Early onset and late acceleration of rapid exhumation in the Namche Barwa syntaxis, eastern Himalaya

Gwladys Govin1†, Peter van der Beek2,3‡, Yani Najman1, Ian Millard4, Lorenzo Gemignani5*, Pascale Huyghe2, Guillaume Dupont-Nivet3,4, Matthias Bernet6, Chris Mark7§ and Jan Wijbrans6

1Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK
2Institut des Sciences de la Terre (ISTerre), Université Grenoble Alpes, 38058 Grenoble, France
3Institute of Geosciences, Potsdam University, 14476 Potsdam, Germany
4NERC Isotope Geosciences Laboratory (NIGL), British Geological Survey, Keyworth NG12 5GG, UK
5Department of Earth Sciences, Vrije Universiteit Amsterdam. 1081 HV, Amsterdam, Netherlands
6Géosciences Rennes, CNRS, Université de Rennes 1, 35042 Rennes, France
7Department of Geography, Trinity College Dublin, Dublin 2, Ireland

ABSTRACT

The Himalayan syntaxes, characterized by extreme rates of rock exhumation co-located with major trans-orogenic rivers, figure prominently in the debate on tectonic versus erosional forcing of exhumation. Both the mechanism and timing of rapid exhumation of the Namche Barwa massif in the eastern syntaxis remain controversial. It has been argued that coupling between crustal rock advection and surface erosion initiated in the late Miocene (8–10 Ma). Recent studies, in contrast, suggest a Quaternary onset of rapid exhumation linked to a purely tectonic mechanism. We report new multisystem detrital thermochronology data from the most proximal Neogene clastic sediments downstream of Namche Barwa and use a thermo-kinematic model constrained by new and published data to explore its exhumation history. Modeling results show that exhumation accelerated to ∼4 km/m.y. at ca. 8 Ma and to ∼9 km/m.y. after ca. 2 Ma. This three-stage history reconciles apparently contradictory evidence for early and late onset of rapid exhumation and suggests efficient coupling between tectonics and erosion since the late Miocene. Quaternary acceleration of exhumation is consistent with river-profile evolution and may be linked to a Quaternary river-capture event.

INTRODUCTION

The Nanga Parbat and Namche Barwa massifs, at the respective western and eastern syntaxial terminations of the Himalaya (Fig. 1), share characteristics that have focused research into the coupling between tectonics and surface processes (Zeitler et al., 2001b; Finnegan et al., 2008; Kurup et al., 2010; Koons et al., 2013; Wang et al., 2014). Both massifs show young (<10 Ma) high-grade metamorphism and partial melting (Burg et al., 1998; Zeitler et al., 2001a, 2014; Booth et al., 2009), extreme relief, and rapid erosion (Burbank et al., 1996; Finnegan et al., 2008), expressed by exceptionally young thermochronologic ages (Stewart et al., 2008; Enkelmann et al., 2011; Braccialli et al., 2016; King et al., 2016). The two largest Himalayan rivers, the Indus and the Yarlung-Tsangpo-Siang-Brahmaputra, show hairpin bends and kilometer-scale steepened knickzones as they cross these massifs (Fig. 1), sparking a debate on potential erosional controls on tectonics (Zeitler et al., 2001b; Finnegan et al., 2008; Seward and Burg, 2008; Wang et al., 2014; King et al., 2016). Several models seek to explain these remarkable features. Purely tectonic mechanisms include range-parallel buckling in the indenter-parallel plate corner (Burg et al., 1998), uplift driven by a geometrically stiffened bend in the subducting plate (Bendick and Ebers, 2014), and orogen-parallel crustal transport arising from velocity and/or strain partitioning (Whipp et al., 2014). In contrast, the tectonic-aneurysm model (Zeitler et al., 2001a, 2001b; Koons et al., 2013) calls for coupling between river incision and rapid exhumation, leading to local crustal weakening and focusing rock pathways into the weakened, rapidly eroding zone. The inflowing material promotes topographic relief growth, localized exhumation, and crustal weakening, creating a positive feedback loop between tectonics and surface processes.

Besides the mechanism, the timing of rapid exhumation is also controversial in the Namche Barwa massif. Early bedrock geochronology and thermochronology studies estimated the onset of rapid exhumation at ca. 4 Ma (Burbank et al., 1998; Seward and Burg, 2008), whereas more recent data (Booth et al., 2009; Zeitler et al., 2014) have suggested 8–10 Ma. Detrital thermochronology studies from the Brahmaputra Valley, the Surma Basin (Bangladesh), and the offshore Bengal Fan have proposed rapid syntaxial exhumation starting at either 4–6 Ma (Najman et al., 2019) or <3 Ma (Chirouze et al., 2013; Braccialli et al., 2016). This inconsistency may arise from downstream modification and dilution of characteristic syntaxial exhumation signals (Braccialli et al., 2016; Gemignani et al., 2018); the most robust signal is therefore expected in proximal sedimentary records. Lang et al. (2016) modeled detrital thermochronology data from the proximal Siji section (Fig. 1) to infer an onset of rapid exhumation in Namche Barwa at 5–7 Ma.

To explore the exhumation history of the Namche Barwa massif in more detail, we present new multisystem detrital thermochronology...
data from Neogene foreland-basin samples collected directly downstream of the syntaxis (Fig. 1) and interpret these using a thermo-kinematic inverse model.

NEW DETRITAL THERMOCRONOLOGY DATA

We collected ten sandstone samples from three sedimentary sections close to the Siang-Brahmaputra confluence (Fig. 1). These sections are described by Govin et al. (2018), who also determined depositional ages ranging from 0.5 ± 0.3 Ma to 10.0 ± 2.0 Ma (see Table S1 in the Supplemental Material). Provenance data indicate that the source region for these deposits included the Namche Barwa massif (Govin et al., 2018). Here we present new zircon fission-track (ZFT), muscovite 40Ar/39Ar (MAR), and rutile U-Pb (RUPb) data. Closure temperatures of these thermochronometers range from ~300 °C (ZFT) to >500 °C (RUPb), depending on grain size, composition, and cooling rate (Reiners et al., 2018; Fig. S5 in the Supplemental Material). Because we target the signal from Namche Barwa, inferred to be the most rapidly exhuming part of the sediments’ source area, we employ the minimum-age approach (Galbraith, 2005) to determine the youngest detrital age populations (see the Supplemental Material for details). Sample preparation and analytical methods are reported in the Supplemental Material; single-grain ages are in Tables S2–S4 and Figures S1–S3. All ages are interpreted as cooling ages, as justified in the Supplemental Material.

A plot of the minimum ages of our samples together with literature data as a function of depositional age (Fig. 2) shows two distinct groups: for all three thermochronometers, samples with depositional ages >7.5 Ma have lag times (Bernet et al., 2001) that are >5 m.y., whereas samples with depositional ages ≤7 Ma show short lag times (~2–3 m.y.). The latter group also shows several age inversions, where the system with lower closure temperature (ZFT) has minimum ages older than those for higher-closure-temperature systems (MAR, RUPb). Such inversions are expected at high exhumation rates in some circumstances (Reiners et al., 2018); alternatively, some of these minimum ages may be unreliable for analytical reasons (i.e., poor counting statistics for grains with low daughter-product abundance; see discussion in the Supplemental Material). We discriminate between (1) “internally consistent” samples, yielding ages ordered with respect to system closure temperatures within a sample and increasing monotonically with depositional age for the same system between samples, and (2) inconsistent samples, which do not meet these criteria.

QUANTIFYING NAMCHE BARWA EXHUMATION

The slope of the lag-time trend indicates whether exhumation rates were steady, increasing, or decreasing through time (Bernet et al., 2001). We used a Bayesian approach (Glotzbach et al., 2011) to fit single- and multi-tier linear regressions to the lag times of internally consistent minimum ages (see the Supplemental Material). The results (Fig. S4) indicate increasing exhumation before ca. 7 Ma, followed by rapid steady exhumation between ca. 7 Ma and 0.5–2.0 Ma, and probable further acceleration since 0.5–2.0 Ma indicated by the youngest two to three samples. However, the onset of rapid exhumation would precede the arrival of young grains in the sedimentary record because of (1) the time required to exhume rocks from the thermochronologic closure depth to the surface, and (2) the time required to re-equilibrate the crustal thermal structure.

To better constrain the exhumation history, we used a one-dimensional version of the thermo-kinematic code Pecube (Braun et al., 2011) to fit single- and multi-tier linear regressions to the lag times of internally consistent minimum ages (see the Supplemental Material). The results (Fig. S4) indicate increasing exhumation before ca. 7 Ma, followed by rapid steady exhumation between ca. 7 Ma and 0.5–2.0 Ma, and probable further acceleration since 0.5–2.0 Ma indicated by the youngest two to three samples. However, the onset of rapid exhumation would precede the arrival of young grains in the sedimentary record because of (1) the time required to exhume rocks from the thermochronologic closure depth to the surface, and (2) the time required to re-equilibrate the crustal thermal structure.
The onset of rapid exhumation at ca. 8 Ma is consistent with the scenario envisaged by Zeitler et al. (2014). The discrepancy between the amount of post–ca. 8 Ma exhumation predicted by our data and that inferred from P-T-t data, for all but our lowest predicted exhumation rates, implies lateral inflow of mid-crustal material, consistent with the tectonic-aneurysm model (Zeitler et al., 2001a, 2001b; Koons et al., 2013). Thus, efficient coupling between crustal rock advection and surface erosion may have initiated at ca. 8 Ma, requiring the existence of a large throughgoing river system at that time. Whereas sedimentary provenance data record a drainage connection between the Yarlung-Tsangpo and the Brahmaputra since the early Miocene (ca. 18 Ma; Lang and Huntington, 2014; Bracciali et al., 2015; Blum et al., 2018), it is unclear when the drainage pathway through the Namche Barwa massif via the Siang was established (Govin et al., 2018).

The trigger for rapid exhumation in Namche Barwa remains debated. It could have been initiated by indenter-corner dynamics (Burg et al., 1998; Bendick and Ehlers, 2014), with coupling between river incision and rapid exhumation developing subsequently, or it could have resulted from capture of the Yarlung-Tsangpo by the Siang shortly before ca. 8 Ma. The latter scenario is consistent with river-incision patterns upstream of Namche Barwa, which have been interpreted to record a wave of incision migrating upstream since ca. 10 Ma (Schmidt et al., 2015). However, that scenario requires prior Yarlung-Tsangpo drainage to the foreland via another, as yet unconstrained, pathway, a prediction that may be tested by provenance analysis of proximal foreland sediment records from candidate fossil trans-orogenic river systems.

Quaternary uplift of the Namche Barwa massif has been inferred from a thick wedge of post–2.6 Ma alluvium preserved immediately upstream (Wang et al., 2014; Fig. 4). This ponded sediment implies that rock uplift temporarily outpaced river incision, steepening the Siang River profile downstream. Quaternary capture of the Parlung River by the Yarlung-Tsangpo-Siang, as suggested by thermochronology (Seward and Burg, 2008; Zeitler et al., 2014) and provenance data (Lang and Huntington, 2014; Govin et al., 2018), would have increased erosional power in the gorge downstream of the capture point. In turn, this may have strengthened the feedback loop and triggered enhanced uplift and exhumation of Namche Barwa. River profiles provide insight into this possibility. The modern Yarlung-Tsangpo-Siang and Indus River profiles differ (Korup et al., 2010; Fig. 4), even though both flow through rapidly exhuming syntectonic massifs (Barbuck et al., 1996; Zeitler et al., 2001b; Finnegan et al., 2008; Korup et al., 2010). The inferred pre-Quaternary profile of the Yarlung-Tsangpo-Siang resembles the modern Indus profile, with a more subdued knickzone across the range,相应的断层在河流侵蚀速率中起到了重要作用。
Namche Barwa and a morphologic plateau edge located farther upstream. Modeling of river incision (Koons et al., 2013) shows that the differences in modern river profiles can be induced by differing rock-uplift rates in the syntaxial massifs of ~5 and ~10 mm/yr (Fig. 4), consistent with the recent acceleration our data imply.

CONCLUSIONS

Our new data and modeling reveal a three-stage exhumation history for Namche Barwa, reconciling previous studies focusing on either an early or a late onset of rapid exhumation. Our results suggest that coupling between crustal rock advection and surface erosion initiated in the late Miocene and strengthened during the Quaternary. They suggest a potential role for river capture events in initiating and strengthening tectonic-erosion couplings in a tectonic aneurysm.

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REFERENCES CITED

Bendick, R., and Ehlers, T.A., 2014, Extreme localized exhumation at syntaxes initiated by subduction geometry: Geophysical Research Letters, v. 41, p. 5861–5867, https://doi.org/10.1002/2014GL061026.

Bernet, M., Zattin, M., Garver, J.I., Brandon, M.T., and Vance, J.A., 2001, Steady-state exhumation of the European Alps: Geology, v. 29, p. 35–38, https://doi.org/10.1130/0191-9617(2001)029<0035:SOTE>2.0.CO;2.

Blum, M., Rogers, K., Gleason, J., Najman, Y., Cruz, J., and Fox, L., 2018, Allogenic and autogenic signals in the stratigraphic record of the deep-sea Bengal Fan: Scientific Reports, v. 8, 7973, https://doi.org/10.1038/s41598-018-25819-5.

Booth, A.L., Chamberlain, C.P., Kidd, W.S.F., and Zeitler, P.K., 2009, Constraints on the morpho-evolution of the eastern Himalayan syntaxis from geochronologic and petrologic studies of Namche Barwa: Geological Society of America Bulletin, v. 121, p. 385–407, https://doi.org/10.1130/B26041.1.

Bracciali, L., Najman, Y., Parrish, R.R., Akhter, S.H., and Millar, I., 2015, The Brahmaputra tale of tectonics and erosion: Early Miocene river capture in the Eastern Himalaya: Earth and Planetary Science Letters, v. 415, p. 25–37, https://doi.org/10.1016/j.epsl.2015.01.022.

Bracciali, L., Parrish, R.R., Najman, Y., Smye, A., Carter, A., and Wijbrans, J.R., 2016, Plio-Pleistocene exhumation of the eastern Himalayan syntaxis and its domal ‘pop-up’: Earth Science Reviews, v. 160, p. 350–385, https://doi.org/10.1016/j.earscirev.2016.07.010.

Braun, J., van der Beek, P., Valla, P., Robert, X., Herman, F., Glotzbach, C., Pedersen, V., Perry, C., Simon-Labirac, T., and Prigent, C., 2012, Quantifying rates of landscape evolution and tectonic processes by thermochronology and numerical modeling of crustal heat transport using PECUBE: Tectonophysics, v. 524–525, p. 1–28, https://doi.org/10.1016/j.tecto.2011.12.035.

Burbank, D.W., Leland, J., Fielding, E., Anderson, R.S., Brozovic, N., Reid, M.R., and Duncan, C., 1996, Bedrock incision, rock uplift and threshold hillslopes in the northwestern Himalayas: Nature, v. 379, p. 505–510, https://doi.org/10.1038/379505a0.

Burg, J.-P., Nievergelt, P., Obeiri, F., Seward, D., Davy, P., Maurin, J.-C., Diao, Z., and Meier, M., 1998, The Namche Barwa syntaxis: Evidence for exhumation related to orogen-normal crustal folding: Journal of Asian Earth Sciences, v. 16, p. 239–252, https://doi.org/10.1016/S0734-9547(98)00002-6.

Chirouze, F., Huyghe, P., van der Beek, P., Chauvel, C., Chakraborty, T., Dupont-Nivet, G., and Bernet, M., 2013, Tectonics, exhumation, and drainage evolution of the eastern Himalaya since 13 Ma from detrital geochemistry and thermochronology, Kameng River Section, Arunachal Pradesh: Earth and Planetary Science Letters, v. 356, p. 523–538, https://doi.org/10.1016/j.epsl.2012.12.017.

Clement, C., 1996, Bedrock incision, rock uplift and threshold hillslopes in the northwestern Himalayas: Nature, v. 379, p. 505–510, https://doi.org/10.1038/379505a0.

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Figure 4. Indus and Yarlung-Tsangpo-Siang River profiles. Zones of rapid uplift and exhumation in Nanga Parbat–Haramosh (NPHM) and Namche Barwa (NBM) massifs are shown as gray boxes with bold outlines; faults in black. The edge of the morphologic Tibetan Plateau is indicated with a vertical arrow. Thickness of Quaternary alluvial sediments (yellow) upstream of Namche Barwa is from Wang et al. (2014); inferred pre-Quaternary profile is indicated with dashed line. Inset (modified from Koons et al., 2013) shows modeled river profile (solid line) and rock uplift (dashed) after 0.5 m.y. for river incising a 3-km-high plateau bounded by a zone of anticlinal uplift (gray), for maximum uplift rates of 0 (black), 5 (blue), and 11 (red) mm/yr. Arrows indicate morphologic edge of the plateau.

Koons, P.O., Zeitler, P.K., and Hallet, B., 2013, Tectonic aneurysms and mountain building, in Owen, L.A., ed., Treatise on Geomorphology, Volume 5; Tectonic Geomorphology; London, Academic Press, p. 318–349, https://doi.org/10.1016/B978-0-12-374739-6.00094-4.

Korup, O., Montgomery, D.R., and Hewitt, K., 2010, Glacier and landslide feedbacks to topographic relief in the Himalayan syntaxes: Proceedings of the National Academy of Sciences of the United States of America, v. 107, p. 5317–5322, https://doi.org/10.1073/pnas.0907531107.

Lang, K.A., and Huntington, K.W., 2014, Antecedence of the Yarlung-Siang/Brahmaputra River, eastern Himalaya: Earth and Planetary Science Letters, v. 397, p. 145–158, https://doi.org/10.1016/j.epsl.2014.04.026.

Lang, K.A., Huntington, K.W., Burmester, R., and Housen, B., 2016, Rapid exhumation of the eastern Himalayan syntaxis since the late Miocene: Geological Society of America Bulletin, v. 128, p. 1403–1422, https://doi.org/10.1130/B31419.1.

Nie, J., et al., 2015, Glacial erosion of a major Himalayan river: Science, v. 347, p. 1242–1245, https://doi.org/10.1126/science.1260912.

Palin, R.M., Searle, M.P., St-Onge, M.R., Waters, D.J., Roberts, N.M.W., Horstwood, M.S.A., Parrish, R.R., and Weller, O.M., 2015, Two-stage cooling history of pelitic and semi-pelitic mylonite (senso lato) from the Dongjiu-Milin shear zone, northwest flank of the eastern Himalayan syntaxis: Gondwana Research, v. 28, p. 509–530, https://doi.org/10.1016/j.gr.2014.07.009.

Reiners, P.W., Carlson, R.W., Renne, P.R., Cooper, K.M., Granger, D.E., McLean, N.M., and Schoene, B., 2018, Geochronology and Thermochronology: Chichester, UK, John Wiley & Sons, 445 p., https://doi.org/10.1002/9781118455876.

Schmidt, J.L., Zeitler, P.K., Pazzaglia, F.J., Tremblay, M.M., Shuster, D.L., and Fox, M., 2015, Knickpoint evolution on the Yarlung river: Evidence for late Cenozoic uplift of the southeastern Tibetan plateau margin: Earth and Planetary Science Letters, v. 430, p. 448–457, https://doi.org/10.1016/j.epsl.2015.08.041.

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

Stewart, R.J., Hallet, B., Zeitler, P.K., Malloy, M.A., Allen, C.M., and Trippett, D., 2008, Brahmaputra sediment flux dominated by highly localized rapid erosion from the easternmost Himalaya: Geology, v. 36, p. 711–719, https://doi.org/10.1130/G24800A.1.

Szulc, A.G., et al., 2006, Tectonic evolution of the Himalaya constrained by detrital 40Ar–39Ar Sm-Nd and petrographic data from the Siwalik foreland basin succession, SW Nepal: Basin Research, v. 18, p. 375–391, https://doi.org/10.1111/j.1365-2177.2006.00307.x.

Thiele, R.C., and Ehlers, T.A., 2013, Large spatial and temporal variations in Himalayan denudation: Earth and Planetary Science Letters, v. 371–372, p. 278–293, https://doi.org/10.1016/j.epsl.2013.03.004.

Wang, P., Scherler, D., Liu-Zeng, J., Mey, J., Avouac, J.P., Zhang, Y., and Shi, D., 2014, Tectonic control of Yarlung Tsango Gorge revealed by a buried canyon in Southern Tibet: Science, v. 346, p. 978–981, https://doi.org/10.1126.science.1259041.

Whipp, D.M., Jr., Beaumont, C., and Braun, J., 2014, Feeding the “aneurysm”: Orogen-parallel mass transport into Nanga Parbat and the western Himalayan syntaxis: Journal of Geophysical Research: Solid Earth, v. 119, p. 5077–5096, https://doi.org/10.1002/2013JB010929.

Zeitler, P.K., et al., 2001a, Crustal reworking at Nanga Parbat: Metamorphic consequences of thermal-mechanical coupling facilitated by erosion: Tectonics, v. 20, p. 712–728, https://doi.org/10.1029/2000TC001243.

Zeitler, P.K., et al., 2001b, Erosion, Himalayan geomorphodynamics, and the geomorphology of metamorphism: GSA Today, v. 11, no. 1, p. 4–9, https://doi.org/10.1130/2001GTS0101-04.

Zeitler, P.K., Melitzer, A.S., Brown, L., Kidd, W.S.F., Lim, C., and Enkelmann, E., 2014, Tectonics and topographic evolution of Namche Barwa and the easternmost Lhasa block, Tibet, in Nie, J., et al., eds., Toward an Improved Understanding of Uplift Mechanisms and the Elevation History of the Tibetan Plateau: Geological Society of America Special Papers, v. 507, p. 23–58, https://doi.org/10.1130/2014.2507(02).

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