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Short Paper

Evidence for Holocene megafloods down the Tsangpo River gorge, southeastern Tibet

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Abstract

Lacustrine and alluvial terraces and sediments record the extent of at least two Holocene glacially dammed lakes immediately upstream of the Tsangpo River gorge at the eastern syntaxis of the Himalaya. The larger lake covered 2835 km^2, with a maximum depth of 680 m and contained an estimated 832 km^3 of water; the smaller lake contained an estimated 80 km^3 of water. Radiocarbon dating of wood and charcoal yielded conventional radiocarbon ages of 8860 ± 40 and 9870 ± 50 ^{14}C yr B.P. for the higher set of lake terraces, and 1220 ± 40 and 1660 ± 40 ^{14}C yr B.P. for sediments from the lower terraces. Catastrophic failure of the glacial dams that impounded the lakes would have released outburst floods down the gorge of the Tsangpo River with estimated peak discharges of up to 1 to 5×10^6 m^3 s^{-1}. The erosive potential represented by the unit stream power calculated for the head of the gorge during such a catastrophic lake breakout indicates that post-glacial megafloods down the Tsangpo River were likely among the most erosive events in recent Earth history.

Keywords: Outburst floods; Tsangpo River; Himalaya; Namche Barwa; Paleolakes

Introduction

Catastrophic outburst floods are important events in the history of both Earth and Mars (Baker, 1981), and scars from ancient catastrophic floods still dominate some contemporary landscapes, notably the famous channeled scablands carved by the Pleistocene Lake Missoula outburst floods of eastern Washington (Bretz, 1923). Recent failures of moraine-dammed lakes in the Himalaya produced peak discharges up to 60 times those of seasonal floods (Cenderelli and Wohl, 2001) and the relative influence of rare vs. common floods on rates of river incision into bedrock is receiving renewed interest in the study of interacting climatic, tectonic, and erosional processes in tectonically active mountain ranges (Hartshorn et al., 2002; Pratt et al., 2002). We report field evidence for extensive Holocene glacially dammed lakes immediately upstream of the gorge of the Tsangpo River, the catastrophic failure of which would have released immense floods down the deepest valley on Earth. Due to the routing of flow through this steep, narrow gorge, estimates of the maximum unit stream power during lake breakout events rival estimates for the largest known terrestrial floods. The erosion potential of such catastrophic events suggests a role for extreme events in the incision of Himalayan rivers in general, where failure of large glacial and landslide dams are recurrent phenomena.

The Tsangpo River flows east nearly 1300 km along the southern edge of the arid Tibetan Plateau before slicing through the Himalaya in a deep gorge at the eastern syntaxis of the range. Flanked by 7856-m Namche Barwa and 7150-m Giala Peri, the river drops through the gorge from greater than 2900 m to less than 500 m in elevation over the course of 200 km. The rugged terrain and remote location of the gorge

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obscured the identity of the Tsangpo River as a major source of the Brahmaputra River until the late 19th century (Montgomerie, 1868). The annual discharge recorded at the lowest gauging station on the Tibetan Plateau, located at Nuxia just upstream from the head of the Tsangpo River gorge, averaged just under 2000 $m^3 s^{-1}$ from 1956 to 2001. Previous work farther upstream attributed the formation of wide valleys, gorges, and terraces along the Tsangpo River to active faulting transverse to the river (Zhang, 1998). The prediction of rapid erosion in the Tsangpo River gorge is supported by isotopic dating of metamorphic rocks that indicate exhumation of rocks now at the surface from depths of 30 km over the past 4 myr, requiring sustained erosion at extraordinarily high rates of up to 10 mm yr^{-1} (Burg et al., 1997). Modeling of the erosive potential of Himalayan rivers highlights the gorge of the Tsangpo River as having the potential for incision rates well above those for most of the range (Finlayson et al., 2002; Zeitler et al., 2001).

Field surveys revealed a prominent set of lacustrine and alluvial terraces on the valley margins along both the Tsangpo River and the Nyang River, a major tributary that joins the Tsangpo about 60 km above the head of its gorge (Fig. 1). Initial observations from road-cut exposures on steep valley walls revealed a second set of higher lacustrine deposits with little physiographic expression. Where time and access permitted, we sought out the highest elevation of lacustrine silt deposits in locations where terraces were observed during vehicular reconnaissance or identified on topographic maps. Terrace elevations were measured with a hand-held GPS (global positioning system) receiver, or surveyed with laser range finders from locations of GPS readings. Downslope of our field area, the width of the Tsangpo River through its gorge was measured from Landsat 7 images and the slope was obtained from elevation profiles extracted from the DTED (Digital Terrain Elevation Data) 90-m DEM (Digital Elevation Model). Other DEM analyses used NASA's 3-arc-second elevation data from the Shuttle Radar Topography Mission.

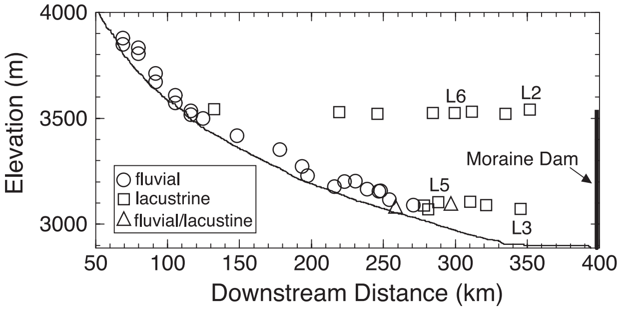

Figure 2. Composite long profile of the Nyang and Tsangpo rivers showing terraces (fluvial terraces, lacustrine terraces, and composite fluvial/lacustrine terraces where fluvial and lacustrine sediments are interstratified within the same terrace). Elevations of terrace tops determined by GPS readings from a hand-held GPS receiver (Garmin 12XL). Labeled terraces refer to those for which ^{14}C dates are reported in Table 1. Thick black bar at 400-km downstream distance (measured from the drainage divide on the Nyang River) represents height of truncated moraine shown in Figure 3.

Collectively, a prominent set of lacustrine terraces forms a well-defined surface part way up the valley walls above the modern floodplain along both the Tsangpo and Nyang Rivers. GPS-measured elevations for the tops of these terraces were from 3071 to 3104 m, a range of values a little greater than the variance expected due to the nominal vertical resolution of the hand-held GPS unit (±10 m) (Fig. 2). Exposed terrace sediments are composed mostly of interbedded silt and sand. Some of the lake sediments also include rounded gravel or cobbles in a silty or sandy matrix that are most likely ice-rafted dropstones. Little evidence of soil formation was observed at these exposures.

The higher lacustrine terraces lack extensive topographic expression and are composed predominantly of silt and sand with some interbedded fluvial gravels, and apparent drop stones. Individual terrace tops are generally preserved only as small exposures in topographic embayments along the main valley. These higher terraces are deeply dissected with a well-defined soil, and contain numerous, but dispersed and thoroughly weathered granitic clasts. Although the higher terraces lack extensive flat tops, GPS-measured elevations for the highest exposures of lacustrine sediments preserved in individual terraces and on valley walls ranged from 3525 to 3540 m, a range close to the nominal vertical accuracy of the GPS unit.

The general stratigraphy of the lower terrace at the town of Bayi provides evidence for a strong glacial association during terrace formation. The uppermost exposures consist of interbedded silts and sands that overlie massive lacustrine silts containing dropstones. These silts, in turn, overlie gravel and imbricated cobbles similar to deposits of the

Figure 1. Location map of the study area around Namche Barwa, southeastern Tibet. Inset box shows area of Figure 5.

modern floodplain. The abundance of dropstones in the lake sediment indicates that glaciers were calving into the lake at the time of terrace deposition.

Immediately upstream from the last terrace in each set of lacustrine terraces (i.e., higher and lower), a set of alluvial terraces rises at gradients typical of gravel-bed rivers (0.01–0.03). Lacustrine and alluvial terraces were readily differentiated based on their composition and internal stratigraphy; lacustrine terraces here consist primarily of well-laminated (mm–cm) silts and sand, and interbedded sand with climbing ripples, whereas alluvial terraces consist of massive deposits of gravel and cobbles. The elevation of the downstream transition from fluvial to lacustrine terraces records the lake-level elevations for each of the two ancient lakes. In some locations, thin silt deposits plastered to the valley walls form several terracettes that define a series of “bathtub rings” at elevations below each set of the lake terraces.

Ages for the terraces were constrained by radiocarbon dating of charcoal from two sets of higher and lower terraces. Two samples from higher lake terraces yielded calibrated age ranges (2σ) of 8210–7810 B.C. and 9350–9240 B.C. Two samples from lower terraces yielded calibrated dates of A.D. 260–450 and A.D. 690–900 (Table 1).

The lake surface elevations established by the transitions from alluvial to lacustrine terraces together with the maximum elevation of lacustrine sediments allow estimation of the volumes of the two ancient lakes from the modern topography if the downstream locations of the lake-forming dams are known. Above the entrance to the gorge, prominent moraines from valley glaciers originating on the northwest side of the Namche Barwa massif (Fig. 3), and extending into and across the valley of the Tsangpo River, are truncated at the elevation of the higher lake level (Fig. 4).

Field inspection of the vicinity of the potential moraine dam reveals evidence that the moraine extended across and dammed the river and that at least the lower (and more recent) of the lakes drained catastrophically. Moraine debris extends across the Tsangpo River and is preserved on both sides of the river. Outwash terraces slope away from the moraine dam both upstream and downstream, further indicating that the dam blocked the river. The ridgeline of a smaller moraine, immediately located downstream of the moraine dam, is truncated by almost 100 m and exhibits fine-scale ripple-like features with meter-scale amplitude and tens-of-meters-scale wavelengths. Together, these observations show that glaciers dammed the Tsangpo River and that at least on one occasion the glacier dam failed catastrophically.

Table 1
Radiocarbon ages for wood samples from lacustrine terraces

	Sample	Conventional ^{14}C age (^{14}C yr B.P.)	Calibrated age[a]
Low terraces			
L3	Beta-169377	1220 ± 40	A.D. 690–900
L5	Beta-168580	1660 ± 40	A.D. 260–450
High terraces			
L2	Beta-168578	8860 ± 40	8210–7810 BC
L6	Beta-168579	9870 ± 50	9350–9240 BC

[a] Two-sigma range (Stuiver et al., 1998).

Figure 3. Photograph of prominent moraines extending into the valley of the Tsangpo River on the flank of Namche Barwa; photograph taken looking east.

The volumes of the two lakes impounded by the moraine dams were estimated from the elevation difference between a digital elevation model of the area upstream of the truncated moraine and the elevation of the reconstructed lake level (Fig. 5). Exposures of steeply dipping gravel in delta front deposits at the end of some of the fluvial terraces along the Tsangpo river confirms that the lake sediments did not fill the entire valley but were instead restricted to the margins of a deep lake. Based on a lake surface elevation of 3530 m, the larger of the two ancient lakes covered 2835 km^2, was about 680-m deep at its outlet, and impounded an estimated 832 km^3 of water. Based on a lake surface elevation of 3088 m, the lower terraces record a smaller lake that covered 789 km^2, was about 240-m deep at its outlet, and impounded 80 km^3 of water.

The sedimentological evidence for a glacial association, together with the agreement between the estimated spillway elevations at the moraines and the lacustrine terrace elevations, shows that glacial dams formed the ancient lakes. This interpretation is independently supported by agreement of terrace ages with the timing of the early Holocene and

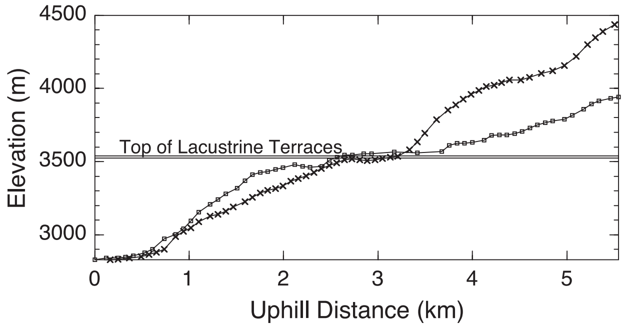

Figure 4. Topographic profiles showing the moraine surface elevation of about 3530 m, approximately 680 m above the elevation of the modern river bed of approximately 2850 m. Note that portions of the ridgeline to the right of the figure may be bedrock cored.

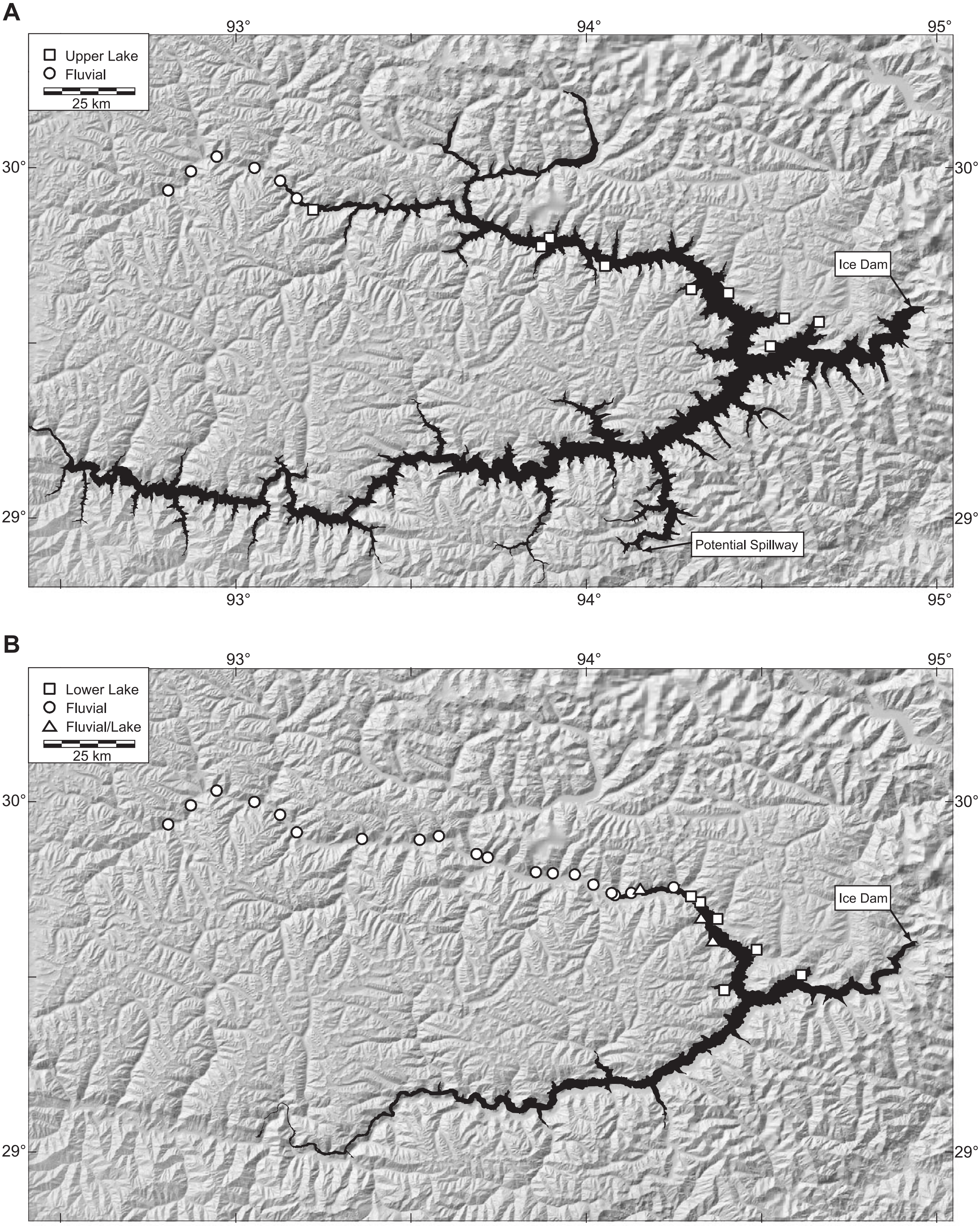

Figure 5. Maps showing the reconstructed extent of the two ancient lakes reported herein, as determined by filling a 3-arc-second digital elevation model from Shuttle Radar Topography Mission (SRTM) data to elevations of 3530 m (higher lake) and 3088 m (lower lake) upstream of the moraine shown in Figure 3. Also shown are the locations of mapped fluvial (circles), lacustrine (squares), and lacustrine/fluvial (triangles) terraces on a shaded relief base derived from 3-arc-second SRTM data, holes in which were filled in with coarser resolution data from the GTOPO30 topographic data set.

Little Ice Age glacial advances elsewhere in the Himalaya, including at Chomolongma (Mount Everest) (Finkel et al., 2003). Advancing valley glaciers, evidently fed by increased moisture delivery during a strengthened monsoon, present a logical mechanism for damming of the Tsangpo at the head of its gorge precisely when the lake sediments were deposited.

Glacier-dammed lakes tend to fail repeatedly (Wohl and Cenderelli, 1998) and most late-glacial moraine-dammed lakes in the northwestern Himalayas failed catastrophically (Bürgisser et al., 1982). Cenderelli (2000) compiled and reanalyzed previous studies of natural and artificial dam failures and reported that peak discharges (Q_p in m^3 s^{-1}) from the failure of moraine-dammed lakes could be approximated by $Q_p = 0.3\ (VD)^{0.49}$ where V is the lake volume (m^3) and D is the lake depth (m). Although subject to large uncertainties based on extrapolation of this empirical relation to an extreme event, catastrophic failure of the glacial dam for the lower lake would have had a peak discharge of up to 1×10^6 m^3 s^{-1} and the peak discharge from the higher ancient lake would have reached up to 5×10^6 m^3 s^{-1}. Until field data are obtained from the gorge of the Tsangpo River downstream of the moraine dam (a place where we have not yet been allowed to work), these estimated flood discharges should be considered preliminary values as the mode of dam failure(s), and therefore the peak discharge, may have varied from those extrapolated here.

Although we lack conclusive direct evidence for repeated outburst floods, several lines of evidence suggest that glacial dams formed and failed many times through the Quaternary. The total annual discharge of about 60 km^3 under the modern climate would take just over a decade to refill the larger lake, and the infilling time during a period of strengthened monsoonal precipitation would have been even shorter. Based on calculated vertically averaged ice velocities for the glacier and consideration of precipitation rates in the accumulation area on the northeast side of Nache Barwa, we estimate that it required decades at most to reform an ice dam. The thick sequences of lacustrine sediments and extensive fluvial gravel terraces graded to the lake levels indicate that the lakes persisted for long periods of time, although they may have been repeatedly drained and refilled to about the same level upon reformation of the glacier dam. In support of this hypothesis, the series of terracettes below the lake terrace levels seem to record progressive lake lowering associated with repeated reformation and breaching of an ice dam during glacier retreat. Hence, we suspect that there were many breakout floods over the life span of either lake.

Table 2
Estimated paleoflood characteristics

	Volume (km^3)	Peak discharge (m^3 s^{-1})	Unit stream power (W m^{-2})
Tsangpo (higher)	835	5×10^6	1×10^6 to 5×10^6
Tsangpo (lower)	81	1×10^6	2×10^5 to 1×10^6
Missoula[a]	2184	1.7×10^7	$2.5–3 \times 10^5$
Bonneville[b]	4750	1×10^6	1×10^5

[a] O'Connor and Baker (1992).

[b] O'Connor (1993).

The Tsangpo River steepens and narrows as it flows from the edge of the Tibetan Plateau down through the Himalaya (Fig. 6). Channel slopes determined from the 90-m DTED data steepen to a gradient of 0.02 through the length of the

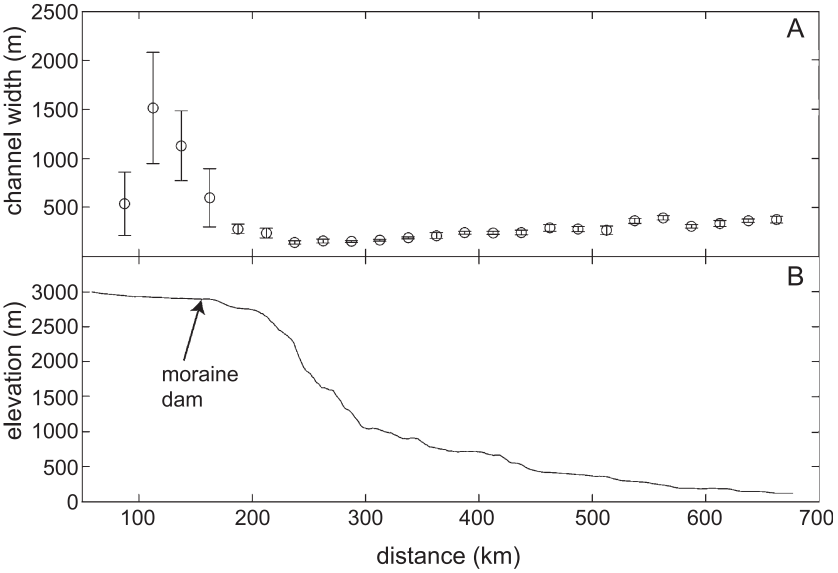

Figure 6. (A) Downstream variation in channel width and (B) elevation through the gorge of the Tsangpo River. Channel widths were measured from 30-m resolution Landsat-7 TM images; circles represent mean of individual width measurements for 25-km-long reaches and error bars represent ±1 SD. Channel elevation profile was extracted from the Defense Mapping Agency's global 3-arc-second digital terrain elevation model.

gorge, except for locally steeper knickpoints associated with waterfalls along the gorge. The bedrock channel width narrows from >500 m at the top of the gorge to between 100 and 200 m through most of the gorge, and widens again only upon leaving the gorge, more than 400 km downstream from the moraine dam.

Using the estimated peak discharges, the power expended per unit area of the channel (expressed as the unit stream power, ω) of outburst floods through the Tsangpo River gorge can be calculated from $\omega = \rho g Q_p S/W$, where S and W are the average channel slope and width through the gorge, ρ is the density of water, and g is gravitational acceleration. Although the Tsangpo River is <200-m wide through its gorge, an outburst flood would have risen partway up the steep valley walls that rise from river's edge and would therefore have occupied a wider cross-section. Using $Q_p = 5 \times 10^6$ m^3 s^{-1}, $S = 0.02$, $\rho = 1000$ kg m^{-3}, $g = 9.81$ m s^{-2}, and a range of $W = 200$ m to 1 km, the estimated range for the unit stream power for the peak of an outburst flood is 1×10^6 to 5×10^6 W m^{-2} for the upper lake and 2×10^5 to 1×10^6 W m^{-2} for the lower lake. Although the discharge from outburst floods draining these ancient lakes would have been smaller than the Bonneville and Missoula floods, lake-breakout floods down the Tsangpo would have been confined within a deep, narrow gorge. Consequently, the estimated peak unit stream power for such Tsangpo floods exceeds by as much as an order of magnitude those reported for the late Pleistocene Missoula and Bonneville floods (Table 2).

What was the role of such megafloods in carving the spectacular gorge of the Tsangpo River, and what does the potential for repeated glacial damming throughout the Quaternary imply for the role of catastrophic events on the phenomenal erosion rates and spectacular topography through the gorge? Substantial downcutting and valley side erosion likely occurred during these floods, and such extreme events may help explain the huge waterfalls and knickpoints in the gorge as features carved during megafloods. However, finding direct evidence for the downstream effects of lake-breakout floods down the Tsangpo gorge may prove challenging due to difficult access, a huge sediment flux, and little potential for preserving sedimentary evidence in the gorge itself. The best potential for a direct sedimentological record of outburst floods from the Tsangpo gorge probably lies in floodplains, terraces, and tributary valleys in remote regions of northeastern India. In addition, it is not clear as to how much rock would be eroded by even spectacular outburst floods because extreme discharges possibly simply remove the weathered material and fractured surficial rock without deeply carving into fresh bedrock.

Our evidence for immense, previously unrecognized late-glacial lakes at Namche Barwa show that monsoon-driven valley glacier advances dammed even the largest Himalayan rivers, and repeatedly created unstable glacier-dammed lakes that would have generated some of the most erosive events in recent Earth history. Hence, immense outburst floods could well have played an important role in carving the deepest valley on Earth and, more generally, the development of the spectacular topography of the Himalaya and other high, glaciated ranges. Although the long-term influence of periodic outburst floods on rates of bedrock erosion is not certain, the occurrence of repeated outburst megafloods with the onset of Pleistocene glaciation at Namche Barwa may have enhanced the feedback between bedrock erosion and rock uplift thought to be responsible for the unique structure of this Himalayan syntaxis, characterized by Zeitler et al. (2001) as a "tectonic aneurysm."

Acknowledgments

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