Impulsive alluviation during early Holocene strengthened monsoons, central Nepal Himalaya

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ABSTRACT

The steep-walled bedrock gorges of the Greater Himalayan rivers currently lack significant stored sediment, suggesting that fluvial erosion and transport capacity outpace the supply of sediment from adjacent hillsides. Despite this appearance of sustained downcutting, such rivers can become choked with sediments and aggrade during intervals of higher precipitation. Cosmogenic dating (^{10}Be and ^{26}Al) of fluvially carved bedrock surfaces indicates that sediment at least 80 m thick filled the Marsyandi River valley in central Nepal during a time of strengthened early Holocene monsoons. Despite threefold differences in height (43–124 m) above the modern river, these fluvial surfaces display strikingly similar cosmogenic exposure ages clustering around 7 ± 1 ka. We speculate that enhanced monsoonal precipitation increased pore pressure and the frequency of landsliding, thereby generating a pulse of hillslope-derived sediment that temporarily overwhelmed this alpine fluvial system's transport capacity. After the easily liberated material was exhausted ca. 7 ka, the hillslope flux dropped, and the river incised through the aggraded alluvium. It concurrently eroded adjacent rock walls, thereby removing previously accumulated ^{10}Be and ^{26}Al and resetting the cosmogenic clock in the bedrock. Unlike previous studies, these exposure ages cannot be used to derive river-incision rates; instead they record a coupled fluvial-hillslope response to climate change.

Keywords: cosmogenic dating, aggradation, bedrock incision, precipitation, hillslope stability, Marsyandi River.

INTRODUCTION

Quantifying patterns, processes, and rates of erosion is essential to understanding orogenic evolution (Molnar and England, 1990; Small and Anderson, 1995) and for predicting erosional impacts of changing climate (e.g., Beniston et al., 1996). At present, rivers within many rapidly deforming collisional mountain belts are flowing on or within meters of bedrock (Tinkler and Wohl, 1998). This circumstance creates an impression of rivers that are persistently and continuously incising through bedrock with insignificant sediment storage in the fluvial network. We argue here that, even within rugged mountains, incision is likely to be discontinuous, because it is punctuated by climatically driven pulses of aggradation.

In active orogens characterized by rock-uplift rates of ≥2 mm/yr that are sustained over several million years, hillslope-erosion and channel-incision rates commonly approach rock-uplift rates over time scales of $\geq 10^5$ yr (Burbank et al., 1996; Willett, 1999). Because rock to regolith conversion rates are typically only fractions of 1 mm/yr (Heimsath et al., 1997, 2000), denudation of valley walls occurs primarily by landsliding and/or glaciation. On shorter time scales, the dynamic behavior of mountainous rivers, as well as the impacts of climatic variability and extreme weather events on fluvial systems (e.g., Watson et al., 1996), are poorly known.

Increases in precipitation commonly enhance discharge, creating higher stream power and more erosive potential. These precipitation increases, however, also affect adjacent hillslopes by raising the water table and increasing pore pressure, thereby amplifying the contribution of detritus into the channel network by landsliding (Hoek and Bray, 1977; Schmidt and Montgomery, 1995). Many studies have demonstrated that times of increased precipitation are marked by river downcutting (e.g., Jones et al., 1999; Porter et al., 1992). In this study we utilize a new early Holocene chronology of river incision and deposition to infer that enhanced monsoonal precipitation has driven impulsive events of aggradation, as well as incision, within the bedrock gorges of the Himalaya.

SETTING

The Marsyandi River is a trans-Himalayan river in central Nepal (Fig. 1) with headwaters on the southern edge of the dry Tibetan Plateau; it cuts between the >8-km-high peaks of Annapurna and Manaslu and flows into the monsoon-soaked Lesser Himalaya (~2000 m), draining an area of ~4800 km^2. The study area is along the Greater Himalayan reach. The medium- and high-grade gneisses of the Greater Himalayan Sequence overthrust the greenschist to lower amphibolite facies rocks of the Lesser Himalayan Sequence along the Main Central thrust (Fig. 2A) (e.g., Hodges, 2000).

The Marsyandi currently flows on or within meters of bedrock as it traverses the Greater Himalaya. This region is characterized by narrow V-shaped valleys, the walls of which are

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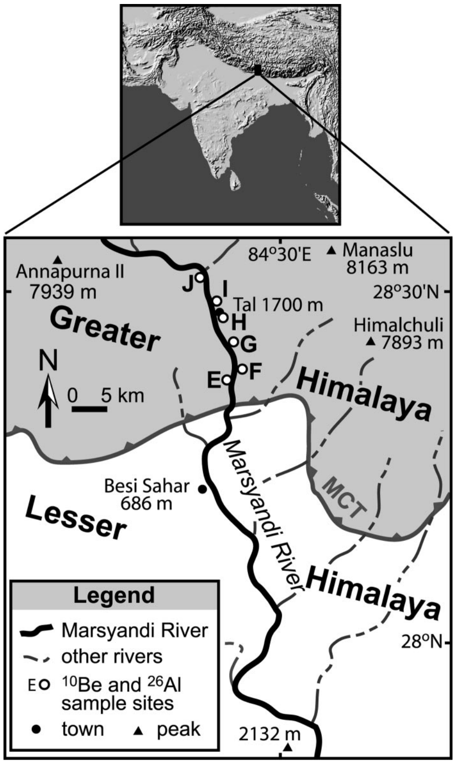

Figure 1. Map of Marsyandi River study area showing locations of cosmogenic sample sites (E–J). MCT—Main Central thrust.

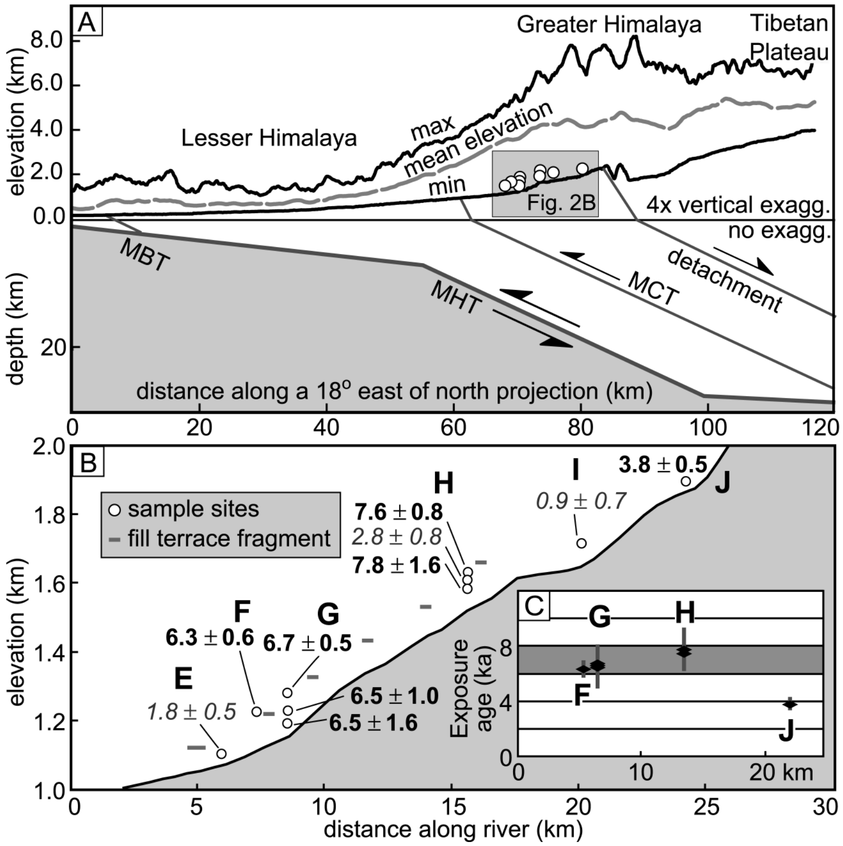

Figure 2. A: Schematic cross section of central Himalayan structure (Brewer, 2001). B: Site locations and exposure ages of ^{10}Be and ^{26}Al samples (E–J). C: Tight grouping of 8–6 ka exposure ages at sites F, G, and H. Final results were averaged for all samples at same location. Bold type indicates results from sites with high-quality geomorphic setting. Italicized ages were excluded, as explained in text. Errors are 2σ. MBT—Main Boundary thrust, MHT—Main Himalayan thrust, MCT—Main Central thrust.

typically close to the critical angle (>30°) for landslides (Burbank et al., 1996). Fluvially polished bedrock surfaces are preserved to 125 m above the modern river level. Along the bedrock reaches, sedimentary deposits are fragmentary and uncommon; they are typically a few meters thick and only a few tens of meters in lateral extent.

METHODS

In the Greater Himalaya, incision by the Marsyandi has created valley walls dotted with fluvially sculpted bedrock. To calculate exposure ages (e.g., Gosse and Phillips, 2001; Lal, 1991) and incision history, we measured concentrations of cosmogenic ^{10}Be and ^{26}Al in samples from 12 of these sculpted surfaces. Typically, samples were collected from relatively small (1–5 m^2), flat (0°–25°) polished surfaces incised into steep bedrock slopes (>30°). Steep hillsides reduce the probability of shielding by lingering colluvium or soil, whereas the locally flat sample sites are easier to correct for topographic shielding. Where possible, two samples were collected from each surface. Owing to limited viable sites, a few samples were taken from less steep hillslopes, despite the greater possibility of shielding by colluvium. To assess the temporal variability of incision rates, we sampled vertical profiles ranging from 28 to 124 m above the modern river. Following sample preparation (Kohl and Nishiizumi, 1992), isotope concentrations were measured on the Lawrence Livermore National Laboratory accelerator mass spectrometer. Exposure ages were calculated using ^{10}Be and ^{26}Al production rates from Nishiizumi et al. (1989) rescaled to 5.1 and 31.1 atoms/g/yr, respectively (Stone, 2000), and corrected for latitude, altitude (Dunai, 2000), and topographic shielding (Dunne et al., 1999).

RESULTS AND INTERPRETATION

We determined 10 exposure ages from sites along the Marsyandi's Greater Himalayan reach from a total of 12 samples (Table 1; Fig. 2B)[1]. Three samples returned improbably young exposure ages (Table 1; Fig. 2B). While in the field, we had designated each of these three as substandard sample sites with a higher likelihood of past burial by landslides or rockfall. All nine samples that we used in the analysis were from surfaces deemed to have little chance of prolonged cover.

Progressive fluvial incision should result in greater exposure ages on surfaces higher above the river. Given the vertical spacing of sample sites at surfaces G and H (Fig. 2B), exposure ages should display an approximately threefold variation from the lowest to the highest sites, if bedrock incision were steady over thousands of years. Instead, all eight samples at sites F, G, and H yielded exposure ages of 6.3–7.8 ka (Fig. 2C). Only at the lowest sampled surface, site J, do we observe the proportionally younger age of 3.8 ka. If the ages at sites F, G, and H are interpreted to result from progressive bedrock incision, they require abrupt and improbable changes in incision rates: ~40 mm/yr between 8 and 6 ka followed by a sixfold decrease to ~7 mm/yr since 6 ka. Because an incision rate of 40 mm/yr is ~10 times greater than the mean denudation rate in this region (Brewer, 2001) and because entire reaches of rivers are rarely eroded at this rate in resistant bedrock, we reject this interpretation.

Uniform exposure ages at variable heights

[1]GSA Data Repository item 2002108, Additional cosmogenic sample information, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

TABLE 1. ^{10}Be AND ^{26}Al EXPOSURE AGES

Site	No.	Height above river (m)	[^{10}Be] (10^3 atoms per 1 g qtz)	^{10}Be age (ka)	[^{26}Al] (10^3 atoms per 1 g qtz)	^{26}Al age (ka)	Site avg. exposure age (ka)
E	*110*	31	*13.7 ± 4.0*	*1.9 ± 0.6*	*71.6 ± 34.2*	*1.7 ± 0.8*	*1.8 ± 0.5*
F	**111**	**81**	**51.8 ± 5.8**	**6.8 ± 0.8**	**291 ± 42**	**5.9 ± 0.9**	**6.3 ± 0.6**
G1	**112**	**43**	**41.6 ± 6.4**	**5.9 ± 1.0**	**150 ± 139**	**3.5 ± 3.0**	**6.5 ± 1.6**
G1	**112B**	**43**	**n.d.**	**n.d.**	**205 ± 142**	**4.8 ± 3.4**	
G1	**113**	**43**	**50.5 ± 4.8**	**7.2 ± 0.8**	**285 ± 62**	**6.7 ± 1.5**	
G2	**115**	**76**	**48.2 ± 5.6**	**6.5 ± 1.1**	**273 ± 111**	**6.1 ± 2.5**	**6.5 ± 1.0**
G3	**116**	**124**	**62.7 ± 5.4**	**7.3 ± 0.8**	**308 ± 64**	**5.9 ± 1.3**	**6.7 ± 0.5**
G3	**117**	**123**	**56.1 ± 4.0**	**6.6 ± 0.6**	**n.d.**	**n.d.**	
H1	**121**	**66**	**71.4 ± 13.8**	**7.8 ± 1.6**	**n.d.**	**n.d.**	**7.8 ± 1.6**
H2	*123*	*89*	*34.9 ± 9.4*	*3.5 ± 1.0*	*66.0 ± 89.4*	*1.1 ± 1.4*	*2.8 ± 0.8*
H3	**124**	**110**	**65.7 ± 5.2**	**7.6 ± 0.8**	**n.d.**	**n.d.**	**7.6 ± 0.8**
I	*127*	*68*	*5.6 ± 4.2*	*0.9 ± 0.7*	*n.d.*	*n.d.*	*0.9 ± 0.7*
J	**128**	**28**	**39.4 ± 6.4**	**3.8 ± 0.7**	**244 ± 46**	**3.8 ± 0.8**	**3.8 ± 0.5**

Note: Bold type indicates results from sites with a high quality geomorphic setting. Italicized ages were excluded, as explained in the text. Errors are 2σ. ^{10}Be and ^{26}Al concentrations normalized to sea level, high latitude production rates of 5.1 and 31.1 atoms/g/yr, respectively.
n.d. = not determined.

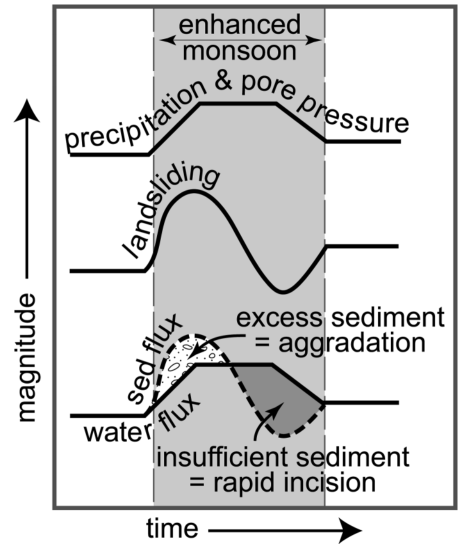

Figure 3. Schematic diagram of proposed precipitation and sediment-flux impact on fluvial aggradation and incision. Increased precipitation leads to more landsliding by raising pore pressure and destabilizing hillslopes. While sediment flux is greater than river's transport abilities, aggradation occurs. When easily removed hillslope-derived material is exhausted, sediment flux falls below river's transport capacity, and rapid incision commences.

above the river are more likely to occur owing to short-lived (1–2 k.y.) secondary erosional events. Cosmogenic production attenuates with rock depth such that >85% of the cosmogenic nuclides form in the uppermost 1 m of bedrock ($\rho \approx 2.7$ kg/m^3) (Gosse and Phillips, 2001). Erosion of 1–2 m of bedrock during rapid removal of alluvium in a valley would reset the rock cosmogenically and lead to subsequent accumulation of similar concentrations of cosmogenic radionuclides at different elevations above a modern river. Under this interpretation, the Marsyandi would have alluviated to a height of at least 125 m above the modern river some time prior to ca. 8 ka. Subsequently, incision of these deposits over a period within the uncertainty interval of the cosmogenic dates (probably ≤2 k.y.) and removal of a veneer of bedrock from the valley walls thus could have removed essentially all prior nuclide concentration. Isolated deposits of bedded sands and rounded cobbles 100–120 m above the modern river support the concept that alluvium aggraded to this height (Fig. 2B).

DISCUSSION

Given a fill of ~100 m and incision occurring over 1–2 k.y., every 100 yr the river would be 5–10 m lower. Could sufficient bedrock be eroded from the valley walls during this interval to reset the rock's cosmogenic clock? Whereas the required horizontal bedrock incision rates are high (≥5–10 mm/yr), comparable rates have been documented elsewhere (e.g., 2–10 mm/yr, Burbank et al., 1996; 10–100 mm/yr, Whipple et al., 2000; 4–17 mm/yr, Hartshorn et al., 2001). Moreover, each of our samples was collected from sites with a clear fluvial overprint, where we expect river erosion to have been focused and intense.

Evidence for Holocene alluviation in the Marsyandi gorge comes from both scattered remnants of fluvial deposits and cosmogenically inferred Holocene bedrock incision to 125 m above the modern river (Fig. 2B). Alluviation occurs when sediment supply exceeds fluvial transport capacity and can be driven by decreases in the fluvial gradient or by increases in the sediment/water discharge ratio. In the Marsyandi valley, river gradient could be reduced by local perturbations, such as a landslide dam that blocks the valley, or downstream tectonic uplift. The nearest structures with observed Holocene offset are ≥50 km downstream and could not have caused the inferred aggradation. Given that the region of Holocene alluviation in the Greater Himalaya spans >600 m of elevation change along a 15-km-long reach, either one colossal landslide or multiple slides spaced closely in time, with few slides before or afterward, would be necessary. We see no evidence of the former along the Marsyandi, and the latter is improbable without climatic or tectonic forcing.

We conclude that climatically stimulated increases in the relative sediment/water discharge ratio are most likely to have caused the cycle of aggradation followed by incision. Summer monsoons dominate the climate in the central Himalaya, and there is strong evidence from marine cores (Clemens et al., 1991; Overpeck et al., 1996; Schulz et al., 1998) and paleolake cores from Tibet (Gasse et al., 1996) and India (Enzel et al., 1999) that the monsoons were stronger than today between 9.5 and 5.5 ka and weaker during the preceding 10–15 k.y. The temporal coincidence of the paleomonsoon with our observed interval of alluviation and reincision suggests a causal linkage.

Enhanced monsoonal precipitation is likely to accelerate the rate of sediment delivery to trunk streams by triggering landslides, flushing out lower order alluvial hollows, and stripping the hillsides of their soil mantle, which had accumulated during the low-precipitation period ca. 24–10 ka. Under this scenario, the primary trigger for landsliding would be higher pore-water pressure, which reduces effective normal stress on failure planes and induces destabilization of hillslopes (Hoek and Bray, 1977). Despite the expected enhancement of monsoonal discharge, the increase in hillslope-derived sediment contribution would temporarily overwhelm a river's transport capabilities and lead to aggradation (Fig. 3). Throughout this aggradational interval, the rivers would be delivering enhanced sediment loads to the downstream basins, including the Ganges-Brahmaputra delta. Presumably, accelerated landsliding would persist until the more readily removed material was exhausted. The sediment flux would diminish as colluvial hollows were emptied, accumulated soil was stripped off the hillslopes, and mountainsides attained a new equilibrium as slopes adjusted to the increased pore pressure. When the transport capacity again exceeded the sediment flux, rivers would incise through the aggraded alluvium and into the underlying bedrock. Our model predicts an increased sediment load during the enhanced monsoon, particularly during the first half as hillslope sediments are liberated. Goodbred and Kuehl (2000) showed that the annual sediment deposition in the Ganges-Brahmaputra delta was more than double modern rates at 11–7 ka, coinciding with the early Holocene strengthened monsoon. This indicates that not just the Marsyandi River, but the entire central and eastern Himalaya underwent a similar increase in sediment flux.

CONCLUSIONS

Impulsive aggradation, followed by bedrock incision and nearly complete removal of the fluvial deposits, has implications for strath-terrace studies. Dating of vertical flights of fluvial surfaces at a given site is a necessary test for the presence of reset cosmogenic ages and should precede any inference of mean bedrock-incision rates.

Changing climate can have complex, often counterintuitive impacts on erosion and deposition in fluvial systems. Our cosmogenic exposure ages and stratigraphic studies provide evidence for alluviation and reincision in the Marsyandi River's steep bedrock gorge during an early Holocene interval of increased monsoonal precipitation. We propose that a switch to a wetter climate increases pore-water pressures on hillslopes and liberates a pulse of debris that, despite a higher water discharge, temporarily overwhelms a river's transport abilities and drives aggradation within formerly bedrock gorges. Once the easily flushed hillslope material is exhausted, the hillslope-derived sediment flux should decrease and allow river incision and removal of the landslide-derived alluvium. Contrary to expectations based on viewing the striking bedrock gorges of the world's active collisional ranges, they do not undergo continuous incision. Rather, they can be transformed to sediment-choked, aggrading valleys when precipitation is increased.

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