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Dominance of tectonics over climate in Himalayan denudation

Vincent Godard[1], Didier L. Bourlès[1], Françoise Spinabella[1], Douglas W. Burbank[2], Bodo Bookhagen[2], G. Burch Fisher[2], Adrien Moulin[1], and Laëtitia Léanni[1]

[1]Aix-Marseille Université, CNRS, IRD, CEREGE UM34, 13545 Aix-en-Provence, France

[2]Earth Research Institute, University of California–Santa Barbara, Santa Barbara, California 93106, USA

ABSTRACT

Landscape denudation in actively deforming mountain ranges is controlled by a combination of rock uplift and surface runoff induced by precipitation. Whereas the relative contribution of these factors is important to our understanding of the evolution of orogenic topography, no consensus currently exists concerning their respective influences. To address this question, denudation rates at centennial to millennial time scales were deduced from ^{10}Be concentrations in detrital sediments derived from 30 small basins (10–600 km^2) in an ~200-km-wide region in central Nepal. Along a northward, strike-perpendicular transect, average denudation rates sharply increase from <0.5 mm/yr in the Lesser Himalayas to ~1 mm/yr when crossing the Physiographic Transition, and then accelerate to 2–3 mm/yr on the southern flank of the high peaks in the Greater Himalayas. Despite a more than five-fold increase in denudation rate between the southern and northern parts of this transect, the corresponding areas display similar precipitation rates. The primary parameter that presents a significant co-variation with denudation is the long-term rock-uplift rate that is interpreted to result from the ramp-flat transition along the Main Himalayan Thrust. We propose that, in this rapidly uplifting mountain range, landscapes adjust quickly to changing climatic conditions, such that denudation is mainly limited by the rate at which material is pushed upward by tectonic processes and made available for removal by surface processes. In this particular context, variations in precipitation appear to have only a second-order role in modulating the denudation signal that is primarily set by the background rock-uplift rate.

INTRODUCTION AND PROBLEM STATEMENT

Identifying and understanding the potential coupling between climate and tectonic processes remains a frontier topic in the field of orogenic processes research. Whereas some modeling studies provide compelling suggestions that external processes modulate the tectonic evolution of mountain ranges (Willett, 1999; Konstantinovskaia and Malavieille, 2005; Whipple and Meade, 2006; Whipple, 2009), others tend to downplay such direct climatic control (Godard et al., 2006; Roe and Brandon, 2011).

The central element of the proposed climate-tectonic coupling is denudation, which is influenced by both (1) rock uplift that builds topographic gradients, and (2) precipitation that provides the water required to weather and erode the earth surface and to transport sediments. However, the respective influence of these two forcing factors remains unclear, and numerous recent studies that have dealt with this problem have reached contrasting conclusions (Moon et al., 2011; DiBiase and Whipple, 2011; Bermudez et al., 2012; Bookhagen and Strecker, 2012; Carretier et al., 2013; Ferrier et al., 2013). For example, in the Himalayas, it has been proposed that exhumation patterns could be either strongly correlated with or independent of precipitation gradients and orographic barriers (Burbank et al., 2003; Thiede et al., 2004; Grujic et al., 2006; Adlakha et al., 2013).

Such conflicting interpretations might result from several, persistent methodological limitations. First, as illustrated by the studies cited above, a significant observational bias exists toward long-term records of denudation provided by low-temperature thermochronology. These methods typically integrate denudation over time scales (several million years) that are orders of magnitude longer than the time scales associated with precipitation measurements. Furthermore, they provide an integrated estimate of denudation that likely averages its effects over several cycles of varying tectonic and climatic conditions. Thus, approaches that reduce such time scale differences for the three studied variables (precipitation, uplift, and denudation) are needed in order to effectively analyze actual causal relationships between them.

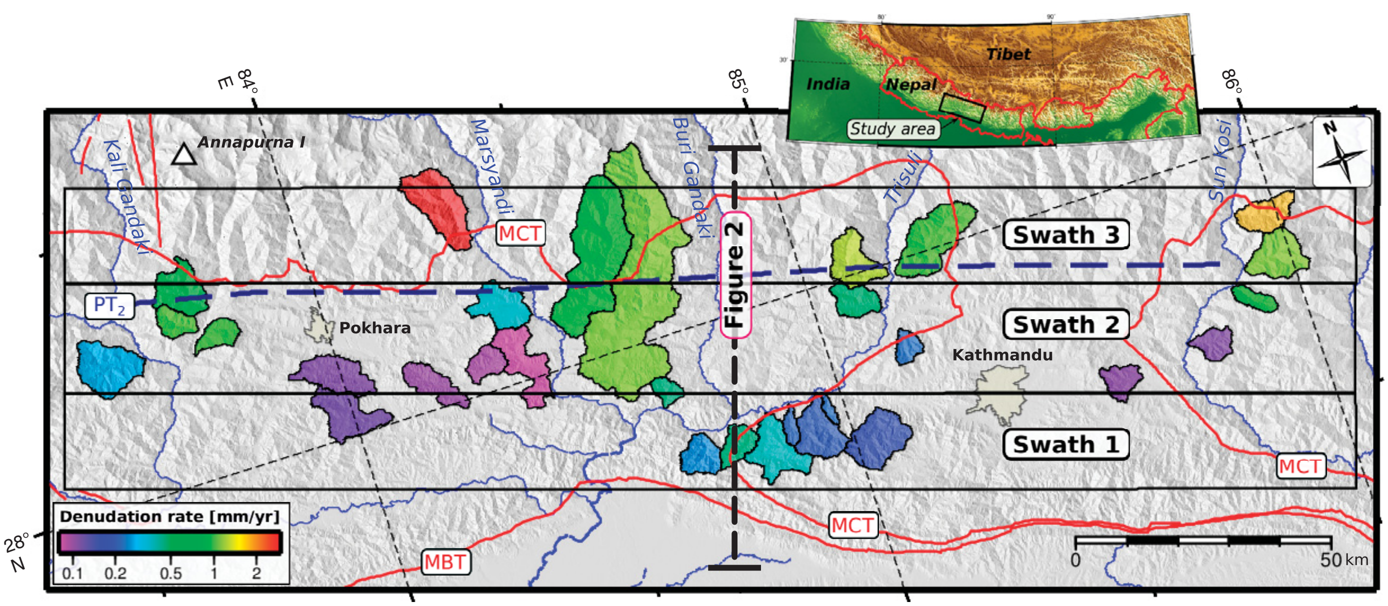

Figure 1. Location map and cosmogenic denudation rates for 30 Himalayan basins. Location of cross-range section presented in Figure 2 and different along-strike swaths (see Fig. DR1 [see footnote 1]) are indicated. MCT—Main Central Thrust; MBT—Main Boundary Thrust.

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Second, whereas modern precipitation at decadal scales has been quantified continuously across wide areas (Bookhagen and Burbank, 2010; Andermann et al., 2011), in most regions, only local estimates of rock uplift are available, and its global pattern is much more difficult to establish on spatial scales similar to those available for precipitation. This lack of regionally extensive rock-uplift data has precluded systematic sensitivity tests concerning the respective influences of precipitation and uplift on denudation. The purpose of this study is to perform such a test by focusing on a particular setting where exceptional controls are available on the long-wavelength patterns of both rock uplift and precipitation.

STRATEGY, METHODS, AND DATA

As one of the most active mountain ranges in the world, the Himalayas have been an important focus area for investigations of connections between tectonics and surface processes (Beaumont et al., 2001; Zeitler et al., 2001; Finlayson et al., 2002). Underthrusting of the Indian lithosphere along the Main Himalayan thrust, which is characterized by a ramp-flat geometry, induces a strong north-south gradient in rock uplift from the Greater to the Lesser Himalayas (Avouac, 2003). We focus our study on the central Nepal region, where this rock-uplift pattern has been modeled by stream-profile analysis over a 1–10 k.y. time scale (Lavé and Avouac, 2001) and is independently supported by thermomechanical modeling and thermochronological studies (Godard et al., 2004; Herman et al., 2010). Similarly, precipitation is highly variable across the range due to large orographic gradients, and also displays significant along-strike variability (Bookhagen and Burbank, 2010). Additionally, variations in bedrock erodibility are rather limited between the Lesser and Greater Himalayas (Lavé and Avouac, 2001; Craddock et al., 2007), a similarity that allows us to minimize the role of lithology as a major controlling parameter in our analysis.

We use cosmogenic ^{10}Be concentrations in river sediments to quantify catchment-scale denudation at the 100–1000 yr time scale (von Blanckenburg, 2005). Such measures of landscape denudation can be considered as instantaneous at the scale of tectonic and climatic fluctuations, as opposed to the longer-term, more integrative record provided by low-temperature thermochronology. This cosmogenic inventory approach permits efficient quantification of denudation in orogenic settings, provided that the catchment is large enough to effectively average out, in space and time, the stochastic contribution of landslides to denudation (Niemi et al., 2005; Yanites et al., 2009). The integration time scale for denudation falls in between those of the available tectonic and precipitation forcing records, and we assume

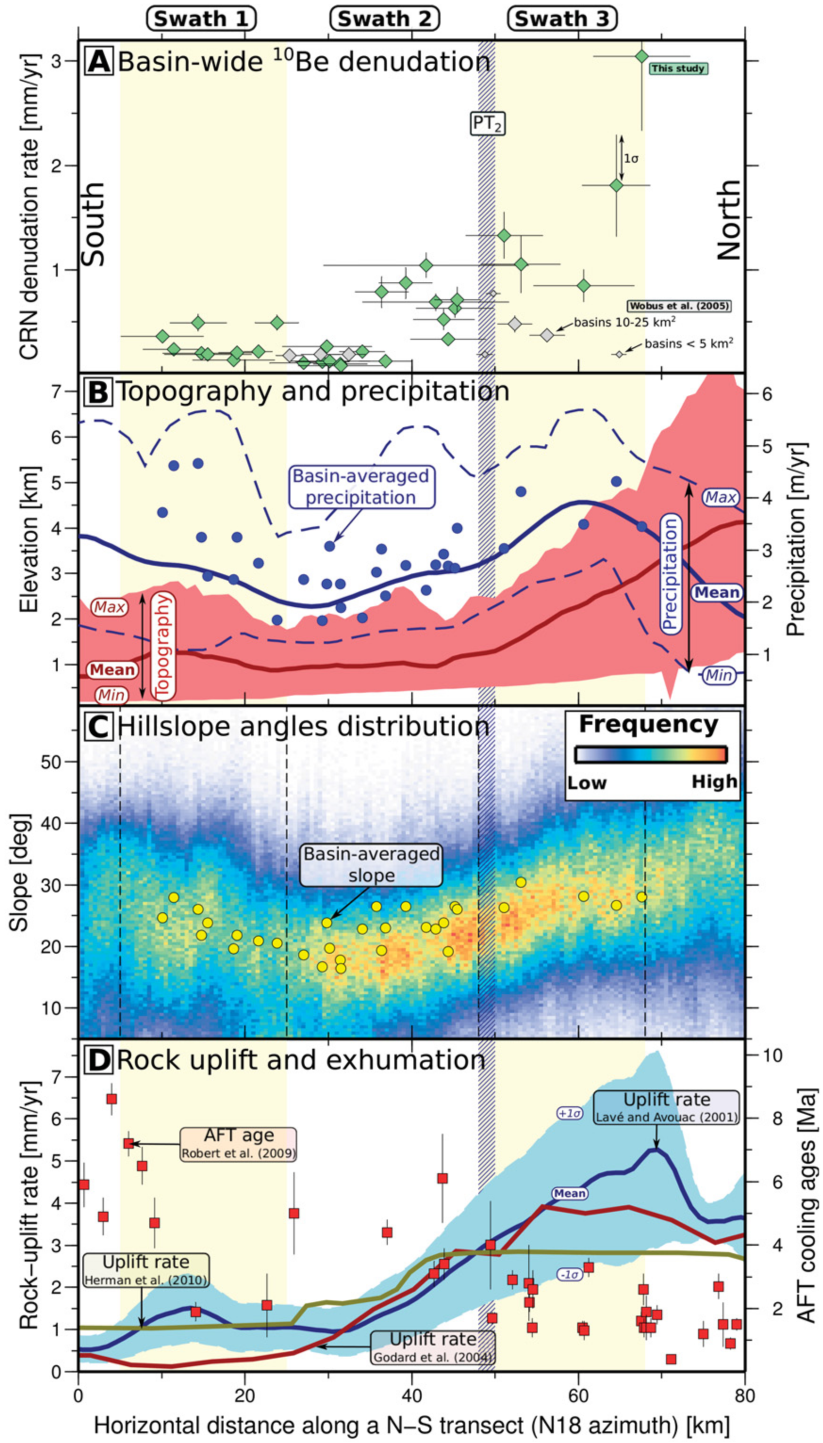

Figure 2. Cross-range section along N18°E azimuth (see Fig. 1 for location). All data are projected perpendicularly on this transect. PT$_2$—Physiographic Transition (Hodges et al., 2001). A: Basin-averaged denudation rates (cross-range denudation, CRN) inferred from ^{10}Be concentration in fluvial sediments from this study (green) and Wobus et al. (2005) (gray). Error bars on denudation rates are ±1σ and error bars on along-strike distances correspond to square root of basin area. B: Topography and precipitation (red and blue, respectively, with mean and extreme values) from 200-km-wide swath profiles (Bookhagen and Burbank, 2010). C: Distribution of hillslope angles along 200-km-wide swath profile. D: Apatite fission-track (AFT) cooling ages (±1σ error bars) in Kathmandu area (Robert et al., 2009) and cross-range rock-uplift rate estimates from river-profile analyses (Lavé and Avouac, 2001) and from thermomechanical (Godard et al., 2004) and thermokinematic models (Herman et al., 2010). Shaded zones 1, 2, and 3 correspond to along-strike swaths depicted in Figure 1 and plotted in Figure DR1 (see footnote 1).

that the spatial patterns can be extrapolated in time and compared.

We sampled 30 unglaciated catchments (Fig. 1), including five from a previous study (Godard et al., 2012), with sizes large enough to efficiently average the different denudation processes at work and small enough to minimize intra-catchment variability in rock-uplift rates and precipitation, such that the catchments can be treated as point measurements from a far-field perspective (Ouimet et al., 2009).

Along a north-south transect, denudation rates are lower than 0.5 mm/yr in the southern part of the Lesser Himalayas, and start to rise significantly just south of the Physiographic Transition, reaching ~1 mm/yr (Fig. 2). This increase in denudation rate accelerates northward toward the high-relief areas of the Greater Himalayas, to reach up to ~3 mm/yr in the northern part of the studied transect. Data by Wobus et al. (2005) support this pattern except for the smaller catchments where the actual denudation might be underestimated (Yanites et al., 2009).

DISCUSSION AND CONCLUSIONS

The major cross-range denudation gradient revealed by our data appears to be unrelated to the distribution of present-day precipitation, given that both ends of the profile receive comparably high amounts of precipitation, but display very sharp contrasts in denudation (Fig. 2). Similarly, the distribution of hillslope angles in the southern and northern regions does not reveal striking differences that could explain the more than five-fold increase in denudation (Fig. 2C). On the other hand, the distribution of denudation across the range mimics the strong gradient in rock uplift across the Lesser-to-Greater Himalayan transition estimated by Lavé and Avouac (2001) (Fig. 2D). Integrated over even longer time scales, low-temperature thermochronology data display comparable north-south trends in cooling ages and implied exhumation-rate gradients, which is consistent with a significant cross-range gradient in rock uplift (Herman et al., 2010). As postulated above, lithology does not appear to exert a significant control on the distribution of denudation (Figs. DR2A–DR2C in the GSA Data Repository[1]).

In this particular setting, we interpret the apparent correlation between denudation and uplift rate to point toward a primary control on the denudation pattern by the tectonic boundary condition, whereas precipitation appears to have only a second-order influence (Fig. 3; Fig. DR1). This correlation with rock-uplift rates also illustrates the tectonically limited nature of landscape denudation in rapidly uplifting environments (Montgomery and Brandon, 2002). We hypothesize that transient deviations in denudation above or below this tectonic baseline can occur due to climatic fluctuations, but they are not typically sustainable over the long term (Burbank, 2002). For example, at the scale of a mountain range, an increase in precipitation might accelerate denudation rates above tectonic rock-uplift rates, but the resulting decrease in relief with respect to the base level will ultimately reduce the efficiency of surface processes, such that the denudation rates will finally return to the pace imposed by tectonic uplift as a new steady state is approached (Whipple and Meade, 2006).

We suspect that this negative feedback could keep denudation rates rather tightly coupled to rock-uplift rates in rapidly deforming mountain ranges. However, in less active settings, climatic variations might have a stronger impact and be able to push landscape denudation rates away from equilibrium by larger amounts and for longer time periods. We note that some studies have argued for a notable influence of climate on the exhumation of the Himalayan wedge (Thiede et al., 2004; Grujic et al., 2006), but their focus on the strongly glaciated hinterland might explain this apparent difference in behavior.

The rock-uplift values derived from river-profile analysis (Lavé and Avouac, 2001) are significantly higher than the ^{10}Be-based denudation rates (Fig. 3A), but the spatial patterns are very similar (Fig. 2). The difference in absolute value may result from a systematic overestimation of rock-uplift rates by the river profile analysis due to uncertainties in the calibration of erodibility coefficients, given that millennial cosmogenic denudation rates are comparable to long-term exhumation-rate estimates in the Lesser (0.3–0.6 mm/yr) and Greater (2–2.5 mm/yr) Himalayas (Robert et al., 2009; Herman et al., 2010). The similarities in both spatial patterns and absolute values between our millennial denudation rates and rock-uplift or exhumation rates support the idea that cosmogenic denudation rates from arrays of medium-sized catchments can provide a relatively straightforward way to delineate first-order, cross-range patterns of rock-uplift rates in actively deforming mountain ranges (Wittmann et al., 2007; Cyr et al., 2010; Kirby and Ouimet, 2011; Gudmundsdottir et al., 2013).

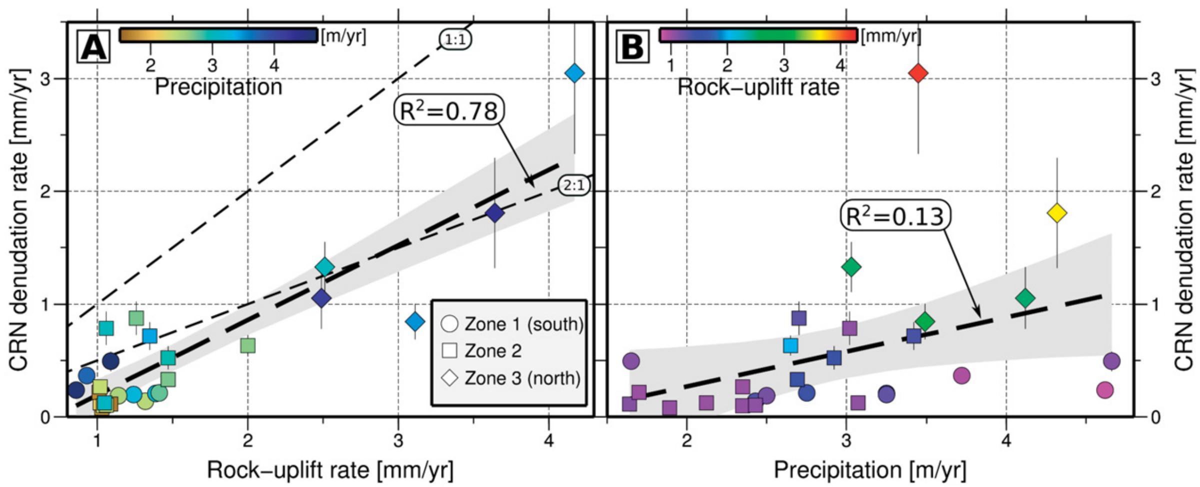

Figure 3. A: Comparison between basin-averaged denudation rates (cross-range denudation, CRN) and rock-uplift rates (Lavé and Avouac, 2001). B: Comparison between basin-averaged denudation rates and precipitation rates (Bookhagen and Burbank, 2010). Thick dashed lines are linear regressions with corresponding correlation coefficients, and light gray envelopes are 95% confidence intervals. In both panels, the two largest catchments have been excluded.

[1]GSA Data Repository item 2014088, analytical methods, data tables and additional figures, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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