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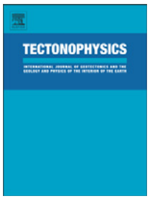

Rapid long-term erosion in the rain shadow of the Shillong Plateau, Eastern Himalaya

Vikas Adlakha [a], Karl A. Lang [b], R.C. Patel [a], Nand Lal [a], Katharine W. Huntington [b,*]

[a] *Department of Geophysics, Kurukshetra University, Kurukshetra-136 119, India*
[b] *Department of Earth and Space Sciences, University of Washington, Seattle, WA 98122, USA*

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ABSTRACT

Geodynamic models of collisional orogens suggest that precipitation gradients profoundly influence spatial patterns of exhumation and deformation in active collisional mountain ranges. A basic tenet of this hypothesis is that in unglaciated areas, spatial patterns of long-term precipitation, erosion and exhumation should be correlated. A correlation of this type has been observed in the Eastern Himalaya, where uplift of the Shillong Plateau by Pliocene time drastically reduced monsoonal rainfall in the Himalayan range downwind. Existing apatite fission-track data suggest that the resulting precipitation gradient caused a twofold gradient in long-term erosion rates across an area with similar geology, suggesting a strong influence of climate on the region's geomorphic and tectonic evolution. We extend this dataset by presenting 53 new bedrock apatite and zircon fission-track ages from deeper within the rain shadow. We expected latest Miocene to Pliocene apatite ages, similar to previously published ages from neighboring areas in the rain shadow. Instead, apatites as young as 1.3 ± 0.2 Ma and zircons as young as 4.5 ± 1.0 Ma (2σ) demonstrate that spatial gradients in precipitation do not correlate with variations in long-term erosion and crustal strain as predicted by geodynamic models. Thermal–kinematic modeling of these data suggests that local exhumation patterns reflect gradients in rock uplift dictated by fault kinematics in this rapidly deforming area, despite a dramatic precipitation gradient. These findings both highlight the need to better understand how erosive processes scale with precipitation amount and intensity in such settings, and suggest a disconnect between the predictions of orogen-scale geodynamic models and the relationship between erosion and tectonics at the regional scale.

1. Introduction

The hypothesis that atmospheric and geodynamic processes are strongly coupled through the action of erosion is one of the most exciting geoscience developments of the past few decades. But while most researchers agree that erosion can localize strain and deformation in the crust (e.g., Beaumont et al., 2001; Champagnac et al., 2008; Dahlen and Suppe, 1988; Hilley and Coutand, 2010; Koons et al., 2003; Willett et al., 1993), the influence of climatic gradients on long-term erosion and deformation is less clear. Although the rate of tectonic convergence controls long-term mass fluxes at the orogen scale (Koppes and Montgomery, 2009; Roe and Brandon, 2011), at sub-orogen scales models predict a strong influence of precipitation on erosion and exhumation-related deformation (e.g., Beaumont et al., 1992, 2001; Dahlen and Suppe, 1988; Koons, 1989; Koons et al., 2002; Willett, 1999). Indeed, many field studies have compared exhumation patterns measured over million-year timescales across climatic gradients as characterized by modern precipitation patterns to argue for coupling of climate, erosion and deformation (e.g., Hodges et al., 2004; Patel et al., 2011; Reiners et al., 2003; Thiede et al., 2005). However, the influence of precipitation gradients on long-term erosion is debated (e.g., Burbank et al., 2003), and clear field evidence for a strong coupling of climate, erosion, and deformation on the scale of mountain ranges has proved difficult to find (e.g., Thiede et al., 2009; Vernon et al., 2009; Whipple, 2009).

One place where a coupling of precipitation gradients and long-term erosion has been proposed is the Bhutan Himalaya, where the Shillong Plateau, a 1600-m high orographic barrier in northeast India, drastically reduces precipitation in the Himalayan range downwind (Biswas et al., 2007; Grujic et al., 2006). In this region, the pattern of erosion rates inferred from apatite fission-track (FT) cooling ages mimics the steep gradient in rainfall caused by the Shillong Plateau, leading Grujic et al. (2006) to suggest a climatic control on erosion and rock exhumation over million-year timescales. New constraints on the region's tectonic and structural evolution (Banerjee et al., 2008; Biswas et al., 2007; Clark and Bilham, 2008; McQuarrie et al., 2008; Tobgay et al., 2012; Yin et al., 2010) make it an ideal setting to examine such patterns in the context of deformation.

We build on previous work by presenting 53 new apatite and zircon FT data from a densely sampled transect deeper in the rain shadow in India (Fig. 1) and examining them in the context of recent

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* Corresponding author. Tel.: +1 206 543 1750; fax: +1 206 543 0489.
E-mail addresses: vikas.himg@gmail.com (V. Adlakha), karllang@uw.edu (K.A. Lang), patelramesh_chandra@rediffmail.com (R.C. Patel), lalkuk@gmail.com (N. Lal), kate1@uw.edu (K.W. Huntington).

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higher-temperature thermochronometer data, structural mapping, and geochronologic constraints on faulting. While our new apatite FT data are directly comparable to the data of Grujic et al. (2006) from the same litho-tectonic units to the west, zircon FT data reflecting a higher closure temperature are more sensitive than young valley bottom apatite samples to differences in erosion rate over million-year timescales, and combined with previous muscovite ^{40}Ar/^{39}Ar data (Yin et al., 2010) extend the cooling history of the study area to the Miocene.

2. Tectonic setting and precipitation gradients in the Eastern Himalaya

In the Eastern Himalaya of Bhutan and Arunachal Pradesh, India, continental convergence between India and Eurasia has been accommodated along a series of major north-dipping structures that can be traced along the 2500-km-long Himalayan arc (Fig. 1a) (Gansser, 1983; Hodges, 2000; LeFort, 1975; Yin, 2006). Moving southward from the Tibetan Plateau, the South Tibetan Detachment separates Tethyan Himalayan strata from the underlying Greater Himalayan Sequence (GHS), and the Main Central Thrust (MCT) places the GHS above the Lesser Himalayan Sequence (LHS). Similar to some other parts of the range, in the Eastern Himalaya the MCT forms the roof of a duplex (Long et al., 2011; McQuarrie et al., 2008; Tobgay et al., 2012; Yin et al., 2006, 2010), and several major thrust faults have been mapped in its footwall in Arunachal (Yin et al., 2010). Although Quaternary deformation and active thrust faulting at the position of the MCT are indicated by observations from some parts of the Central Himalaya (e.g., Hodges et al., 2004; Huntington and Hodges, 2006; Huntington et al., 2006; Wobus et al., 2003, 2005), the MCT in Arunachal has been folded and is cut by east-dipping normal faults of the Cona Rift zone, indicating that it is no longer active (Yin et al., 2010). In the footwall of the MCT, the LHS is bounded below by the Main Boundary Thrust, and the underlying sub-Himalayan strata are deformed by the Main Frontal Thrust zone. These thrusts are thought to sole into a mid-crustal décollement at depth, the Main Himalayan Thrust (MHT; Jackson and Bilham, 1994).

Although this sequence suggests along-strike uniformity, the structure, tectonics and geomorphology of the Eastern Himalaya are unique in several respects (e.g., Bookhagen and Burbank, 2006, 2010; Yin, 2006). One key difference is that in the east the Shillong Plateau, a 400-km-long anticlinal basement fold (Clark and Bilham, 2008; Das Gupta and Biswas, 2000) or pop-up structure (Biswas et al., 2007) rises ~1600-m from the Gangetic Plain between ~90 and 93°E, creating the only topographic barrier in the Himalayan foreland for moisture sourced from the Bay of Bengal.

The Shillong Plateau strongly influences rainfall across the Eastern Himalaya, reducing mean annual precipitation in the rain shadow to half of that observed in neighboring regions (Biswas et al., 2007; Bookhagen and Burbank, 2010; Grujic et al., 2006; Fig. 1b). The east–west gradient is even more pronounced during the Indian summer monsoon, which accounts for 90% of precipitation in the region (Bookhagen and Burbank, 2010) and was established by the late Miocene (ca. 12–8 Ma; e.g., An et al., 2001; Dettman et al., 2001, 2003; Molnar et al., 1993), or possibly much earlier (e.g., Clift et al., 2008; Guo et al., 2002; Sun and Wang, 2005). Although past intensified monsoon phases might have delivered more precipitation deeper into higher elevation regions (Bookhagen et al., 2005a,b), as long as the orography remained unchanged, variations in monsoon strength would not change the location of the major peak in rainfall at the Himalayan range front or the strong east–west precipitation gradient (Bookhagen and Burbank, 2010; Grujic et al., 2006). Recent thermochronometric studies show that deformation of the Shillong Plateau began by 8–14 Ma, with rock uplift rates outpacing erosion by a factor of two or more (Clark and Bilham, 2008), and suggest the establishment of the orographic barrier and general east–west precipitation gradient at least by Pliocene time (Biswas et al., 2007).

3. Low-temperature thermochronology

In the Bhutan Himalaya, previous apatite FT data suggest a correlation between the pattern of long-term erosion rates and steep rainfall gradients that have persisted for millions of years in the wake of the Shillong Plateau (Grujic et al., 2006; Fig. 1). Apatite FT ages record the time since cooling from ~90 to 120 °C and are commonly interpreted to reflect relative 10^6-yr averaged erosion rates (e.g., Braun et al., 2006; Ketcham et al., 2007). In western Bhutan, in the zone of intense monsoonal precipitation outside the rain shadow of the Shillong Plateau, apatite FT ages as young as 1.4 Ma indicate rapid erosion at 1.0–1.8 mm/yr (Grujic et al., 2006). In eastern Bhutan, within the rain shadow, older ages (most ~6 Ma) suggest a twofold decrease in erosion rates, leading previous workers to argue for a spatial correlation and causal link between precipitation and long-term erosion (Biswas et al., 2007; Grujic et al., 2006).

We estimate long-term erosion rates deeper in the rain shadow by dating bedrock samples along a 100-km transect in Arunachal using both apatite and zircon FT thermochronometry (Figs. 1b and 2; see Appendix A for details of methods and results). Zircon FT data reflect cooling through ca. 230–330 °C (Tagami and Shimada, 1996) and extend cooling history constraints to Miocene time. The densely sampled transect crosses all major structures in both the GHS and LHS, including the Bomdila Thrust in the footwall of the MCT (Yin et al., 2010). Consequently, we can also use the spatial pattern of thermochronometer ages to examine the degree to which cooling might reflect not only regional precipitation gradients but also local fault kinematics.

Following the hypothesis of Grujic et al. (2006), we would expect our new analyses from Arunachal to reveal ages similar to those observed in the rain shadow in eastern Bhutan with all else being equal. Systematic changes in convergence rate (Banerjee et al., 2008; Styron et al., 2011) and river steepness patterns across the study area (Fig. A1) are not observed. Nevertheless, along-strike structural variability (e.g., Tobgay et al., 2012; Yin et al., 2010) may contribute to variations in fracture density, influencing erodibility (Molnar et al., 2007). However, some of the new GHS samples from Arunachal were collected at similar structural levels and within only ~25 km of samples analyzed by Grujic et al. (2006) (Figs. 1b, 2), and although fracture density may vary across this zone, there is no reason to expect a priori that the strength of GHS rocks of similar lithology should change systematically from east to west. Thus if precipitation is the main driver of long-term erosion and exhumation, the new apatite FT ages should fit the previously observed correlation of ages with the east–west precipitation gradient.

We expected cooling ages similar to those in nearby eastern Bhutan (~6 Ma), but instead we find cooling ages in the GHS of Arunachal just as young as the youngest ages observed by Grujic et al. (2006) in rapidly eroding western Bhutan (Table A1). Apatites as young as 1.3 ± 0.2 Ma (2σ) suggest similarly high Pleistocene erosion rates of 1.0–1.8 mm/yr (Grujic et al., 2006), and zircons as young as 4.5 ± 1.0 Ma (2σ) indicate that rapid cooling and exhumation extended to the Pliocene (Table A1). Together with published muscovite ^{40}Ar/^{39}Ar ages from the GHS (Yin et al., 2010) reflecting cooling through ca. 425 °C (Harrison et al., 2009), the data indicate rapid average cooling rates of 40 °C/Myr since at least 12 Ma in the hanging wall of the MCT (Fig. 3a).

In contrast, both apatite and zircon FT ages for LHS rocks along our transect are much older (5.7–9.7 Ma and 10.9–14.1 Ma, respectively), reflecting slower cooling. Although the average (linear) cooling rate of the LHS since 14 Ma is 20 °C/Myr—half that of the GHS over this interval, the apatite FT data require an even lower average LHS cooling rate of just 13 °C/Myr post ~9 Ma (Fig. 3a). Time–temperature paths constrained by the thermochronometer data show that temperatures for GHS and LHS rocks along our transect now juxtaposed at the