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Erosion rates of the Bhutanese Himalaya determined using *in situ*-produced ^{10}Be

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ABSTRACT

Western Bhutan provides an ideal setting to understand the interplay between uplift, erosion, and fluvial sediment transport in an active mountain environment. Using *in situ*-produced ^{10}Be (49 samples) and ^{26}Al (5 samples) in fluvial sediment from nested catchments throughout the Puna Tsang Chhu drainage basin, we examine erosion rates in different geomorphic environments including two high-relief regions – a glacierized zone in the north and a high-rainfall zone in the south – as well as remnants of an uplifted, lower-relief paleosurface between them. The erosion rates roughly mirror this north–south zonation: lower rates (avg. 388 ± 32 m My^{-1}, $n = 16$) prevail in the low-relief zone, roughly coinciding with lower-relief terrain where mean annual precipitation is ~1500 mm yr^{-1}; the highest rates (avg. 956 ± 160 m My^{-1}, $n = 13$) are in the south (27.10°–27.35°N), where rainfall is >4000 mm yr^{-1}; high rates (avg. 700 ± 62 m My^{-1}, $n = 15$) also occur in the northern, glacierized region (27.70°–28.10°N). All 49 purified mineral separates used in this study contain measurable amounts of native ^{9}Be (up to 900 µg), violating the assumption of negligible ^{9}Be that is commonly made in the isotope dilution method used to quantify ^{10}Be. To correct for this native ^{9}Be, we use high precision, replicate measurements of ^{9}Be in each sample to calculate ^{10}Be concentrations from measured isotopic ratios. Neglecting native ^{9}Be would have led to erosion rate overestimates from <20% to >400%. The pervasive nature of ^{9}Be in these samples underscores the importance of quantifying the native ^{9}Be concentration in mineral separates used for cosmogenic ^{10}Be analysis.

1. Introduction

Understanding the relative rates, mechanisms, and feedbacks involved in the evolution of mountain belts from a variety of perspectives including bedrock uplift and incision (Burbank et al., 1996; Hodges et al., 2004; Thiede et al., 2005; Godard et al., 2014), deformation and metamorphism (Zeitler et al., 2001; Finlayson et al., 2002), hillslope processes (Shroder and Bishop, 1998; Niemi et al., 2005), geochemistry and sediments (Derry and France-Lanord, 1996), ocean chemistry and climate (Raymo et al., 1988; Huntington et al., 2006), and geodynamics (Hodges et al., 2001) is essential for determining the interplay between tectonics, geomorphology, and climate. Catchment-wide erosion rates, estimated from cosmogenic nuclide abundances in fluvial sediment (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996), are a key tool for illuminating the relationships among tectonic uplift, topography, climate, and denudation in active mountain belts such as the Himalaya (Wobus et al., 2005, 2006; Ouimet et al., 2009). In tectonically active areas, surface processes can operate rapidly and can influence Earth system processes over local to global spatial scales (Raymo et al., 1988; Ruddiman and Prell, 1997; Meyer et al., 2006; Gabet et al., 2010; Burbank et al., 2012; Godard et al., 2012, 2013).

Cosmogenic nuclide measurements from nested sites throughout a drainage basin can support a quantitative accounting of sediment fluxes over a large and diverse landscape in which the controls on erosion may vary considerably (Nichols et al., 2005a; Bekaddour et al., 2014). For

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example, nuclide measurements of river sediment samples collected from the Nepalese Himalaya have allowed geomorphologists to decouple glacial from fluvial contributions to the cosmogenic erosion rate signal (Godard et al., 2012) and investigate relationships between uplift rates and denudation rates (Vance et al., 2003; Godard et al., 2014).

This study presents denudation rate estimates based on the analysis of *in situ*-produced ^{10}Be in 49 fluvial sand samples from the Puna Tsang Chhu and its tributaries in western Bhutan (Fig. 1). In a small number of samples ($n = 5$), we also measured ^{26}Al and investigated the effect of grain-size on isotope concentration. Our field area experiences high modern precipitation rates – up to 5000 mm yr^{-1} (Bookhagen et al., 2005; Hijmans et al., 2005) – and has extensive high-relief terrain — both a fluvially-dissected region of steep hillslopes, steep stream gradients, and high cross-valley curvature, and a glacially-dissected region with active glaciers and deep U-shaped valleys (Duncan et al., 2003; Grujic et al., 2006), conditions which imply ongoing elevated incision rates and, presumably, denudation rates.

2. Study location

Bhutan straddles the Indo-Eurasian collisional belt and its landscape is dominated by steep, mountainous terrain deeply incised by several transverse rivers (Fig. 1A), including the Puna Tsang Chhu in western Bhutan (Fig. 1B, C) – a significant tributary to the Brahmaputra River in northern India – that drains >8000 km^2 of landscape composed of heavily metamorphosed Greater Himalayan Sequence (GHS) and significant portions of a remnant Tethyan Sedimentary Sequence (TSS), all overlying the Indian Craton (Fig. 1A). Tectonic activity during the Miocene was focused on the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT) that bound the Lesser Himalayan Sequence (LHS). This active tectonic focus has since shifted to the Main Frontal Thrust (MFT). The Kakhtang Thrust (KT) separates high-grade metamorphic rocks in the hanging wall of the GHS from lower grade rocks and has led to extremely high peaks and steep valleys in Bhutan's north (Gansser, 1983; Chakungal et al., 2010, and references therein; Long et al., 2011, and references therein).

The Himalayan front is affected by the South Asian Monsoon (Burbank et al., 2012), which facilitates erosion-driven exhumation along the southern slopes (Grujic et al., 2006; Biswas et al., 2007) and the western Himalayas (Bookhagen and Burbank, 2010). Apatite fission track exhumation rates in western Bhutan (1.4 mm yr^{-1} since 2.5 Ma) are higher than those in eastern Bhutan (0.7 mm yr^{-1} since 5.1 Ma), and may reflect a difference resulting from the uplift of the Shillong Plateau in northern India (Fig. 1A; Grujic et al., 2006; Biswas et al., 2007; Adlakha et al., 2013a; Coutand et al., 2014). The Shillong Plateau creates an orographic rain shadow along the front ranges in eastern Bhutan (Fig. 1B inset), which may (Grujic et al., 2006; Biswas et al., 2007) or may not (Adlakha et al., 2013b; Coutand et al., 2014) have caused decreased erosion rates and thus decreased erosion-driven exhumation rates. In contrast, greater precipitation along the western Bhutanese front ranges may facilitate higher exhumation rates and oversteepened slopes in the Puna Tsang Chhu region (Duncan et al., 2003; Grujic et al., 2006; Adlakha et al., 2013a). The far northern reaches of the Puna Tsang Chhu basin are glaciated and fed by the summer monsoonal precipitation with evidence for numerous glacial advance-retreat cycles since the Pleistocene (Iwata et al., 2002; Meyer et al., 2009). Glaciers began retreating ~4700 calibrated ^{14}C years BP, but most glaciers have remained within 1 km of their current termini during the late Holocene (Meyer et al., 2009). Nearly all glaciers are now shrinking (Komori, 2008; Liu et al., 2012; Rupper et al., 2012).

North–south swath profiles of western Bhutan (Duncan et al., 2003) show two zones of steep hillslopes. The first is within the Deep Eastern Valleys physiographic province (Fig. 1B; Norbu et al., 2003). The second steep zone occurs in the High Himalayan Peak and Plateau provinces (Fig. 1B, see figure caption; Norbu et al., 2003) and is associated with extensive glaciation and crustal thickening in the hanging wall of the Kakhtang Thrust through the GHS (Grujic et al., 1996, 2002; Daniel et al., 2003). However, between these zones is an uplifted, low-relief paleosurface within the GHS (Grujic et al., 2006) through which knickpoints actively propagate (Duncan et al., 2003; Baillie and Norbu, 2004). The range of erosion regimes, physiographic provinces, and geologic units exhibited in western Bhutan provide a unique setting to understand erosion and fluvial sediment transport along an active continent-continent convergence zone.

3. Cosmogenic isotope systematics

In order for *in situ* ^{10}Be from quartz sand to be used successfully as an erosion rate monitor, it is typically assumed that quartz extracted from river sediment represents uniformly distributed upstream lithologies, is continuously exposed to cosmic radiation, and contains insignificant concentrations of native ^{9}Be. It is also assumed that stream sediment is eroded from surfaces that have achieved equilibrium. In addition, ^{10}Be accumulated during fluvial sediment transport to the sample collection site is assumed to be minimal compared to ^{10}Be production in bedrock and while the sediment resides on hillslopes. If any of these assumptions are not met, denudation rates calculated from ^{10}Be concentrations can only be interpreted as apparent erosion rates, rather than long-term average erosion rates.

The majority of the field area (Fig. 1A) is underlain by the Greater Himalayan Sequence (GHS), which consists predominantly of high-grade metamorphic rocks (e.g. amphibolite and granulite) with marble in its upper unit in the hanging wall of the KT, while its lower unit contains mostly amphibolite and aluminosilicate mineral assemblages (e.g. staurolite, kyanite, sillimanite), granite orthogneiss, paragneiss, biotite–muscovite–garnet schists, quartzite, and marble. Large regions of leucogranite are found throughout the GHS. The Chekha Formation and TSS are combinations of limestone, shale, and quartz sandstone found along drainage divides in the northwestern and eastern regions of the Puna Tsang Chhu. When non-quartz-bearing lithologies are present within a catchment, such as in catchments draining the LHS in Nepal (Scherler et al., 2014), the supply of quartz to stream sediment can be unequally distributed; correcting for this unequal distribution of quartz supply can change calculated erosion rates by upward of 80%. Geologic units of the GHS underlying the Puna Tsang Chhu drainage contain quartz throughout (Gansser, 1983; Daniel et al., 2003; Long et al., 2011), and thus we presume quartz in Puna Tsang Chhu sediments is representative of the entire basin area.

Measurements of ^{10}Be are typically made using an isotope dilution method (Gosse and Phillips, 2001; Corbett et al., 2011) in which the concentration of cosmogenic ^{10}Be is measured in relation to the amount of stable ^{9}Be, added using a ^{9}Be carrier. The method relies upon the observation that there is rarely native ^{9}Be (the stable nuclide) in the purified quartz mineral separate (Kohl and Nishiizumi, 1992) that is dissolved for isotopic analysis (e.g., Douglass et al., 2006). In most samples, this assumption is valid; little if any native ^{9}Be is present (Corbett et al., 2013). However, for samples we collected from Bhutan, analysis of both purified mineral separates, and of the solution resulting from dissolution of those separates, show that ^{9}Be is present in purified quartz at levels up to tens of ppm. If the native ^{9}Be present in quartz separates were not accounted for, ^{10}Be-based erosion rates would be overestimated and exposure ages would be underestimated. Precise quantification of native ^{9}Be concentrations in samples can provide the information needed to correctly calculate total ^{10}Be from measured ^{10}Be/^{9}Be ratios, thereby allowing robust data to be generated even when samples contain measurable levels of native ^{9}Be. This same type of correction is routinely made for ^{26}Al analyses as ^{27}Al is ubiquitous in quartz separates.

Isotopic equilibrium is achieved in surface materials when the production of ^{10}Be in a landscape is balanced by its removal through radioactive decay and erosion; ^{10}Be concentrations in fluvial sediment can only be interpreted as true erosion rates if such equilibrium has been achieved. Because glaciers attenuate much of the incoming cosmic