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Contrasting tectonically driven exhumation and incision patterns, western versus central Nepal Himalaya

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ABSTRACT

Although the Himalayan range is classically presented as cylindrical along strike, segmentation of the range in terms of structure, topography, precipitation, and erosion patterns is becoming widely recognized. The potential climatic or tectonic controls on these lateral variations remain controversial. Thermokinematic models predict that the geometry of the main Himalayan detachment controls the kinematics, exhumation, and topography of the orogen: where the detachment includes a major crustal ramp, the topography shows a steep gradient that focuses orographic precipitation and exhumation, whereas the topography is gentler and exhumation less focused above a flatter detachment. We test this prediction by comparing the patterns of river incision (specific stream power) and long-term exhumation (from apatite fission track thermochronology) in central Nepal, where a major crustal ramp has been imaged by geophysical methods, with new exploratory data from the remote Karnali River transect in western Nepal, where a ramp is predicted to be absent or minor. Our results show that both exhumation rates and river incision capacity are significantly higher and focused on the crustal ramp in central Nepal, whereas they are lower and the pattern is more diffuse in western Nepal. These differences support a model in which lateral variations in topography and exhumation are controlled by variations in the geometry of the detachment, and imply that along-strike climatic variations in the Himalaya respond to tectonics rather than driving it.

INTRODUCTION

The Himalaya has become a key natural laboratory for studying the interactions between tectonics, climate, and erosional processes (e.g., Burbank et al., 2003; Wobus et al., 2003; Grujic et al., 2006; Godard et al., 2014). Although the range is commonly presented as cylindrical along strike, it is characterized by significant lateral variations in geological structure (e.g., Yin, 2006), topography (Duncan et al., 2003; Bookhagen and Burbank, 2006), precipitation (Bookhagen and Burbank, 2006, 2010), and exhumation rates (Robert et al., 2011; Thiede and Ehlers, 2013). In particular, segments of the belt that are characterized by a pronounced topographic step between the Lesser and Greater Himalaya, associated with a peak in precipitation and focused exhumation, alternate with segments where the topography increases more linearly to the north, precipitation peaks at lower elevations, and exhumation rates are lower (Duncan et al., 2003; Bookhagen and Burbank, 2006; Robert et al., 2011; Thiede and Ehlers, 2013). The potential climatic or tectonic controls on these spatially variable topographic, precipitation, and exhumation patterns have been widely discussed in recent years but remain controversial (e.g., Wobus et al., 2003; Bollinger et al., 2006; Herman et al., 2010).

In earlier work (see Robert et al., 2009, 2011) we combined apatite fission-track (AFT) thermochronology and numerical thermokinematic modeling to suggest that (1) the steep gradient in topography that focuses exhumation and orographic precipitation in the central Nepal Himalaya (e.g., Wobus et al., 2003) is sustained by active rock uplift above a major mid-crustal ramp in the Main Himalayan Thrust (MHT; the interface along which the Indian plate underthrusts the Himalaya), as invoked by structural studies (cf. Bollinger et al., 2006; Elliott et al., 2016) and imaged by seismic methods (Schulte-Pelkum et al., 2005; Nábelek et al., 2009); and (2) lateral variations in the geometry of the MHT, in particular the presence or absence of a major mid-crustal ramp, may explain the observed topographic and exhumation patterns of the orogen. A growing body of work has corroborated the strong control of the geometry of the plate interface on Himalayan kinematics and patterns of denudation rates, from instantaneous to million-year time scales (Brewer and Burbank, 2006; Herman et al., 2010; Grandin et al., 2012; Coutand et al., 2014; Godard et al., 2014; Scherler et al., 2014; Le Roux-Mallouf et al., 2015; Elliott et al., 2016). However, most of these studies focused on single transects across the orogen, without addressing potential along-strike variations.

Here we test this model by comparing erosion patterns in the Karnali River catchment, in western Nepal, to those in the Trisuli River catchment in central Nepal. Topographic and geodetic data point to an abrupt change in the geometry of the MHT between western and central Nepal, with the major mid-crustal ramp disappearing toward the west (Berger et al., 2004; Harvey et al., 2015). We combine new AFT data from the Karnali catchment with an analysis of erosional stream power (a proxy for incision capacity) of both rivers to determine whether this inferred major difference in the geometry of the plate interface is reflected in patterns of rock exhumation and river incision.

STUDY AREA AND METHODS

Topographic patterns strongly differ between central and western Nepal (Figs. 1 and 2). In central Nepal, a steep gradient in topography occurs just south of the Main Central Thrust (MCT), which separates the high-grade metamorphic rocks of the Greater Himalaya to the north from lower-grade metasedimentary rocks of the Lesser Himalaya to the south. North of this topographic transition zone is a range of impressive massifs, with numerous summits of >7000 m elevation. In contrast, the topography in western Nepal rises much more linearly, no peaks >7000 m occur west of the Dhaulagiri massif, and both the line of highest elevations and the MCT are shifted north by nearly 100 km (Fig. 1). As a result, the Lesser Himalaya is much wider in western than in central Nepal. In both areas, the Lesser Himalaya encloses a series of Greater Himalayan klippen, of which the Dadeldhura and Kathmandu klippen are the largest.

Practically no thermochronology data have been reported previously from remote western Nepal. We present new AFT data from a transect along the Karnali River. Samples were collected at the valley bottom, close to the main river. Because all samples had to be carried out on foot, and the lithologies of the Lesser Himalaya yield few good-quality apatites, our data set is limited to 10 samples. Sample preparation and

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analysis followed standard procedures (see the GSA Data Repository[1] for details).

We estimate exhumation rates from the AFT data using a simple one-dimensional (1-D) steady-state model (Willett and Brandon, 2013). This approach provides only a first-order estimate of exhumation rates; a more complete calculation would require a 3-D thermokinematic model that takes into account non-vertical exhumation paths as well as surface topography (Robert et al., 2009, 2011; Herman et al., 2010; Coutand et al., 2014). However, we choose a simple 1-D approach here because the current database is insufficient to firmly resolve the kinematics (Robert et al., 2011).

To better resolve erosion patterns in the area, we complement the AFT data with stream-power analysis of the Karnali and Trisuli Rivers, the two major rivers draining western and central Nepal. Various measures of stream power provide useful proxies of river incision capacity and potentially rock-uplift rate (e.g., Lavé and Avouac, 2001; Scherler et al., 2014; Harvey et al., 2015). We use the specific stream power, ω, defined as $\omega = \rho_w\, g\, Q\, S/W$, where ρ_w is water density, g is gravitational acceleration, Q is discharge, S is local river gradient, and W is river width (for details of the analysis and potential uncertainties, see the Data Repository).

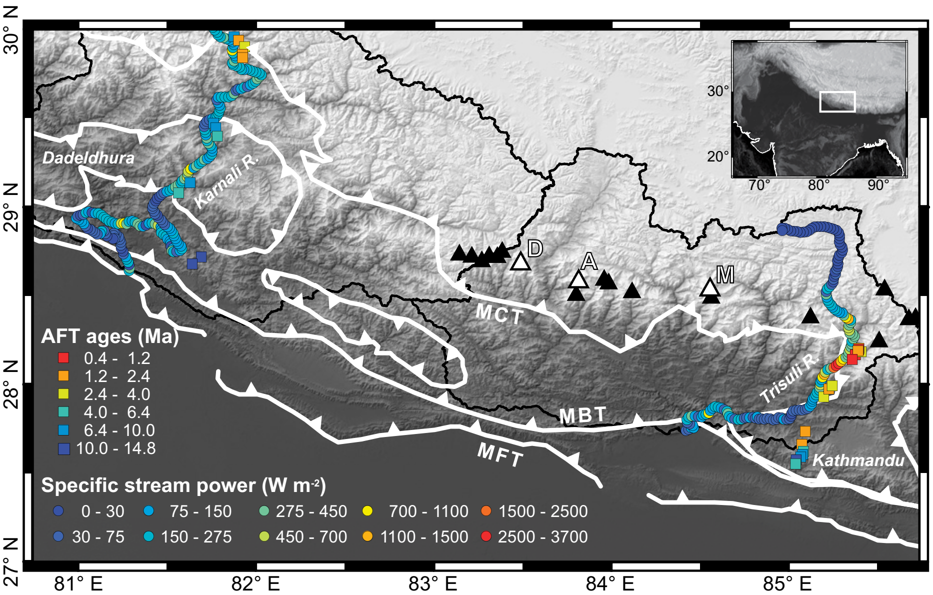

Figure 1. Apatite fission track (AFT) ages from samples collected along the Karnali River, western Nepal (this study; Sakai et al., 2013) and the Trisuli River, central Nepal (Robert et al., 2009), and specific stream power of these rivers, overlaid on shaded digital topography. Inset shows location within Himalayan range. Major Himalayan thrusts (MCT—Main Central Thrust; MBT—Main Boundary Thrust; MFT—Main Frontal Thrust) are in white; catchment boundaries are in black. Black and white triangles indicate summits over 7000 m and 8000 m elevation, respectively (D—Dhaulagiri; A—Annapurna; M—Manaslu).

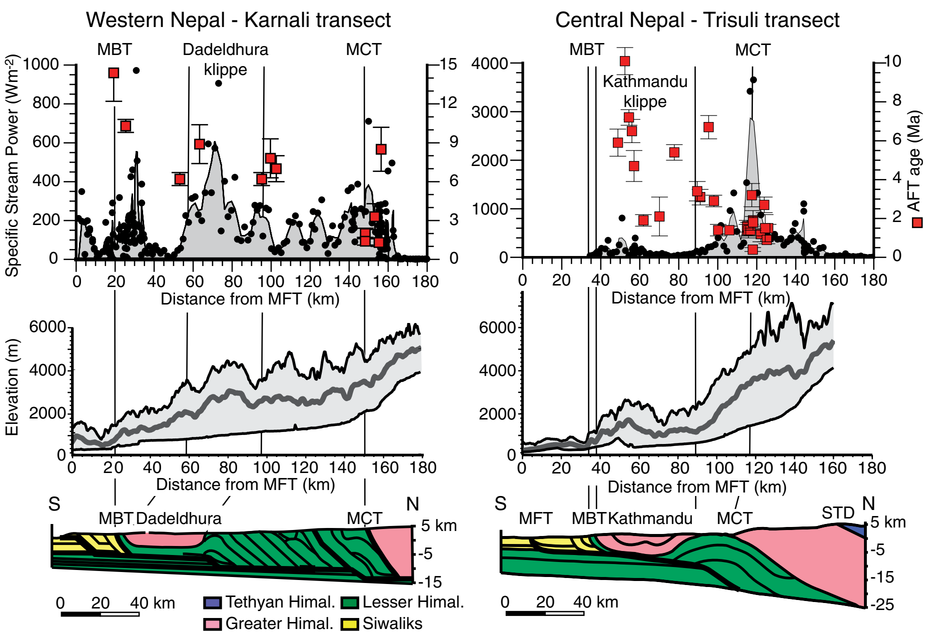

Figure 2. Simplified geological structure (lower panels; after Jouanne et al., 2004), topographic swaths (middle panels), projected apatite fission-track (AFT) ages (upper panels; red squares with error bars), and specific stream power (upper panels: dots—individual measurements; shaded area—3-point running average) projected onto north-northeast–south-southwest transects along the Karnali and Trisuli Rivers, Nepal. Topographic profiles show average (thick gray line) and maximum and minimum (thin black lines) elevations in a 40-km-wide swath. Note the different scales for specific stream power and AFT ages for the two transects. MFT—Main Frontal Thrust; MCT—Main Central Thrust; MBT—Main Boundary Thrust; STD—South Tibetan Detachment; Himal.—Himalaya.

RESULTS

Thermochronology Data

Our AFT data from the Karnali transect plot in two groups (Figs. 1 and 2; Table DR1 in the Data Repository): samples collected within a few kilometers of the MCT have young AFT ages, between 1.3 ± 0.3 and 3.3 ± 1.0 Ma. All other samples, collected both within the Greater and Lesser Himalaya as well as the Dadeldhura klippe, have AFT ages between 6.2 ± 0.5 and 8.9 ± 1.5 Ma. We include two AFT ages reported by Sakai et al. (2013) from south of the Dadeldhura klippe, which are somewhat older, 10.5 ± 0.5 and 14.4 ± 2.2 Ma (the latter sample was collected at >2000 m elevation). Ages decrease gradually to the north, in contrast to the data from central Nepal (Robert et al., 2009), which show a rapid drop in ages across the Kathmandu klippe (Fig. 2).

Stream Power

Calculated specific stream-power values along the Karnali and Trisuli Rivers are shown in Figures 1 and 2. The Karnali River shows 3 distinct peaks in specific stream power, none of which exceed 1000 W m^{-2}. The northernmost

[1]GSA Data Repository item 2016101, supplementary methods and apatite fission-track data, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

peak is quite narrow and coincides with the MCT and the location of the youngest AFT ages; the middle peak is the largest and is located in the southern half of the Dadeldhura klippe, where the Karnali flows through a 2-km-deep gorge; the southern peak corresponds to a series of rapids where the river flows parallel to the strike of the range between two conspicuous hairpin bends in its lower reaches. In contrast, the Trisuli River in central Nepal shows a single major specific stream-power peak of >3600 W m^{-2}, coinciding with the topographic transition zone. Smaller peaks, with specific stream powers of 800–1100 W m^{-2}, occur at Chongsecun in southern Tibet, where the river has incised a major landslide deposit, and just downstream of the confluence with the Marsyandi River, where the river flows through a gorge across the Mahabaratha Range before crossing the Main Boundary Thrust.

DISCUSSION AND CONCLUSIONS

Before comparing the patterns of thermochronological ages and specific stream power between western and central Nepal, we need to establish whether these two measures record a similar signal. Because they pertain to exhumation and incision rates on largely different space and time scales, a strong correlation between the two should not be expected a priori (e.g., Vernon et al., 2009; Bermúdez et al., 2013; Abrahami et al., 2016). To test this, we compare inferred local exhumation rates with calculated specific stream power close to the sampling sites (Fig. 3). We find a positive correlation ($r^2 = 0.44$; $p = 0.001$), suggesting that the two measures are recording the same signal of rock uplift and the erosional response to it, albeit on different time scales. This inference is consistent with the finding that short-term erosion rates in central Nepal, as recorded by detrital cosmogenic nuclide analysis, mimic the pattern of long-term exhumation rates inferred from thermochronology data (Godard et al., 2014).

When comparing the data from the two transects, the differences between western and central Nepal are conspicuous. AFT ages are significantly younger and inferred exhumation rates correspondingly higher in the Trisuli transect of central Nepal. This difference is particularly pronounced for the samples collected from the Lesser Himalaya between the (Dadeldhura and Kathmandu) klippen and the Greater Himalaya: AFT ages are 8–6 Ma along the Karnali River, whereas they are only 3–2 Ma along the Trisuli River. Similarly, the specific stream-power trend of the Trisuli River is dominated by a major peak coinciding with the topographic transition zone and the region of youngest AFT ages, whereas the Karnali profile shows a more evenly distributed pattern, with three distinct peaks along the river. Maximum specific stream-power values along the Trisuli River are nearly four times those along the Karnali River.

These differences appear consistent with the different geometries of the MHT in western versus central Nepal as inferred from geodetic data and topographic patterns (Berger et al., 2004; Harvey et al., 2015). The young thermochronological ages and specific stream-power peak observed along the Trisuli River, at the topographic transition zone between the Lesser and the Greater Himalaya, can both be explained by focused rock uplift and exhumation over a major crustal ramp in the MHT (Lavé and Avouac, 2001; Robert et al., 2009, 2011; Herman et al., 2010). In contrast, the gradually northward younging and generally older AFT ages observed along the Karnali River, combined with the lower values and more diffuse pattern of specific stream power, reflect lower and spatially more uniform exhumation and incision rates, consistent with the kinematics imposed by a gently (<10°) dipping detachment without a major ramp (Robert et al., 2011; Coutand et al., 2014). In detail, the peak in specific stream power observed where the Karnali River crosses the southern part of the Dadeldhura klippe could reflect incision in response to recent rock uplift above a newly formed smaller ramp in the MHT in western Nepal, as suggested by Harvey et al. (2015). The current thermochronological data set is insufficient to resolve any long-term exhumational response to movement along this structure.

Farther north along the Karnali transect, the young ages in the immediate vicinity of the MCT are not consistent with the kinematics of exhumation above a planar dipping detachment and may suggest the existence of a minor ramp beneath the MCT in western Nepal as well (Harvey et al., 2015). Alternatively, they could record the more complex kinematics of this region, which is affected by an active, west-northwest–striking (i.e., oblique to the orogen) system of right-lateral shear zones (Murphy and Copeland, 2005; Murphy et al., 2014; Nagy et al., 2015). This system overprints the MCT zone in the Karnali valley (Mercier, 2014) and may have resulted in localized recent exhumation along this zone. It could also constitute the lateral ramp separating the segments of the MHT with different geometries in western and central Nepal.

The strong apparent link between the geometry of the crustal-scale detachment underlying the Himalaya and the surface patterns of topography, exhumation, and incision capacity of rivers, both across and along the orogen, suggests that the primary driver for the lateral variations in these observables is tectonics, with climate playing a subordinate role. In the model that emerges, the topography and kinematics of the range are controlled by the geometry of the plate interface, lateral variations in which may be due to inherited structures on the underthrusting Indian plate (Gahalaut and Kundu, 2012; Godin and Harris, 2014) or, alternatively, may reflect transient behavior of the accreting Lesser Himalayan thrust stack, oscillating between frontal accretion without a major ramp, and basal accretion in the presence of a ramp (Duncan et al., 2003; Mercier, 2014). The topographic steps focus orographic precipitation (Bookhagen and Burbank, 2006, 2010), and thereby the erosional power required to counteract rock uplift above the ramp (where it exists). Our results therefore imply that along-strike climatic variations in the Himalaya respond to tectonically controlled topographic changes, rather than driving them.

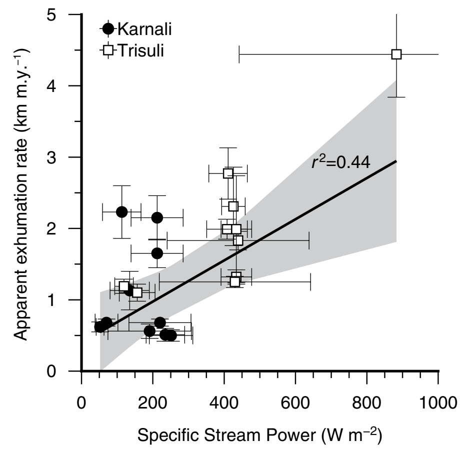

Figure 3. Comparison between specific stream power and exhumation rate estimated from apatite fission-track (AFT) ages. Specific stream power and its standard deviation correspond to that of the three measurements in the river closest to the AFT sampling site. Note that only AFT data sampled directly along the rivers are included in this plot. Continuous black line and gray shading show linear error-weighted correlation and 95% confidence interval, respectively.

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