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Erosion of the Tsangpo Gorge by megafloods, Eastern Himalaya

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ABSTRACT

At the southeastern margin of the Tibetan Plateau, the Yarlung-Tsangpo River plunges through the Himalaya to drop >2 km through the Tsangpo Gorge. Upstream, relict glacial dams and impounded lake terraces suggest that Quaternary lakes as large as 800 km^3 catastrophically drained through the gorge as megafloods. We report on new megaflood deposits downstream of the gorge and use detrital zircon U-Pb provenance data to demonstrate that these high-magnitude events originated in Tibet, and more effectively focused erosion in the gorge than both the extremely erosive modern peak flows and one of the largest landslide-dam outburst floods ever documented. Our findings support the proposition that in this steep, narrow gorge, where hillslope angles are near the threshold angle of bedrock failure, megafloods provide a mechanism to rapidly evacuate hillslope material and focus erosion on channel-adjacent hillslopes. Although megaflood frequency remains unconstrained, we demonstrate the capability of these events to contribute substantially to rapid exhumation in this region.

INTRODUCTION

Where the Yarlung-Tsangpo River (southeastern Tibetan Plateau) descends through the easternmost Himalaya, it carves the Tsangpo Gorge, a <200-m-wide, 200-km-long bedrock knickzone descending more than 2 km between two peaks with elevations >7 km (Fig. 1A). Within the gorge, high stream power and high topographic relief (Finnegan et al., 2008) drive contemporary erosion rates of >5 mm/yr (Larsen and Montgomery, 2012) and possibly as high as 10 mm/yr (Stewart et al., 2008) (Fig. 1C). On a longer time scale, focused erosion has exhumed the Namche Barwa massif, an active crustal-scale antiform (Burg and Podladchikov, 1999), at an average rate of 3–5 km/m.y. since 5–10 Ma (Booth et al., 2004, 2009), and at a rate as high as 10 km/m.y. since 3–5 Ma (Burg et al., 1998; Seward and Burg, 2008; Enkelmann et al., 2011). This co-occurrence of focused surface erosion and active rock uplift led previous researchers to hypothesize a self-sustaining relationship between the two, localized to the gorge region since at least 3–5 Ma (Zeitler et al., 2001).

During the Quaternary (after 2.6 Ma), glacial ice and debris from Tibetan tributaries

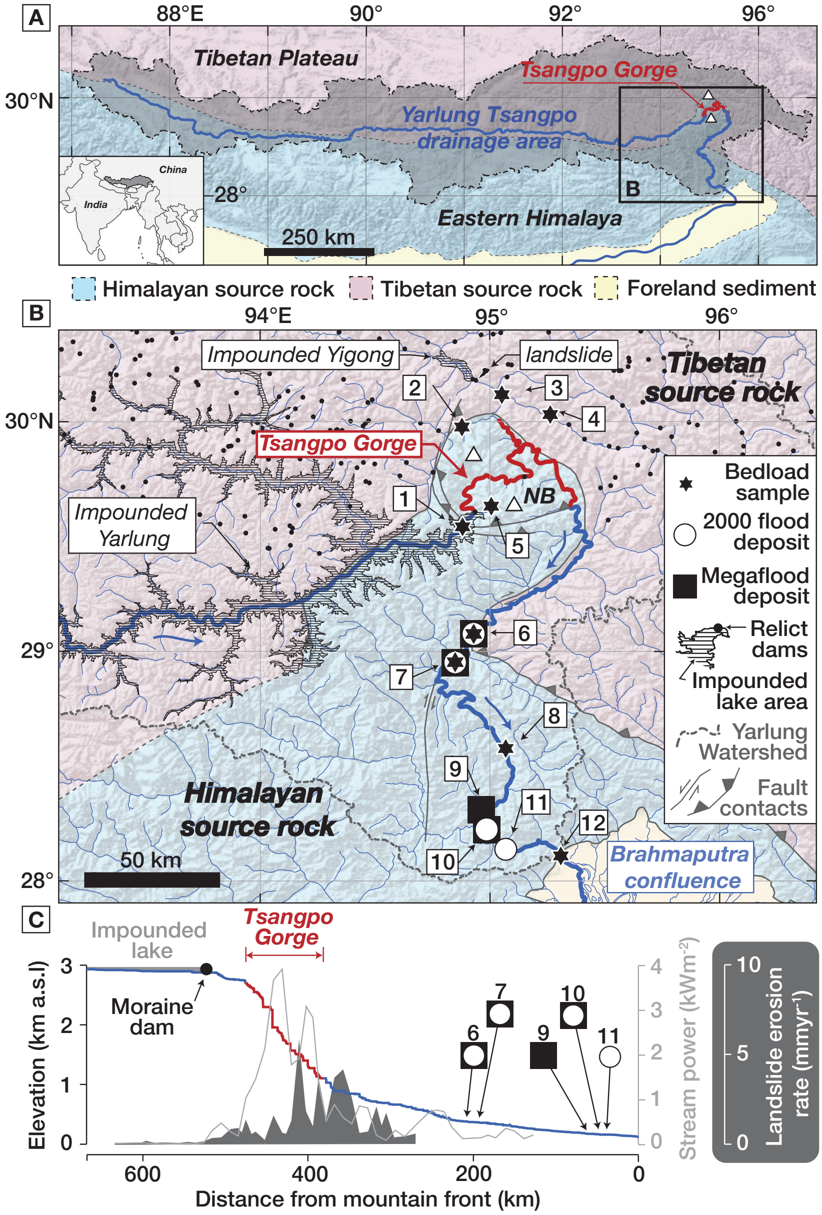

Figure 1. A: Location of Yarlung-Tsangpo River (Tibetan Plateau). Where the river turns southward and plunges from the Tibetan Plateau through the Tsangpo Gorge, it begins to erode Himalayan source rocks of the Namche Barwa massif (NB) (Booth et al., 2009; Zhang et al., 2012). B: Relict glacial dams upstream of Tsangpo Gorge record impoundment of massive Quaternary lakes (Montgomery et al., 2004; Chen et al., 2008; Korup and Montgomery, 2008), which catastrophically drained through the gorge. An A.D. 2000 landslide impounded the Yigong River, a tributary to the gorge; failure of the landslide dam released an analogous smaller-magnitude flood through the gorge. C: We sampled megaflood and 2000 flood slackwater deposits downstream of the gorge (adapted from Montgomery et al., 2004; Finnegan et al., 2008; Larsen and Montgomery, 2012), and modern river sediment samples (locations 3, 5–8) throughout the watershed where previously published data (locations 1, 2, 4, 12 from Stewart et al., 2008; Cina et al., 2009; Zhang et al., 2012) did not exist. Sample 5 is from a small cirque draining the western Namche Barwa massif; a.s.l.—above sea level.

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impounded massive lakes on the Yarlung-Tsangpo River in the immediate headwaters of the Tsangpo Gorge, with volumes estimated to be as much as ~800 km^3 (Montgomery et al., 2004; Korup and Montgomery, 2008). Glacial ice and debris dams of main stem valleys by tributary glaciers often fail by overtopping or ice-marginal breaching, producing some of the largest freshwater floods on Earth (O'Connor et al., 2013). These megafloods may generate extreme discharges of water (>10^6 m^3 s^{-1}) capable of focused downstream erosion (O'Connor et al., 2013) and sparse slackwater deposition in hydraulically sheltered areas (Atwater, 1984). Glacial moraines crosscut by the river at the entrance to the Tsangpo Gorge, and immediately downstream of multiple lake terrace levels extending throughout the upstream drainage network (Montgomery et al., 2004; Chen et al., 2008), provide evidence for lake impoundment and the possibility that megaflooding recurred. Here we present new evidence that megaflooding through the Tsangpo Gorge preferentially eroded the Namche Barwa massif where it is exposed in the gorge.

SLACKWATER DEPOSITS

We identified slackwater deposits in hydraulically sheltered areas along the main stem of the Yarlung Tsangpo (locally named Siang) River and at local tributary mouths downstream of the Tsangpo Gorge at elevations as much as 150 m above the modern channel. These deposits drape existing topography, in many cases unconformably overlying bedrock or unreworked landslide deposits. Four identified deposits, as much as 30 m above the modern channel, originated from an A.D. 2000 flood (Evans and Delaney, 2011) resulting from the temporary impoundment of the Yigong River by a massive landslide 40 km upstream of the Tsangpo Gorge (Fig. 1B). The 2000 flood deposits are generally very fine to medium-grained sand with millimeter-scale coarse-grained laminations and occasional scour features within fining-upward and massive sequences, indicating deposition from suspension. The deposits are tabular and laterally extensive, with vegetated surfaces occasionally capped by landslide debris. Four additional deposits span higher elevations as much as 120 m above the 2000 flood deposits; these higher deposits are also very fine to medium sands, with occasional scour features and isolated pebbles. Unlike the 2000 flood deposits, the higher deposits show moderate soil development and destruction of primary depositional features by bioturbation; they are commonly overlain by poorly sorted, angular to subangular landslide deposits. Based on their similarity to the 2000 flood deposits, we interpret these older, higher deposits to have originated from megaflood events. In contrast to the megaflood deposits, alluvial terraces in the valley are characterized by discontinuous lenses of coarser grained sand that exhibit fluvial bedforms (e.g., cross-bedding) and are overlain by subrounded, imbricated gravel consistent with fluvial bedload transport.

Petrographic and detrital zircon U-Pb data indicate that the 2000 flood and megaflood sediments reflect a mixed Tibetan and Himalayan provenance (Fig. 2), indicating that these floods originated in Tibet and entrained some amount of Himalayan input prior to deposition. In this region, detrital zircon U-Pb crystallization ages younger than 1000 Ma are characteristic of two primary sources: Tibetan zircons are younger than 300 Ma (Cina et al., 2009; Zhang et al., 2012), whereas Himalayan zircons are typically older than 300 Ma with a peak probability density ca. 500 Ma (Stewart et al., 2008; Cina et al., 2009; Amidon et al., 2005), except anatectic zircons younger than 30 Ma observed only in the Namche Barwa massif (Booth et al., 2009). These anatectic zircons are further distinguishable by high U/Th ratios of >10 (Booth et al., 2004; Zhang et al., 2012; see Hoskin and Schaltegger, 2003, for discussion; Fig. 2). The U-Pb ages from Yarlung-Tsangpo River sediment upstream from the Tsangpo Gorge are dominantly Tibetan, and because zircon is an effective sediment tracer in this system (Stewart et al., 2008; Enkelmann et al., 2011), the downstream change in detrital Himalayan zircons is a proxy for the contribution of sediment flux originating within the gorge (Stewart et al., 2008) (Fig. 2A).

TSANGPO GORGE EROSION

To constrain the contribution of sediment flux originating within the Tsangpo Gorge

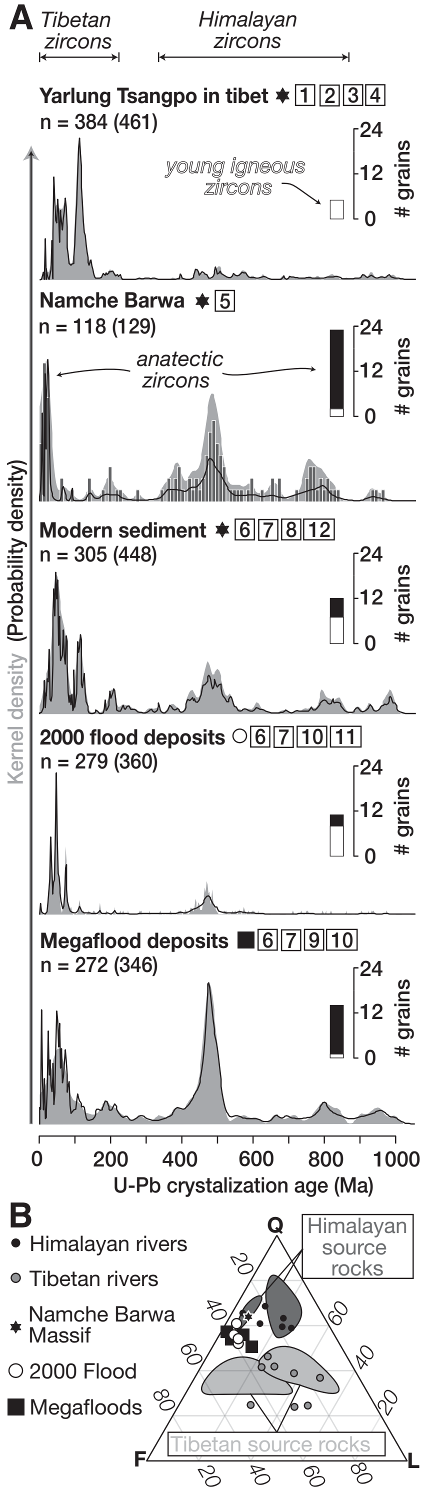

Figure 2. A: Detrital zircon U-Pb crystallization age probability density functions (black lines) and kernel density estimates (gray) characterize two primary sources: Tibetan zircons are younger than 250 Ma, shown in the Tibetan tributaries flowing into Tsangpo Gorge (compiled from this study and Zhang et al., 2012); and gorge-derived Himalayan zircons are typically ca. 500 Ma, with small component of <30 Ma anatectic grains from the western side of Namche Barwa massif (Booth et al., 2004), shown in both a detrital sample from a small west-draining cirque and compiled bedrock ages from Namche Barwa massif (gray histogram from Booth et al., 2004; Zhang et al., 2012; n = 325). Inset bar shows proportion of young (<30 Ma) anatectic zircons sourced only from Namche Barwa (black) with U/Th of >10, and young igneous zircons (white) with U/Th of <10. Himalayan-age zircons in modern sediment downstream of Tsangpo Gorge (compiled from this study; Stewart et al., 2008; Cina et al., 2009) demonstrate the addition of zircons eroded from the gorge, including a few young anatectic grains. A.D. 2000 flood deposits show a similar proportion of gorge-derived zircons, with slightly fewer anatectic grains. Megaflood deposits contain a much higher proportion of Himalayan zircons and anatectic grains sourced only from Namche Barwa, indicating extreme focusing of erosion in the gorge by megafloods. Sample numbers refer to locations in Figure 1. B: Petrographic analyses of flood sediments rule out local sources for the deposits and confirm a mixed provenance between Himalayan and Tibetan source rocks (Himalayan and Tibetan source data from Zhang et al., 2012; Garzanti et al., 2004). Q—quartz; F—feldspar; L—lithics.

from each of three different events (the 2000 flood event, megaflood events, and the modern river discharge), we fit cumulative probability density functions (CDFs) from observed U-Pb ages to modeled CDFs representing variable contributions from upstream source areas and the Tsangpo Gorge (Fig. 3A; see the GSA Data Repository[1] for more details of U-Pb data and modeling). Our modeling confirms previous work (Stewart et al., 2008; Singh and France-Lanord, 2002; Garzanti et al., 2004) showing that the Tsangpo Gorge is the source of ~40%–50% of zircons in modern river sediment downstream, an impressive contribution from just ~2% of the Yarlung-Tsangpo drainage area (Fig. 3B).

The best-fit models of the A.D. 2000 flood deposits require a smaller contribution of sediment from the Tsangpo Gorge and a large contribution specifically from the Yigong River, where the 2000 flood was sourced. This difference in provenance suggests that preferential erosion immediately downstream of the Yigong landslide dam and along the path to the Tsangpo Gorge diluted the gorge sediment contribution typical of modern river discharge. This interpretation is consistent with accounts of extreme erosion downstream of the breached dam by channel incision and landsliding (Evans and Delaney, 2011).

While megaflood samples contain both Tibetan and Himalayan age components, they are significantly enriched in both ca. 500 Ma Himalayan zircons and anatectic zircons younger than 30 Ma relative to modern river samples. Our modeling indicates that this enrichment is best explained by a nearly twofold increase in the contribution of zircons from the Namche Barwa massif rocks exposed in the Tsangpo Gorge. We interpret this increase to indicate preferential erosion of the gorge during megafloods that originated in Tibet, possibly by processes similar to those observed after the 2000 flood.

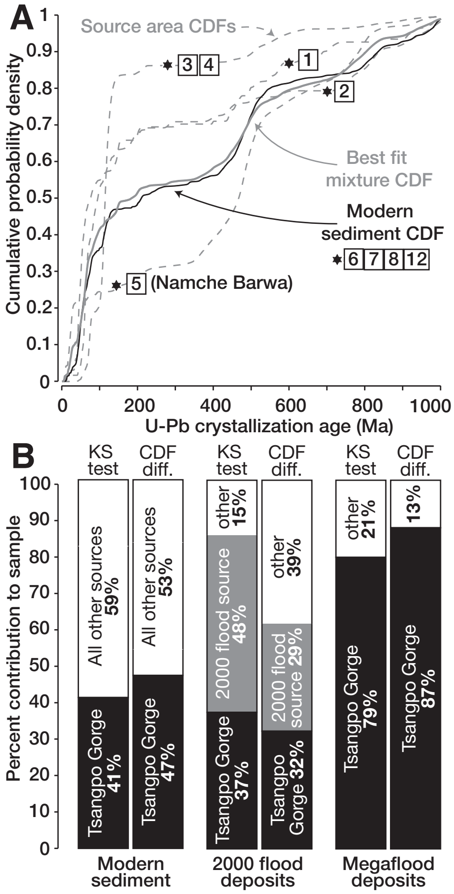

Figure 3. A: Cumulative probability density functions (CDFs) for mixtures of four source-area samples and fit of modeled CDF to observed CDFs of modern river sediment samples, an A.D. 2000 flood, and megaflood deposits. Sample numbers refer to locations in Figure 1. Models were fit using both the two-sample Kolmogorov-Smirnov (KS) test and the total difference (diff.) between the modeled and observed CDF (for model details and results, see the Data Repository [see footnote 1]). B: Best fit model results are insensitive to fit calculation, demonstrating a twofold increase in the contribution from the Tsangpo Gorge to megaflood deposits, relative to modern sediment. Modeling also demonstrates a significant contribution to the A.D. 2000 flood deposits from their source area in the Yigong River.

ROLE OF MEGAFLOODS

Larsen and Montgomery (2012) observed that the A.D. 2000 flood triggered landsliding along the channel immediately downstream of the failed dam, by eroding the base of channel-adjacent hillslopes. Hillslope angles within the Tsangpo Gorge region are high (mode angles of 37°–39°) and decoupled from long-term (>10^5 yr) averaged erosion rates, suggesting that hillslopes in this region are persistently near the threshold of slope failure (Larsen and Montgomery, 2012). In such a region characterized by threshold angle hillslopes, we expect large floods to act as an efficient mechanism to contemporaneously trigger landsliding and transport fine-grained soil and landslide debris downstream.

The combined influence of steep hillslopes and narrow river valleys maximizes flood depth and therefore bed shear stress. Calculations of bed shear stress for valley widths and hillslope angles similar to those observed in the Tsangpo Gorge indicate that peak megaflood discharges on the order of 10^6 m^3 s^{-1} (Montgomery et al., 2004) are capable of moving landslide debris up to ~8–18 m in diameter (Fig. 4), and fully suspending 1 m blocks (for calculation details, see the Data Repository). Given long-term exhumation rates of 5–10 km/m.y., a single event capable of removing this much material would be equivalent to ~1–4 k.y. worth of erosion.

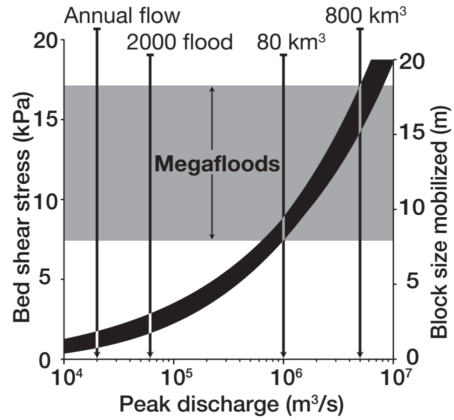

Figure 4. Calculation of bed shear stress and maximum intermediate axis diameter (block size) of mobilized blocks as a function of peak discharge through a 200-m-wide gorge. Narrow range of solutions (thickness of black line) shows that this relationship is insensitive to hillslope angle and valley width for values similar to those observed (see the Data Repository [see footnote 1] for details).

Our results demonstrate the capability of Quaternary megafloods to preferentially erode the Tsangpo Gorge. While the number and recurrence intervals of such events are currently unknown, their impressive erosive potential raises the possibility that megafloods contributed substantially to the long-term exhumation of the gorge.

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[1]GSA Data Repository item 2013280, methods (sampling, U-Pb, and petrographic analyses, modeling), and U-Pb and petrographic data, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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