of the thickened Tibetan crust to the side of the Indian indenter could diminish eastward due to surficial mass removal in the Three Rivers region, a process that could be sustained indefinitely if rock uplift is balanced by erosion. Quite a modest erosion rate of only 0.2 mm/yr could account for a significant component of the eastward mass flux from Tibet (~10%), and 2 mm/yr would allow all easterly crustal advection to be consumed by erosion; erosion rates of this magnitude almost certainly pertain to high-relief regions like the hinterland of the active eastern syntaxis. Clearly, quantitative assessment of these erosional fluxes will be required before we understand the relative importance of erosion versus “tectonic escape” as mechanisms to accommodate mass removal in the India-Asia collision.

Local-Scale Dynamics of the Namche Barwa Knickpoint

Although modest in spatial extent, the Namche Barwa knickpoint may play a key role in controlling the geodynamic evolution of some 200 000 km² of the southern and southeastern Tibetan Plateau. The knickpoint currently maintains the upper Tsangpo River at a high base level of more than 3000 m (Figs. 4, 6), and by reducing available relief thus limits the degree to which southeastern Tibet can be exhumed.

The key issue that arises is whether the Namche Barwa knickpoint exists in a state of dynamic equilibrium between rapid uplift of its host massif and rapid incision by the Tsangpo, or whether the co-

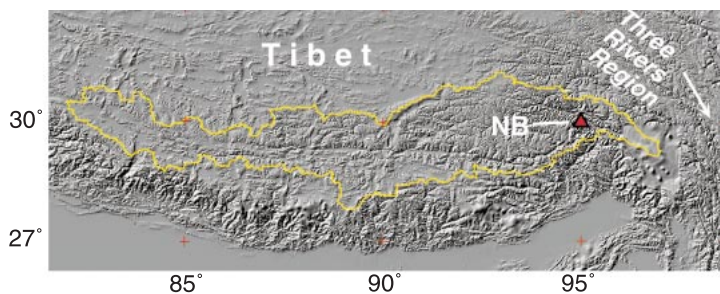
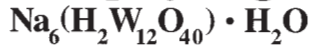


Figure 6. Topography of southeastern Tibet, showing extensive drainage basin (yellow line) of Yarlung-Tsangpo River above Namche Barwa knickpoint. NB—Namche Barwa massif.

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location of the knickpoint and massif is a coincidence. The Tsangpo knickpoint is remarkable for being the largest among the major knickpoints on Himalayan rivers (Brookfield, 1998), for its location on an active antiformal structure, for the significant deposition occurring immediately upstream of it, and for having peak erosion indices unsurpassed in the Himalayas, except for a few reaches of the Arun River. Simple two-dimensional models of fluvial bedrock incision show that the knickpoint would migrate upstream rapidly in the absence of rock uplift. This migration would uncover a swath of relatively shallow rocks; this is not consistent with the observed exposure at Namche Barwa of young metamorphic rocks originating from considerable depth. Knickpoint migration can be essentially halted, however, by offsetting the erosion with the uplift that would be predicted near the Namche Barwa antiform by our aneurysm model, in which local rock uplift and deep-gorge excavation are linked. In any case, the knickpoint would have to have been sustained and essentially stationary to erode the perhaps 15–20 km of crust that reconnaissance petrological and geochronological data (Burg et al., 1997) suggest has locally been removed at Namche Barwa in only the past 3–4 m.y.

The nature of the Namche Barwa knickpoint has broader ramifications, because development of an erosionally mediated metamorphic massif requires rapid cutting of a deep and extensive gorge, something that might be possible only in regions such as syntaxes offering the potential for focused erosion and capture of large rivers. This would suggest multiple links between surface and crustal geodynamics at two scales: at orogen scale, to explain the localization of the great Tsangpo gorge within the eastern syntaxis; locally, to explain the thermal-erosional weakening, extreme relief, and long-

sustained knickpoint at Namche Barwa; and again at orogen scale, as the dynamic knickpoint at Namche Barwa serves as a throttle on the exhumation of southeastern Tibet. If all this is true, then the geomorphic, structural, and metamorphic evolution of southeastern Tibet and the interior of the eastern syntaxis are all genetically related. If, on the other hand, the Namche Barwa knickpoint is merely migrating passively, then within a fairly short time the topography of the southeastern Tibetan Plateau would be doomed to deep and extensive dissection, removing the topographic buttress behind the eastern Himalaya with attendant alterations to the geodynamics of this part of the range.

SUMMARY

In the hinterland of orogens, direct records of erosion are cryptic and fleeting. Earth scientists have only recently begun to develop the insight, analytical methods, and modeling techniques required to assess the diverse ramifications of synorogenic erosion and to design field studies to determine its significance in collisional orogenesis. We acknowledge that we have probably raised more questions than we have answered, but we remain convinced that surface processes are of first-order importance in geodynamics, and that it does make sense to talk about the geomorphology of metamorphism as a new discipline at the interface between traditionally distant fields.

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In order to broaden our discourse in 2001, I'm sharing this column with GSA officers and Council members over the next 12 months. I look forward to reading what is sure to be an interesting and diverse series and hope you find it valuable.

—Sara Foland, CEO

DIALOGUE



Charting GSA's Course at the Start of the 21st Century

Sharon Mosher, President of GSA

In the next few years, GSA will face many decisions about its future course. These opportunities for change will challenge our vision of our role as a Society and as individual geoscientists and will influence the way we conduct and disseminate our science. Following is an outline of some of these challenges and a brief look at the direction GSA is taking. Future articles will explore GSA's response to the challenges ahead.

Our science has become increasingly interdisciplinary. How can we as a Society facilitate the interaction of diverse scientists, support new fields of research, and disseminate research results? Our upcoming Earth System Processes meeting (June 24–28, Edinburgh, Scotland, cosponsored with the Geological Society of London) will bring diverse scientists together to explore links between earth systems and changes in those links with time. Future global meetings will focus on different topics, but each should bring together scientists with different disciplinary perspectives. Our modification of the GSA annual meeting program structure has encouraged significantly more interdisciplinary sessions as demonstrated by the 1999 and 2000 technical programs, and we are planning future joint meetings with nongeoscience societies in related disciplines. A group of members met recently to organize a new division for geobiology and geomicrobiology. Perhaps we also can open membership to nongeoscientists, publish new journals, or cosponsor more conferences and meetings.

Decisions regarding publications may represent our most significant challenge, but also present one of our greatest opportunities. Rather than have our decisions be driven by constantly changing technology and the marketplace, we must decide how to best use new technology to optimize publication of information geoscientists require, to ensure the continued use of our past literature, and to increase interactive access to all geoscience journals.

How do we meet the broader mission of GSA? We have the potential to make an impact or to continue to let the geosciences be nearly invisible in the public arena. What role should we play? Education, used in the broadest sense, is the key to most of these goals. We need to use GSA's strengths in effective ways to educate ourselves through initiatives in the area of professional development and for students, K–16 educators, the public through outreach initiatives, and public policy makers.

Lastly, all of these challenges should not be addressed in a vacuum. Our voice and impact is muted because we are splintered into a multitude of geoscience societies; we waste our resources, both in terms of people and finances, by trying to address similar problems and goals independently. GSA is committed to increased collaboration and coordination of efforts within the geosciences and is actively pursuing stronger working relationships with our associated societies, geological societies from other countries, and other member societies, including the American Geophysical Union and the American Association of Petroleum Geologists.

The decisions that will shape GSA's future are in our hands. It is through our collective efforts as members that GSA's course at the start of the 21st century will be charted. GSA is able to take the initiative because we are financially sound and have a dedicated headquarters staff, but the input from members, guidance of committees, and the leadership of officers are required for us to meet the challenges ahead. Participate, volunteer, contribute suggestions—think about what we want GSA to do and be in the future. This is our Society. What will we accomplish in the next 112 years of our history?

The mission of the Geological Society of America is to advance the geosciences, to enhance the professional growth of its members, and to promote the geosciences in the service of humankind.