# Brahmaputra sediment flux dominated by highly localized rapid erosion from the easternmost Himalaya

R.J. Stewart[1], B. Hallet*[1], P.K. Zeitler[2], M.A. Malloy[2], C.M. Allen[3], D. Trippett[4]
[1]Quaternary Research Center and Department of Earth and Space Sciences, University of Washington, Seattle, Washington 98195, USA
[2]Department of Earth and Environmental Sciences, Lehigh University, Bethlehem, Pennsylvania 18015, USA
[3]Research School of Earth Sciences, Australian National University, Canberra, 0200 ACT, Australia
[4]Quaternary Research Center, University of Washington, Seattle, Washington 98195, USA

## ABSTRACT

**The Brahmaputra River slices an exceptionally deep canyon through the eastern Himalaya. Fission-track and laser-ablation U-Pb ages of detrital zircon grains from the river document very rapid erosion from this region and its impact on sediment fluxes downstream in the Brahmaputra. Downstream from the canyon, 47% of the detrital zircons in the river's modern sediment load comprise a fission-track age population averaging only 0.6 Ma. Equally young cooling ages are reported from bedrock in the canyon through the Namche Barwa–Gyala Peri massif but are absent from riverbank sands of major tributaries upstream. Simple mixing models of U-Pb ages on detrital zircons from samples taken above and below this massif independently suggest that 45% of the downstream detrital zircons are derived from the basement gneisses extensively exposed in the massif. Constraints on the extent of the source area provided by bedrock cooling ages together with sediment-flux estimates at Pasighat, India, suggest exhumation rates averaging 7–21 mm yr$^{-1}$ in an area of ~3300 km$^2$ centered on the massif. This rapid exhumation, which is consistent with the very young cooling ages of the detrital zircons from this area, produces so much sediment that ~50% of the vast accumulation in the Brahmaputra system at the front of the Himalaya comes from only ~2% of its drainage. This extreme localization of rapid erosion, sediment evacuation, and bedrock cooling bear on (1) common assumptions in geodynamic and geochemical studies of the Himalaya about sources of sediment, and (2) plans for hydroelectric development and flood management in southeastern Tibet and the heavily populated areas of eastern India.**

**Keywords:** Himalaya, Yarlung-Tsangpo River, Siang River, Brahmaputra River, fission-track dating, U-Pb ICP-MS dating, detrital-mineral thermochronology.

## INTRODUCTION

We report fission-track and U-Pb ages of detrital zircon grains in sediments of the Brahmaputra River that reflect both the areal extent and the tempo of erosion for an erosional "hot spot" in this drainage basin, which is among the top three sediment producers on the planet (Summerfield and Hulton, 1994). Herein, we use "Brahmaputra" to refer liberally to the main stem of this large river system where it traverses the easternmost Himalaya. We focus on the "Big Bend" region, where the river changes direction 180° after running east for 1300 km in southern Tibet. Here, it cuts one of the world's deepest canyons (>5000 m) between the peaks of Namche Barwa (7782 m) and Gyala Peri (7151 m) (Fig. 1; Fig. DR1 in the GSA Data Repository[1]) and plummets 2000 m over a spectacular knickpoint while crossing an active antiform developing in Proterozoic rocks that were deformed and metamorphosed in the Pleistocene (Burg et al., 1997, 1998; Ding et al., 2001; Zeitler et al., 2001) (Fig. 1). The antiform has been exhuming at rates of 3–5 mm yr$^{-1}$ over the past 5–10 m.y. as shown by petrological data and U-Pb dating of accessory phases (Booth et al., 2004, 2008), and even higher rates up to ~10 mm yr$^{-1}$ have been estimated for more recent intervals (Burg et al., 1997, 1998). Together with the ubiquity of steep slopes, landsliding (Bunn et al., 2004), and high relief (Finnegan et al., 2008), this long history of rapid erosion suggests that sufficient fluvial incision has occurred to bring most portions of the canyon landscape close to steady state, with long-term erosion everywhere occurring at the same rate. This simplifies our interpretation because detrital zircons are likely to originate from throughout the landscape, and their age distribution will not be significantly impacted by erosional transients.

## METHODS

We separated zircon grains from fluvial sands collected from the banks of the Brahmaputra and its tributaries at seven sites upstream from the canyon, and at Pasighat, India (sample 301; Fig. DR1; Table DR1), 180 km downstream from the canyon, where the Brahmaputra emerges from the Himalayan foothills on its way to the Bay of Bengal (Fig. DR1). The Pasighat site is of particular interest because the sediment flux has been measured there, and we will examine the corresponding erosion rates in the source area.

Details of the samples collected, the methods and standard assumptions used, and the data reported in this paper are given in the GSA Data Repository. For fission-track dating, data for 296 grains (Fig. 2; Table DR1; GSA Data Repository) were analyzed using the BINOMFIT peak-fitting routine (Ehlers et al., 2005; Stewart and Brandon, 2004) which searches for the best-fit set of significant components in the grain-age distribution. U-Pb analyses of 312 detrital zircons from samples 301 (downstream of the canyon, at Pasighat) and 302 (upstream, near Pai) were conducted at the Research School of Earth Sciences, Australian National University, using laser-ablation ICP-MS (Tables DR2, DR4a and DR4b).

[1]GSA Data Repository item 2008179, detrital zircons from the easternmost Himalaya, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

*E-mail: hallet@u.washington.edu.

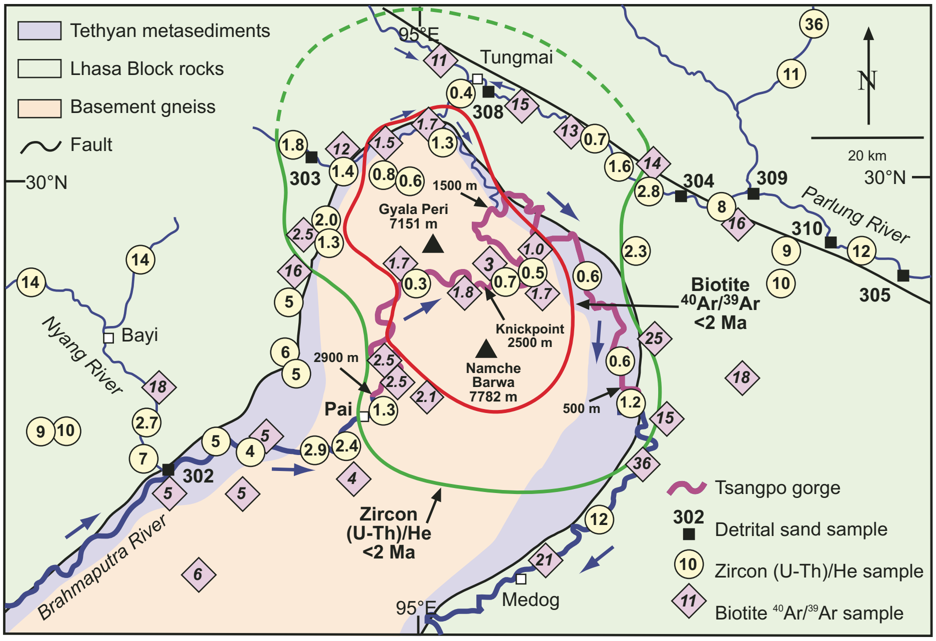


**Figure 1. Geologic sketch map of Namche Barwa–Gyala Peri massif and the Brahmaputra canyon (Pan et al., 2004, with modifications courtesy of W.S.F. Kidd). Black squares are locations of detrital sand samples. Circles represent bedrock zircon (U-Th)/He cooling ages; diamonds represent bedrock $^{40}Ar/^{39}Ar$ biotite cooling ages (Malloy, 2004). Green line is contour for zircon (U-Th)/He ages younger than 2 Ma, and red line is contour for $^{40}Ar/^{39}Ar$ biotite ages younger than 2 Ma.**

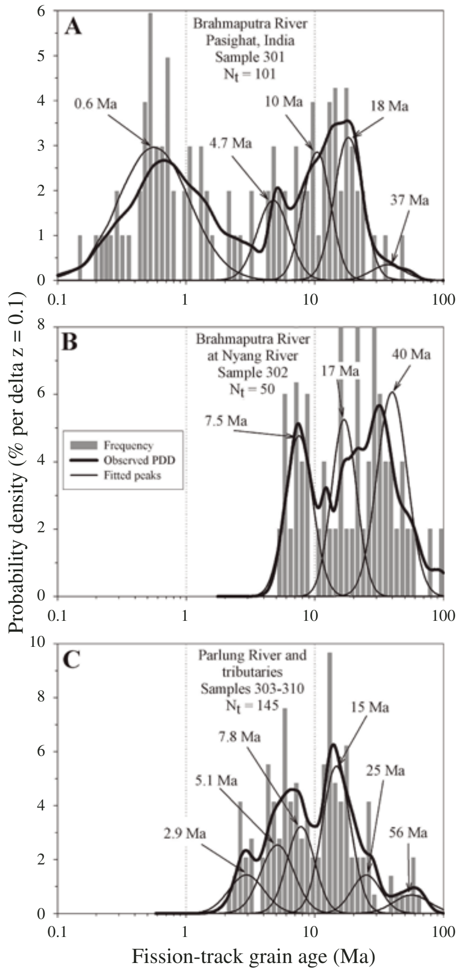


**Figure 2. Grain frequencies, probability density distributions (PDD), and best-fit peaks (Ehlers et al., 2005) for detrital zircon fission-track grain-age distributions for three river-bank samples. A: From the Brahmaputra at Pasighat, India, well downstream of the canyon (Fig. DR1). B: From the Brahmaputra upstream of the canyon, at the confluence with the Nyang River (Fig. 1). C: Composite of samples 303, 304, 305, 308, 309, and 310, from the Parlung River and its tributaries before it enters Brahmaputra canyon (Fig. 1).**

## RESULTS FROM DETRITAL ZIRCON FISSION-TRACK DATING

The fission-track grain-age distribution of 101 zircon crystals from the composite Pasighat sample (Fig. DR1) contains five components with "peaks" at 0.6 ± 0.1, 4.7 ± 1, 10 ± 2, 18 ± 3, and 37 ± 15 Ma (Tables DR1and DR3; Fig. 2A). The 0.6 Ma peak consists of 48 individual grain ages ranging between 0.1 and ca. 2.2 Ma, and it is robust, remarkably young, and large, as it comprises 47% of the total population. For comparison, the 0.6 Ma zircon population at Pasighat is three times younger than the youngest coherent population of zircons in comparable samples from the Indus River, which drains a similar area of fast cooling and denudation in the western syntaxis of the Himalaya (Cerveny et al., 1988).

In sharp contrast, zircon grains with such young fission-track ages are entirely absent from the major rivers entering the canyon. The grain-age distribution for 50 zircon crystals from a sample collected along the Brahmaputra ~40 km upstream of the canyon (Fig. 1) contains peaks at 7.5, 17, and 40 Ma (Fig. 2B; Tables DR1 and DR3). The youngest single grain in this distribution is 5.7 Ma. Similarly, the youngest grain-age population in samples entering the Brahmaputra via the Parlung River and its tributaries from the north (Fig. 1) is 2.9 Ma, with older peaks at 5.1, 7.8, 15, 25, and 56 Ma (Fig. 2C; Tables DR1 and DR3). The youngest grain in this population is 2.2 Ma. The absence of young grains entering the canyon, coupled with the absence of major tributaries to the Brahmaputra between the canyon and Pasighat, suggests that the canyon region through the Namche Barwa–Gyala Peri massif is the source of the very young grains observed at Pasighat (Fig. DR1). The fraction of grains in the 0.6 Ma peak at Pasighat also suggests that ~50% of the suspended sediment in the Brahmaputra downstream of the canyon is derived from source areas having similarly young bedrock zircon fission-track ages. This result is valid, making the reasonable assumption (see GSA Data Repository) that the gneisses and granitoids that dominate the geology of the eastern Himalaya and southern Tibet have broadly similar zircon concentrations overall.

## RESULTS FROM DETRITAL ZIRCON U-Pb DATING

As an independent determination of sediment provenance, we measured U-Pb laser-ablation ICP-MS ages on zircons obtained from sand samples collected at Pasighat (downstream) and near Pai (upstream) (Tables DR2, DR4a and DR4b). Rocks of the Namche Barwa–Gyala Peri massif are distinct because they are almost entirely composed of basement gneisses with zircon crystallization ages older than ca. 450 Ma; very young granites are volumetrically insignificant (Burg et al., 1997; Booth et al., 2004, 2008). In contrast, the watersheds upstream from the Brahmaputra canyon include substantial volumes of Mesozoic and younger granitoids of the Gangdese arc, in addition to older Lhasa Block basement, mostly Precambrian in age with a few Permian plutons (Ding et al., 2001; Booth et al., 2004) (Table DR2). Passage through the canyon in the Brahmaputra River should substantially increase the fraction of old "basement" zircons relative to younger "Gangdese" zircons, the increase being proportional to the mass flux derived from the canyon. Based on the ages of mapped units and bedrock U-Pb data from the Lhasa Block and Namche Barwa (Booth et al., 2004, 2008), a useful criterion for assessing provenance is whether a grain exceeds 300 Ma U-Pb age, as there are no known ages younger than 300 Ma from Namche Barwa other than the ages younger than 10 Ma reported for the volumetrically insignificant anatectic material (Zeitler et al., 2006). U-Pb analyses (Tables DR2, DR4a and DR4b) demonstrate that ~55% of the detrital zircons in the river sands upstream from the Tsangpo canyon are younger than 300 Ma, but only 30% of the grains in the Brahmaputra samples at Pasighat are younger than 300 Ma.

The U-Pb data from Pasighat reflect substantial dilution with older material derived from erosion in the canyon. Treating the data as a two-component weighted average, and assuming that passage through the canyon only adds >300 Ma material, our U-Pb analyses suggest that 45% of the Brahmaputra sand sampled at Pasighat, India (Fig. DR1), is derived from the old basement gneisses exposed largely in the Brahmaputra canyon.

This result is remarkably similar to the estimate of 47% derived from our fission-track data. Averaging the two data sets yields an estimate that 46% of the sediment flux of the Brahmaputra River is derived from the canyon area. Note that although both our fission-track and U-Pb data sets utilized the same zircon separates and are thus subject to any sampling bias inherent in using zircon as a tracer, different grains were used for these analyses. Thus our similar relative-flux estimates are based on essentially independent chronological tracers: near-surface cooling ages and metamorphic/crystallization ages.

## EXHUMATION RATES IN THE NAMCHE BARWA–GYALA PERI AREA

Bedrock geochronological data from around the Namche Barwa–Gyala Peri massif and the Brahmaputra canyon support our conclusion that this region is the source for the very young fission-track zircon ages in river sands from Pasighat. Fission-track dates are as young as 0.2 Ma for zircon and 0.5 Ma for apatite (Burg et al., 1997, 1998; Seward and Burg, 2008). $^{40}Ar/^{39}Ar$ cooling ages from biotite range between only 0.9 and 2.5 Ma within the structural boundaries of the massif, and (U-Th)/He cooling ages from zircon range between 0.3 Ma and 1.0 Ma within the massif, although ages younger than ca. 3.0 Ma extend into some areas outside the massif before increasing rapidly (Malloy, 2004) (Fig. 1). Finally, U-Pb and petrological data (Booth et al., 2004, 2008) document that Indian basement within the massif has been rapidly decompressed and unroofed at rates of 3 mm yr$^{-1}$ or more over at least the past several million years.

Knowing the approximate area of the young-zircon source region, we can place limits on mean modern exhumation rate using our finding that nearly half of the measured sediment flux in the Brahmaputra at Pasighat, India, derives from this area. Based on limited direct measurements of suspended sediments in the Brahmaputra at Pasighat, Goswami (1985; 2006, personal commun.) estimates the annual flux to be 210 Mt, recognizing that this flux is difficult to measure and highly variable. This estimate gains support from the more extensive measurements of sediment flux farther downstream together with geochemical studies; they suggest a flux of 233 Mt (GSA Data Repository). Converting 46% of the smaller annual sediment load (210 Mt, to be conservative) to a bedrock volume, using a bedrock density of 2850 kg m$^{-3}$, gives an annual eroded-rock volume of $3.4 \times 10^7$ m$^3$.

Next, using the bedrock cooling data we constrain the size of the area producing zircons having cooling ages younger than ca. 2 Ma. For fast cooling (100 °C m.y.$^{-1}$), the closure temperature for zircon fission tracks (~250 °C; Rahn et al., 2004) lies between that of helium in zircon (~200 °C; Reiners et al., 2004) and that for argon in biotite $^{40}Ar/^{39}Ar$ dating (~350 °C; McDougall and Harrison, 1999). Thus, it follows that the probable source region for our detrital zircons having fission-track ages younger than ca. 2 Ma has an area between ~1600 ± 400 and 5030 ± 1000 km$^2$, as determined by the distribution of young He-zircon and Ar-biotite ages in bedrock (Fig. 1). Given the systematic and geologic uncertainties associated with closure temperatures, we take the simple average of 3300 ± 550 km$^2$ as the best estimate for the area of exposed zircons having fission-track ages younger than 2 Ma, with the principal source of uncertainty occurring in the region to the WNW of Tungmai where there are few bedrock cooling ages (Fig. 1).

Distributing the $3.4 \times 10^7$ m$^3$ volume of annually eroded bedrock over the 3300 km$^2$ source area gives an estimate for the modern-day aerially averaged exhumation rate of ~10 mm yr$^{-1}$. (Using the alternative values for area of the source region discussed above, the range would be 7–21 mm yr$^{-1}$.) This estimate is conservative because (1) fluvial sediments may derive from only a fraction of this 3300 km$^2$ source area, such as the Tsangpo canyon itself, and erosion rates would increase by the inverse of that fraction, and (2) the measured sediment-flux values reported above do not include the bedload and dissolved loads, and the former could approach the suspended-sediment flux (Galy and France-Lanord, 2001).

Using the modal age of ca. 0.6 Ma observed for 47% of our detrital zircons, we can also estimate a rough longer-term exhumation rate for their source region, taking advantage of the spatial averaging these detrital grains provide. Caution is required in interpreting the results from this approach because the thermal structure in and around Namche Barwa is likely to be complex, and perhaps transient at localities bordering the massif, and this could lead to underdetermined and thus inaccurate thermal models (Parrish, 1983; Mancktelow and Grasemann, 1997). Taking 250 °C as the closure temperature for fission tracks in zircon and using the upper-crustal thermal gradients of 50–100 °C km$^{-1}$ determined for the region from fluid inclusions (Craw et al., 2005) yields exhumation rates of 4–8 mm yr$^{-1}$ integrated over the past 0.6 m.y. This is comparable to our estimate for modern rates of ~10 mm yr$^{-1}$ as well as the estimates for longer-term rates of ~3–5 mm yr$^{-1}$ and up to 10 mm yr$^{-1}$ discussed above. We do note that both our modern-day estimates and bedrock estimates for the past 0.6 m.y. are a bit higher than the long-term values and those predicted by simple steady-state thermal models (Reiners and Brandon, 2006), but whether this difference is a real one reflecting variations in rate and integration time, or uncertainties in thermal structure, is an intriguing question beyond the scope of this paper but worthy of further study.

## CONCLUSIONS

Our results establish a clear and direct connection between a large fraction of the Brahmaputra River's sediment and its source in a very small portion of the drainage basin. They highlight very large spatial variations in erosion rates and fluvial evacuation of crustal material from an active orogen, and strengthen earlier evidence for rapid exhumation in the eastern syntaxis. Published mineralogical and geochemical data suggest that the eastern syntaxis contributes fully 50% of the total sediment flux of the Brahmaputra and ~20% of the total detritus reaching the Bay of Bengal (Singh and France-Lanord, 2002; Garzanti et al., 2004; Tibari et al., 2005) (Fig. DR1). Our data support these results and permit considerably more precise definition of the source region; they suggest that nearly 50% of the sediment in the Brahmaputra system at the foot of the Himalaya originates from only 2% of the vast basin draining much of the northern side of the Himalaya and southern Tibet (260,000 km$^2$). Our results are particularly significant given that the sediment flux in the Brahmaputra is one of the highest on the planet (Summerfield and Hulton, 1994). Despite a significantly smaller catchment area, the Brahmaputra transports much more sediment than the adjacent Ganga and Indus Rivers (Fig. DR1) and is surpassed only by the Yellow and Amazon Rivers.

Extreme localization of rapid erosion is expected to have significant impact on crustal deformation, active tectonics, and landscape evolution (Zeitler et al., 2001; Beaumont et al., 2001; Koons et al., 2002). Our results, which show that nearly half of the sediment in the Brahmaputra derives from a miniscule, unrepresentative area composed only of Indian plate lithologies, suggest that caution is in order when developing tectonic interpretations founded on geochemical, mineralogical, and thermochronological characteristics of sediments from orogens. This caution is especially warranted as our results differ from those of other major rivers, including the Indus, that do not reflect prominent sediment inputs from areas of exceptionally fast erosion (Clift et al., 2004). Moreover, documentation of the source and evolution of the Brahmaputra River's prodigious sediment load has considerable practical relevance to hydrological management of this river system and the heavily populated regions downstream.

**ACKNOWLEDGMENTS**

This is a posthumous article; sadly, Richard Stewart passed away after carrying out this work. This research was supported by the National Science Foundation Continental Dynamics Program (EAR-0003561, EAR-0003462). It benefited substantially from samples of river sands collected by N. Finnegan and D. Montgomery; discussions with J.-P. Burg, P. Davy, N. Finnegan, B. Higman, P. Koons, and D. Montgomery; detailed reviews of earlier versions of this paper by D. Burbank, M. Brandon, R.A. Jamieson, C. France-Lanord, and P. Reiners; and previews of unpublished data of D. Seward and J.-P. Burg.

**REFERENCES CITED**

Beaumont, C., Jamieson, R.A., Nguyen, M.H., and Lee, B., 2001, Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation: Nature, v. 414, p. 738–742, doi: 10.1038/414738a.

Booth, A.L., Zeitler, P.K., Kidd, W.S.F., Wooden, J., Liu, Y., Idleman, B., Hren, M., and Chamberlain, C.P., 2004, U-Pb zircon constraints on the tectonic evolution of southeastern Tibet, Namche Barwa area: American Journal of Science, v. 304, p. 889–929, doi: 10.2475/ajs.304.10.889.

Booth, A.L., Chamberlain, C.P., Kidd, W.S.F., and Zeitler, P.K., 2008, Metamorphic and geochronologic constraints on the tectonic evolution of the eastern Himalayan syntaxis, Namche Barwa: Geological Society of America Bulletin (in press).

Bunn, J.T., Finnegan, N., and Montgomery, D.R., 2004, Landsliding and stream power in the vicinity of the Tsangpo Gorge at Namche Barwa, eastern Tibet: Geological Society of America Abstracts with Programs, v. 36, no. 4, p. 33.

Burg, J.-P., Davy, P., Nievergelt, P., Oberli, F., Seward, D., Diao, Z., and Meier, M., 1997, Exhumation during folding in the Namche-Barwa syntaxis: Terra Nova, v. 9, p. 53–56, doi: 10.1111/j.1365-3121.1997.tb00001.x.

Burg, J.-P., Nievergelt, P., Oberli, F., Seward, D., Davy, P., Mauring, J.-C., Diao, Z., and Meier, M., 1998, The Namche Barwa syntaxis: Evidence for exhumation related to compressional crustal folding: Journal of Asian Earth Sciences, v. 16, p. 239–252.

Cerveny, P.F., Naeser, N.D., Zeitler, P.K., Naeser, C.W., and Johnson, N.M., 1988, History of uplift and relief of the Himalaya during the past 18 million years: Evidence from fission-track ages of detrital zircons from sandstones of the Siwalik Group, *in* Kleinspehn, K.L., and Paola, C., eds., New perspectives in basin analysis: New York, Springer-Verlag, p. 43–61.

Clift, P.D., Campbell, I.H., Pringle, M.S., Carter, A., Zhang, X., Hodges, K.V., Kahn, A.A., and Allen, C.M., 2004, Thermochronology of the modern Indus River bedload: New insight into the controls on the marine stratigraphic record: Tectonics, v. 23, TC5013, doi: 10.1029/2003TC001559.

Craw, D., Koons, P.O., Zeitler, P.K., and Kidd, W.S.F., 2005, Fluid evolution and thermal structure in the rapidly exhuming gneiss complex of Namche Barwa–Gyala Peri, eastern Himalayan syntaxis: Journal of Metamorphic Geology, v. 23, p. 829–845, doi: 10.1111/j.1525-1314.2005.00612.x.

Ding, L., Zhong, D., Yin, A., Kapp, P., and Harrison, T.M., 2001, Cenozoic structural and metamorphic evolution of the eastern Himalayan syntaxis (Namche Barwa): Earth and Planetary Science Letters, v. 192, p. 423–438, doi: 10.1016/S0012-821X(01)00463-0.

Ehlers, T.A., Chaudhri, T., Kumar, S., Fuller, C.W., Willett, S.D., Ketcham, R.A., Brandon, M.T., Belton, D.X., Kphn, B.P., Gleadow, A.J.W., Dunia. T.J., and Fu, F.Q., 2005, Computational tools for low-temperature thermochronometer interpretation, *in* Reiners, P.W., and Ehlers, T.A., eds., Low Temperature Thermochronology: Techniques, Interpretations, and Applications: Reviews in Mineralogy and Geochemistry, v. 58, p. 600–622, doi: 10.2138/rmg.2005.58.22.

Finnegan, N.J., Hallet, B., Montgomery, D.R., Zeitler, P.K., Stone, J.O., Anders, A.M., and Liu, Y., 2008, Coupling of rock uplift and river incision in the Namche Barwa–Gyala Peri massif, Tibet, China: Geological Society of America Bulletin, v. 120, p. 142–155, doi: 10.1130/B26224.1.

Galy, A., and France-Lanord, C., 2001, Higher erosion rates in the Himalaya: Geochemical constraints on riverine fluxes: Geology, v. 29, p. 23–26, doi: 10.1130/0091-7613(2001)029 <0023:HERITH>2.0.CO;2.

Garzanti, E., Vezzoli, G., Ando, S., France-Lanord, C., Singh, S.K., and Foster, G., 2004, Sand petrology and focused erosion in collision orogens: The Brahmaputra case: Earth and Planetary Science Letters, v. 220, p. 157–174, doi: 10.1016/S0012-821X(04)00035-4.

Goswami, D.C., 1985, Brahmaputra River, Assam, India: Physiography, basin denudation, and channel aggradation: Water Resources Research, v. 21, p. 959–978, doi: 10.1029/WR021i007p00959.

Koons, P.O., Zeitler, P.K., Chamberlain, C.P., Craw, D., and Meltzer, A.S., 2002, Mechanical links between erosion and metamorphism in Nanga Parbat, Pakistan Himalaya: American Journal of Science, v. 302, p. 749–773, doi: 10.2475/ajs.302.9.749.

Malloy, M., 2004, Rapid erosion at the Tsangpo knickpoint and exhumation of southeastern Tibet [M.S. thesis]: Bethlehem, Pennsylvania, Lehigh University, 67 p.

Mancktelow, N.S., and Grasemann, B., 1997, Time-dependent effects of heat advection and topography on cooling histories during erosion: Tectonophysics, v. 270, p. 167–195, doi: 10.1016/S0040-1951(96)00279-X.

McDougall, I., and Harrison, T.M., 1999, Geochronology and thermochronology by the $^{40}Ar/^{39}Ar$ method: New York, Oxford University Press, 269 p.

Pan, G., Ding, J., Yao, D., and Wang, L., 2004, Geological map of Qinghai-Xizang (Tibet) and adjacent areas: Chengdu Cartographic Publishing House, scale 1:1,500,000, 6 sheets.

Parrish, R.R., 1983, Cenozoic thermal evolution and tectonics of the Coast Mountains of British Columbia, 1: Fission track dating, apparent uplift rates, and patterns of uplift: Tectonics, v. 2, p. 601–631, doi: 10.1029/TC002i006p00601.

Rahn, M.K., Brandon, M.T., Batt, G.E., and Garver, J.I., 2004, A zero-damage model for fission-track annealing in zircon: American Mineralogist, v. 89, p. 473–484.

Reiners, P.W., and Brandon, M.T., 2006, Using thermochronology to understand orogenic erosion: Annual Review of Earth and Planetary Sciences, v. 34, p. 419–466, doi: 10.1146/annurev.earth.34.031405.125202.

Reiners, P.W., Spell, T.L., Nicolescu, S., and Zanetti, K.A., 2004, Zircon (U-Th)/He thermochronometry: He diffusion and comparisons with $^{40}Ar/^{39}Ar$ dating: Geochimica et Cosmochimica Acta, v. 68, p. 1857–1887, doi: 10.1016/j.gca.2003.10.021.

Seward, D., and Burg, J.-P., 2008, Growth of the Namche Barwa Syntaxis and associated evolution of the Tsangpo Gorge: Constraints from structural and thermochronological data: Tectonophysics, v. 451, p. 282–289, doi: 10.1016/j.tecto.2007.11.057.

Singh, S., and France-Lanord, C., 2002, Tracing the distribution of erosion in the Brahmaputra watershed from isotopic compositions of stream sediments: Earth and Planetary Science Letters, v. 252, p. 645–662, doi: 10.1016/S0012-821X(02)00822-1.

Stewart, R.J., and Brandon, M.T., 2004, Detrital-zircon fission-track ages for the "Hoh Formation": Implications for late Cenozoic evolution of the Cascadia subduction wedge: Geological Society of America Bulletin, v. 116, p. 60–75, doi: 10.1130/B22101.1.

Summerfield, M.A., and Hulton, N.J., 1994, Natural controls of fluvial denudation rates in major world drainage basins: Journal of Geophysical Research, v. 99, p. 13,871–13,883, doi: 10.1029/94JB00715.

Tibari, B., Pik, R., France-Lanord, C., Carnigan, J., and Lave, J., 2005, Extreme uplift and erosion rates in eastern Himalayas (Siang-Brahmaputra Basin) revealed by detrital (U-Th)/He thermochronology: Eos (Transactions, American Geophysical Union), v. 85, Fall Meeting Supplement, Abstract T23C–0574.

Zeitler, P.K., Meltzer, A.S., Koons, P.O., Craw, D., Hallet, B., Chamberlain, C.P., Kidd, W.S.F., Park, S.K., Seeber, L., Bishop, M., and Shroder, J., 2001, Erosion, Himalayan geodynamics, and the geomorphology of metamorphism: GSA Today, v. 11, no. 1, p. 4–9, doi: 10.1130/1052-5173(2001)011<0004:EHGATG> 2.0.CO;2.

Zeitler, P.K., Malloy, M.A., Kutney, M.P., Idleman, B.D., Liu, Y., Kidd, W.S., and Booth, A.L., 2006, Geochronological evidence for the tectonic and topographic evolution of SE Tibet: Eos (Transactions, American Geophysical Union), v. 87, Fall Meeting Supplemnet, Abstract T32B–02.

Manuscript received 16 March 2008
Revised manuscript received 15 May 2008
Manuscript accepted 27 May 2008

Printed in USA