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Bedload-to-suspended load ratio and rapid bedrock incision from Himalayan landslide-dam lake record

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Abstract

About 5400 cal yr BP, a large landslide formed a >400-m-tall dam in the upper Marsyandi River, central Nepal. The resulting lacustrine and deltaic deposits stretched >7 km upstream, reaching a thickness of 120 m. ^{14}C dating of 7 wood fragments reveals that the aggradation and subsequent incision occurred remarkably quickly (~500 yr). Reconstructed volumes of lacustrine (~0.16 km^3) and deltaic (~0.09 km^3) deposits indicate a bedload-to-suspended load ratio of 1:2, considerably higher than the ≤1:10 that is commonly assumed. At the downstream end of the landslide dam, the river incised a new channel through ≥70 m of Greater Himalayan gneiss, requiring a minimum bedrock incision rate of 13 mm/yr over last 5400 yr. The majority of incision presumably occurred over a fraction of this time, suggesting much higher rates. The high bedload ratio from such an energetic mountain river is a particularly significant addition to our knowledge of sediment flux in orogenic environments.

Keywords: Bedload; Suspended load; Himalaya; Nepal; Bedrock incision; Landslide dam

Introduction

Quantifying the erosional flux from the Himalaya is of primary importance for calibrating Himalayan tectonic evolution models (Willett, 1999; Beaumont et al., 2001), assessing the impact of Himalayan erosion on atmospheric CO_2 levels (France-Lanord and Derry, 1997; Raymo and Ruddiman, 1992), and understanding hillslope and channel processes and rates within mountainous environments (Whipple et al., 1999). Though glaciers can be important erosive agents at higher altitudes (Brozovic et al., 1997) and landsliding is the primary Himalayan hillslope-lowering process (Burbank et al., 1996; Shroder and Bishop, 1998), rivers receive all the eroded material and are ultimately responsible for carrying it to the ocean. Therefore, accurately measuring river sediment flux is a key to quantifying orogenic erosion. Most studies rely on suspended load measurements alone (e.g., Subramanian and Ramanathan, 1996; Collins, 1998), because the bedload component of the sedimentary flux in alpine rivers is typically difficult to measure (Leopold and Emmett, 1976). Many geomorphologic studies incorporate accepted, though essentially unconfirmed, estimates of bedload (Lane and Borland, 1951) that place it at a seemingly unimportant 2–12% of the suspended load for rock and gravel-bedded mountain streams. The largest bedload estimate made in the Himalaya (Galy and France-Lanord, 2001) suggests that the true bedload flux may be as high as 50% of the total, but this work is predicated on a geochemical mass balance and centers on the large alluvial-plain rivers, Ganga and Brahmaputra, rather the smaller mountain rivers that do the majority of the erosive work and are less complicated by significant sediment storage in foreland basins.

Sustained currents of 3–5 m/s and boulder-sized bedload in the swift and turbulent rivers of the Himalaya render direct measurement of bedload flux nearly impossible via conventional

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methods (e.g., Eugene, 1951). Consequently, we depend on fortuitous field conditions to trap both bedload and suspended load in such a way that they can be measured. In the upper Marsyandi catchment of central Nepal near the village of Latamrang, a large mid-Holocene landslide dammed the river (Weidinger and Ibetsberger, 2000; Korup et al., 2006; Weidinger, 2006), created a lake, and trapped a high percentage of the incoming sediments. The river has subsequently incised through the original dam and sedimentary deposits, leaving exposed remnants along the margins of the valley. Reconstructed volumes of the lake and delta deposits yield a suspended load-to-bedload ratio. The same landslide event allows us to quantify a bedrock incision rate since the mid-Holocene, where the reincising channel cut through fresh bedrock.

Mountain rivers not only remove all the eroded sediments from orogens, but they control the hillslope (Burbank et al., 1996) and glacial (Alley et al., 2003) base levels through bedrock incision. Thus, the rate at which rivers are capable of incising is also fundamentally important to understanding orogenic erosion. Clearly, geologically instantaneous incision rates (<100 yr duration) can be remarkably rapid (100 mm/yr, Whipple et al., 2000; 182 mm/yr, Hartshorn et al., 2002) and even sustained rates (10^3–10^4 yr duration) reach tectonic speeds (e.g., 12 mm/yr, Burbank et al., 1996). More independent field measurements from a variety of rivers and timescales are important for calibrating fluvial incision models. Bedrock incision below the landslide dam in the upper Marsyandi River provides an estimate of the possible incision rate through crystalline bedrock for a medium-sized Himalayan river in the rain-shadow side of the range crest.

Study area

The Marsyandi River drains a 4800-km^2 region of central Nepal, sourcing from the Tibetan border and traversing south, between the >8000-m peaks of Annapurna and Manaslu, into the foothills of the Lesser Himalaya (Fig. 1). The sedimentary deposits that are the focus of this study lie along the upper Marsyandi River at 2200–2800 m altitude, where 1620 km^2 of catchment remain upstream. Whereas these deposits rest on Greater Himalayan metasedimentary marbles and gneisses, the majority of the upper catchment drains low-grade Tibetan Sedimentary Sequence slates, limestones, and quartzites and the Manaslu leucogranite (Colchen et al., 1986). The Tibetan Sedimentary Sequence is separated from the Greater Himalayan Sequence by the South Tibetan Detachment (e.g., Searle and Godin, 2003), a normal-motion structure with down-to-the-north displacement.

The sedimentary deposits in this study are below the limits of late Pleistocene and present glaciation. Glaciers and paraglacial conditions currently cover only 11% and 40%, respectively, of the upper Marsyandi catchment (Pratt et al., 2002). Farther up the Marsyandi valley, thick glacial and outwash deposits have been preserved since sometime in the late Pleistocene when glacial/paraglacial processes affected ~90% of the region (Owen et al., 1998). As part of a larger regional study (Burbank et al., 2003; Gabet et al., 2004), water and sediment discharges

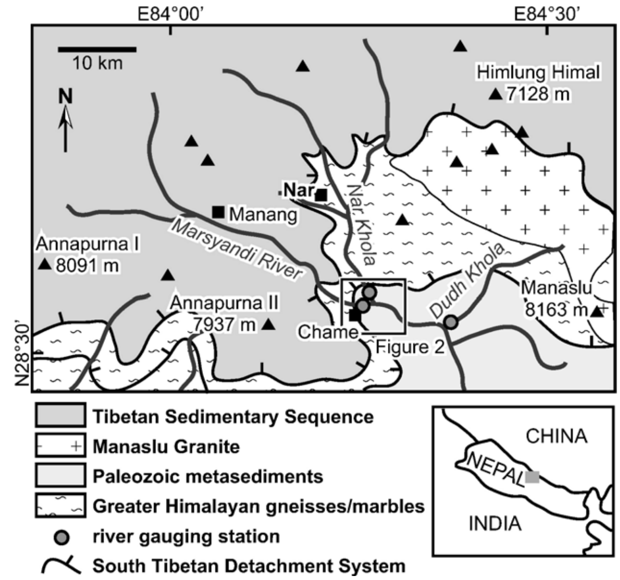

Figure 1. Simplified geologic map of the Upper Marsyandi region based on Searle and Godin (2003) and Coleman (1996).

were measured during the 2002–2004 summer monsoons at 3 sites relevant to this study in the upper Marsyandi catchment (Fig. 1). Based on a local weather-station network (Barros et al., 2000), monsoonal rainfall as high as 5 m/yr occurs along the lower Marsyandi River, but in the upper Marsyandi catchment, north of the highest Himalayan peaks, precipitation is <0.5–1.5 m/yr (Burbank et al., 2003).

Methods

Field work conducted during spring of 2002 included mapping the extent of the sedimentary deposits along the Marsyandi and its tributaries at 2200–2800 m altitude; stratigraphic analysis of exposed deposits; collection of wood fragments for ^{14}C dating; and collection of sediment samples for grain-size analysis. Sedimentary sequences were measured by tape and Laser Range Finder. Exposures are numerous (Fig. 2a) but discontinuous, such that stratigraphic sections were measured where possible, and the continuity of the intervening sediments was inferred. Seven ^{14}C dates were measured by Geochron Laboratories using accelerator mass spectrometry (AMS) or conventional procedures, depending on the sample size (Table 1). ^{14}C ages were corrected using CALIB 5.0.2 (Stuiver and Reimer, 1993) with the calibration curve by Reimer et al. (2004). The vertical distance of bedrock incision was measured by Laser Range Finder.

Original sediment volumes were reconstructed from field observations and analysis of a digital elevation model (DEM). A 10-meter-pixel DEM was generated by digitizing contours from 1:50,000-scale Nepal Survey Department maps with a 40-meter contour interval (Nepal and Finland, 2001). Points were sampled along each contour to form vertices of a triangular irregular network in Arc/Info, and elevations of triangular elements were sampled over a 10-meter-pixel grid to generate the DEM. Topographic cross-sectional profiles were produced