LETTERS

Tibetan plateau river incision inhibited by glacial stabilization of the Tsangpo gorge

Oliver Korup[1] & David R. Montgomery[2]

A considerable amount of research has focused on how and when the Tibetan plateau formed in the wake of tectonic convergence between India and Asia[1]. Although far less enquiry has addressed the controls on river incision into the plateau itself[2], widely accepted theory[3] predicts that steep fluvial knick points (river reaches with very steep gradients) in the eastern Himalayan syntaxis at the southeastern plateau margin should erode rapidly[4], driving a wave of incision back into the plateau. Preservation of the plateau edge thus presents something of a conundrum that may be resolved by invoking either differential rock uplift matching erosional decay[5–7], or other mechanisms for retarding bedrock river incision[8,9] in this region where high stream power excludes the potential for aridity as a simple limit to dissection of the plateau[10]. Here we report morphologic evidence showing that Quaternary depression of the regional equilibrium line altitude, where long-term glacier mass gain equals mass loss, was sufficient to repeatedly form moraine dams on major rivers: such damming substantially impeded river incision into the southeastern edge of the Tibetan plateau through the coupled effects of upstream impoundment and interglacial aggradation. Such glacial stabilization of the resulting highly focused river incision centred on the Tsangpo gorge could further contribute to initiating and accentuating a locus of rapid exhumation, known as tectonic anaeurysm[6].

Few studies have quantified the geomorphic consequences of glaciers that block mountain rivers beyond the perspective of hazard implications of catastrophic dam failure and outburst flows[11]. Hence little is known about the potential topographic implications of glacial dams at a regional scale[12]. Here we focus on the Yarlung Tsangpo and its major tributaries, the Yigong and Parlung Tsangpo that drain the southeastern margin of the Tibetan plateau near Namche Barwa (Fig. 1). In this area, where the Yarlung Tsangpo cuts through one of the deepest gorges on Earth, several independent methods—thermochronometric[6], stream-power[4,13], and sediment provenance analyses[14]—reveal some of the highest erosion rates in the Himalaya, capable of exhuming young migmatitic gneisses since ~3.5 Myr ago[6].

Montgomery *et al.*[15] recognized evidence for repeated Holocene glacial damming of the Yarlung Tsangpo immediately above its gorge through the Himalaya, and similar blockages also occur on major tributaries upstream of moraine dams from deeply incised bedrock gorges. In this study, we mapped 260 moraine dams (Fig. 1), including numerous large laterofrontal moraines and associated debris fans, formed by glaciers flowing from tributary basins that blocked the Yarlung, Yigong and Parlung Tsangpo.

Topographic data on former glacier surfaces are not available for the study area, so we used the toe-to-summit-altitude method

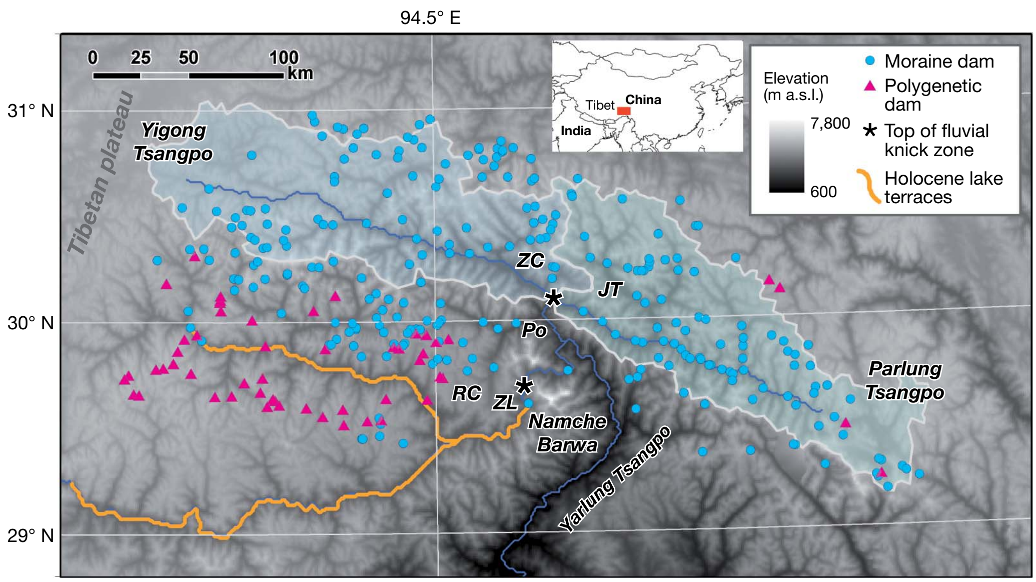

Figure 1 | Locations of 303 natural dams in the eastern Nyainqentanglha mountains and the Namche Barwa syntaxis, southeastern Tibetan plateau margin. JT, Jepu Tsangpo; Po, Po Tsangpo; RC, Rong Chu; ZC, Zhamu Creek landslide; ZL, Zelongnong glacier. Inset, location of study area. Orange lines (see key) indicate estimated upstream extent of Holocene moraine-dammed lakes on the Yarlung Tsangpo[15]. Polygenetic dams composed mainly of glacial and landslide debris occur in fully deglaciated headwaters west of Rong Chu. a.s.l., above sea level.

[1]Swiss Federal Research Institutes WSL/SLF, Flüelastr. 11, CH-7260 Davos, Switzerland. [2]Quaternary Research Center, Department of Earth and Space Sciences, University of Washington, Seattle, Washington 98195-1310, USA.

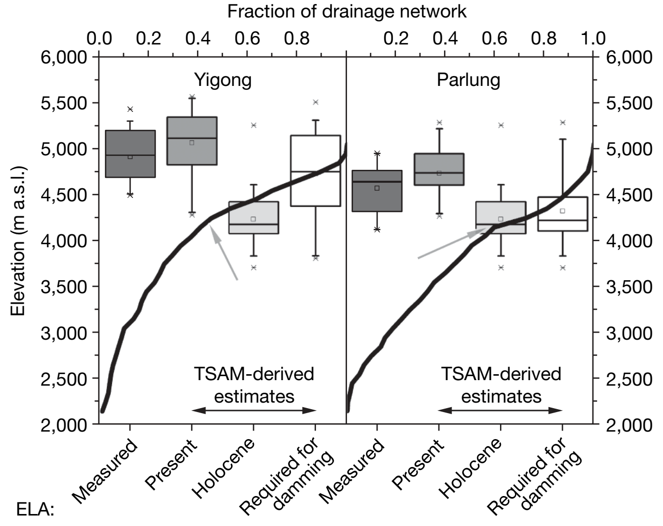

Figure 2 | Box-and-whisker plots of equilibrium line altitudes (ELAs) for Yigong and Parlung Tsangpo. ELAs are derived from field data[16–19] and LANDSAT satellite imagery ('Measured'), and TSAM ('Present', 'Holocene', 'Required for damming'). TSAM systematically overestimates measured ELAs by ~200 m (Supplementary Information). TSAM-derived Holocene ELAs were inferred from locations of major moraine dams; also shown are ELAs required for tributary glaciers to dam trunk rivers where suspected moraine dams are poorly preserved. Solid line shows cumulative elevation distribution (hypsometry) of each drainage network with contributing catchment areas $>10\,km^2$, that is, exclusive of low-order channels and hillslopes. Arrows indicate glacial-fluvial transition. Box gives lower and upper quartiles and median; whiskers show 5th and 95th percentiles; small open square is mean, and crosses are 1st and 99th percentiles.

(TSAM) to calculate the likely range of depressions of the equilibrium line altitude, ΔELA, required to explain observed moraine dams and to dam major rivers. Advancing modern glaciers to the positions of 38 large laterofrontal moraines that blocked or constricted the Yigong, Parlung and Yarlung Tsangpo requires a mean ΔELA of 420 ± 170 m ($\pm 1\sigma$; Fig. 2). Sediments deposited in moraine-dammed lakes on the Yarlung Tsangpo[15] document several episodes of substantial glacial advance throughout the Holocene, although the ΔELAs associated with dated Little Ice Age (LIA) and Late Holocene (~1–2 kyr ago) moraines are smaller, that is, 10–60 m and 110–160 m, respectively[16]. From a sample of 89 basins with less direct evidence for glacial damming throughout the region, we computed that, on average, ΔELA > 360 m is required for glaciers from tributaries to dam trunk rivers. These estimates are remarkably consistent, despite the high local and regional variance in ELA due to local variations in the effects of topography, climate and supraglacial sediment flux.

The fraction of the drainage network length situated above a given moraine dam, and thus affected by glacial damming through direct occupancy and indirect impoundment or aggradation, increases with ΔELA. This fraction increases from a regional mean of 13% for the present ELA, to Holocene glacial advances that impounded between 30% and 55% of the length of the Yigong and Parlung Tsangpo, and commensurately higher for the greater ELA depression (which is currently debated, but may have amounted to ~1,000 m (refs 17, 18)) during earlier Pleistocene glacial advances. Hypsometric curves of river-channel elevations with contributing catchment areas $>10\,km^2$ indicate that 40–60% of this drainage network may have been above our TSAM-derived Holocene ELA. Consequently, ELA depressions during both the Holocene and Pleistocene glacial maxima were more than adequate to block major rivers. The distinct kink in the drainage network hypsometry at ~4,200 m coincides well

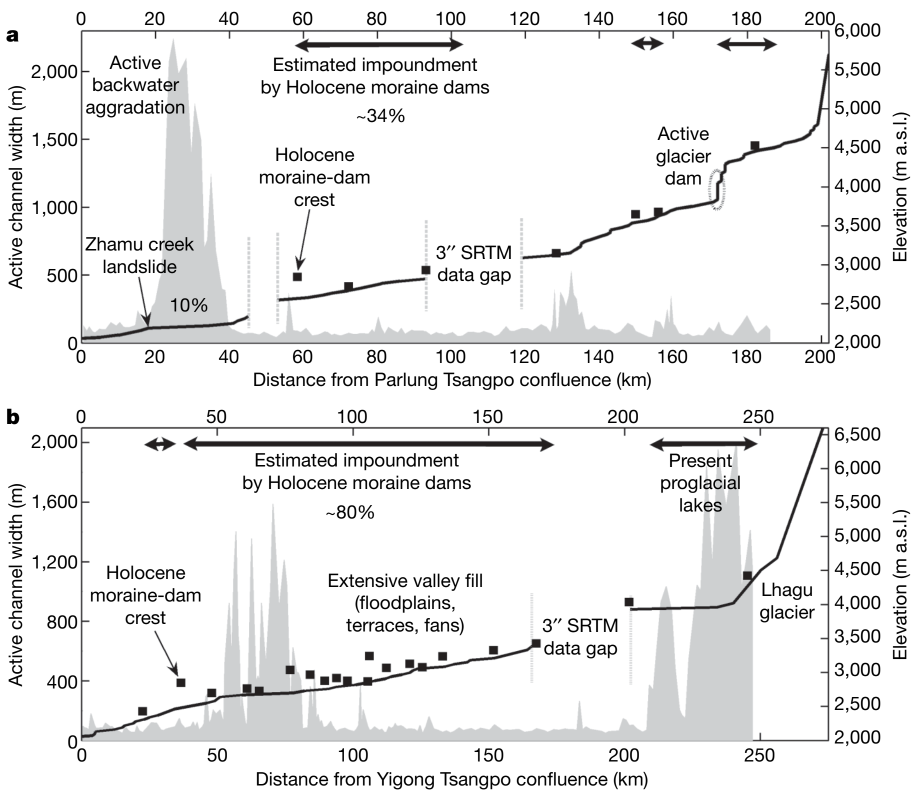

Figure 3 | Long profiles (lines) and active channel width (grey shaded areas) of Yigong Tsangpo and Parlung Tsangpo. **a**, Yigong Tsangpo; **b**, Parlung Tsangpo. Percentage of trunk-river length impounded by preserved Holocene moraine dams (extent shown by horizontal arrows) is estimated from horizontally projecting effective dam-crest elevations above the present valley floor onto the river-long profile. Large historic landslides at Zhamu creek[19] forced aggradation over 10% of trunk-river length. Large proglacial lakes inhibit bedrock incision in headwaters. Grey vertical dashed lines bracket SRTM data gaps.

with our reconstructions of the Holocene ELA, suggesting that either all the region's major river profiles reflect the influence of a sustained base level at elevations in the range of the Quaternary ELAs, or that headward knick point migration in these bedrock rivers has either stalled or not yet progressed any further into the Tibetan plateau.

Several major knick points in the long profiles of the Yigong and Parlung Tsangpo separate steep bedrock gorges from broad alluviated reaches with densely vegetated valley fills composed of floodplains, terraces and fans or wide, braided channels (Fig. 3). Although the most prominent of the active depositional 'valley trains' along the Yigong Tsangpo occurs upstream of an enormous modern landslide dam (Zhamu creek[19]), horizontal projections of the crests of major Holocene moraine dams onto the river-long profiles indicate that ~34% and ~80% of the Yigong and Parlung Tsangpo, respectively, were inundated or aggraded upstream of the dams. In many locations, the valley trains change to narrower single-thread channels where diverted around the toes of moraine dams, showing that the moraine dams exert a primary control on active channel width and thereby reduce specific stream power. Upstream of glacial dams, river incision into bedrock is dramatically impeded by impoundment during glacial occupancy. Moreover, glacial 'retreat' fosters blockage-induced backwater aggradation and infill of meltwater lakes with sediment. Even partial blockage by coarse moraine debris can control local base level through channel narrowing and armouring, backwater formation, and upstream alluviation. Hence, bedrock river incision below moraine dams contributes to further steepening river profiles; in contrast, glacier-controlled damming forces pervasive sediment trapping on valley floors upstream, thereby inhibiting bedrock river incision in upstream areas from somewhat below the ELA during interglacial periods up to about the ELA during glacial advances. Coupled numerical simulations of glacial and fluvial valley profile evolution show such inflections associated with the transition from glacial to fluvial bedrock incision[20].

The mapped pattern of moraine dams indicates that Holocene advances may have impeded bedrock incision over up to 80% of the trunk channel network. This appears realistic, given that the regional glacier extent was an estimated 30% larger during the LIA, and associated with blockage of major rivers, such as the Jepu Tsangpo[21] (Fig. 1). Lake and backwater terraces extending over 560 km upstream associated with at least two Holocene glacier damming episodes of the Yarlung Tsangpo by the Zelongnong glacier, on the western flank of Namche Barwa, strikingly attest to widespread fluvial transport limitation forced by glacier advances[15] (Fig. 1). This inundation affected 15–22% of the length of the Yarlung Tsangpo directly upstream of the moraine dams, and consequently contributed to retarding upstream knick point migration in this part of the plateau margin.

On all three rivers, channel-damming moraines extend downstream to the head of pronounced knick zones with inferred high stream power (Fig. 4). Moraine-dammed lakes not only inhibit bedrock incision during their lifetime, but also promote upstream aggradation and burial of bedrock valley floors under glaciofluvial sediment long after the dams are breached and the glaciers melt off. Hence, trunk river incision may be greatly reduced above these moraine dams, leaving glaciers alone responsible for excavating the valleys. Glaciers achieve most of their erosion near and above the ELA[20,22], and glacial over-excavation of these valleys will promote interglacial aggradation, thereby limiting the potential for further bedrock incision during interglacial periods. The 'fluvial' valleys downstream, however, will keep incising more rapidly, as long as episodic blockage or armouring by landslides[19,23] is not as widespread, persistent or effective as that by glacial dams. Unlike moraine dams that repeatedly block the same location, landslide dams recur at variable locations along a river profile[8]. Hence, we propose that the juxtaposition of repeated glacier-controlled damming upstream and fluvial bedrock incision downstream contributes to stabilizing the position of the plateau edge at Namche Barwa by retarding the propensity for bedrock knick points to migrate upstream. This generates a positive feedback, through which the rise of the Tibetan plateau to above the ELA would help preserve high topography, despite the innate tendency for river incision to sweep inland from steep plateau margins.

From a long-term perspective, we also find that when projecting published mineral cooling ages from the Namche Barwa region[13] onto the closest point along the river profiles, the zone of youngest

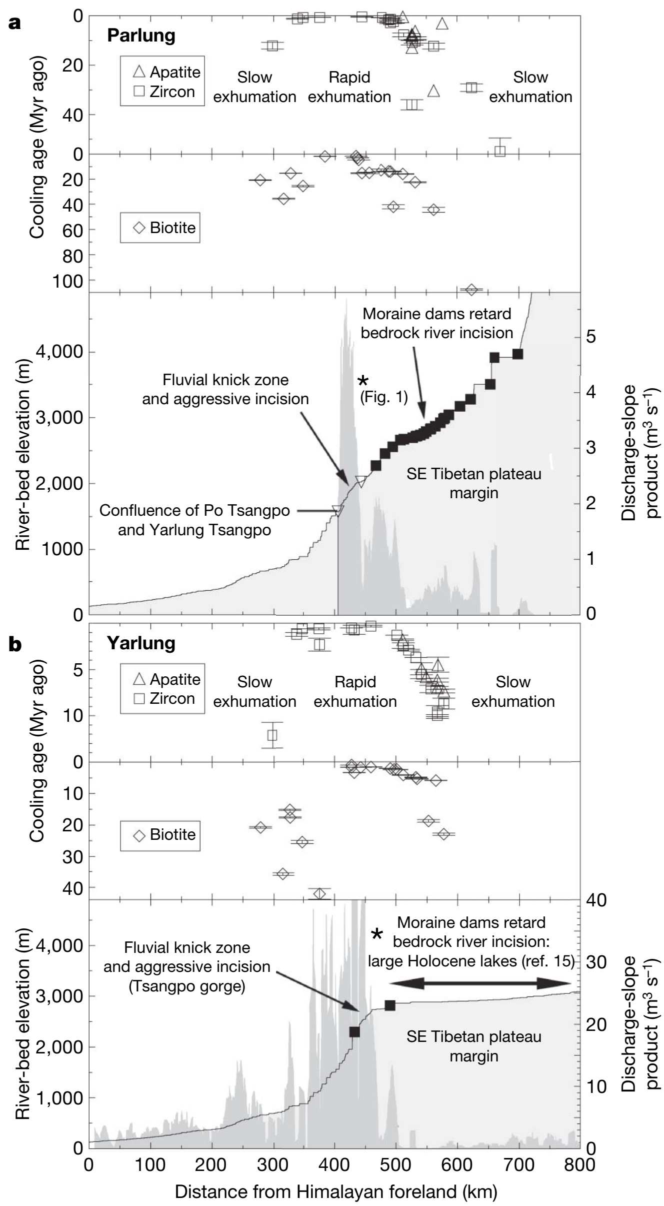

Figure 4 | Cooling ages (open symbols) and longitudinal profiles (dark lines) of the Parlung and Yarlung Tsangpo across the southeastern Tibetan plateau margin. **a**, Parlung Tsangpo; **b**, Yarlung Tsangpo. Profiles (lower panels) are measured from where the river leaves the Himalaya and enters the lowlands of northeastern India. They contain mapped locations of moraine dams (filled black squares), and local values of stream-power index (dark grey shading). This index is determined as the product of discharge and channel slope. Discharge is calculated using mean annual flow estimated as the area-weighted summation of local, TRMM-derived precipitation totals using data of ref. 27 and methods of ref. 4; channel slope is determined from a 10-km running average of local river elevation. Triangles on profile of the Parlung indicate confluences where the Yigong and Parlung merge to form the Yarlung Tsangpo (upstream), and where the Po Tsangpo enters the Yarlung Tsangpo (downstream). Asterisks show top of fluvial knick zones (see Fig. 1). Upper panels show projected locations of apatite, zircon and biotite cooling ages[13] (error bars, ±1s.d.).

cooling ages (<1 Myr ago), and thus highest exhumation rates, extends downstream from the zone where 'string-of-pearls' clusters of moraine dams trap sediment and impede trunk-river incision into bedrock. On neither the Yarlung nor the Parlung Tsangpo is there evidence for a major offset in the dome-shaped pattern for different mineral cooling ages, as would be expected from substantial incision-driven headward migration of the Tsangpo knick points. However, new low-temperature chronology data not only confirm that the Namche Barwa antiform is <4 Myr old, but point to its gradual northeastward growth[24].

The proximity of repeated glacier blockage to rapid downstream fluvial incision that spatially focuses high erosive power means that drainage-blocking advances of temperate monsoonal valley glaciers from tributary channels could impede fluvial bedrock incision in trunk river systems. Whether driven by changes in monsoon precipitation[18,25], temperature[16,17] or supraglacial sediment flux[26], Quaternary glacier advances appear capable of substantially retarding river incision into southeast Tibet in the region around Namche Barwa[15]. Although this is not the only viable mechanism for maintaining a plateau margin (as aridity[10] and local fault offset[7] provide viable complementary alternatives that are clearly important in some areas), our hypothesis frames a previously unrecognized and potentially important interaction between climate, tectonics and erosion in governing landscape evolution. In any case, glacial damming at the onset of mountain glaciation in the Quaternary may have produced a positive feedback that helped preserve a distinct plateau edge in close proximity to the extraordinary spatially focused exhumation of the Tsangpo gorge.

METHODS SUMMARY

Moraine dam mapping and ELA reconstruction. Moraine dams were identified and mapped from LANDSAT ETM+ satellite imagery. In the absence of data on former glacier surface topography, we used TSAM to reconstruct steady-state ELAs necessary for glacial advances preserved in conspicuous moraine ridges and loops. TSAM uses the arithmetic mean of the elevation difference between the highest summit peak and the lowest terminal moraine position for each catchment, determined from Space Shuttle Topographic Radar Mission (SRTM3) data at ~80-m resolution.

TSAM results were calibrated with field-measured ELAs[16–19] and estimates from LANDSAT (ETM+) imagery. To account for potential undersampling of moraine dams, we also used TSAM to estimate the ΔELA required to advance glaciers to tributary junctions, and thereby block mainstem rivers.

Estimating fluvial erosion potential. We extracted river-long profiles and active channel widths from the SRTM and Landsat ETM+ imagery (band 8 at 15-m resolution), respectively. We mapped impounded or aggraded reaches upstream of present and former terminal moraines along the Yigong and Parlung Tsangpo. We calculated the cumulative elevation distribution (hypsometry) of this drainage network, that is, excluding all low-order channels and hillslopes in order to estimate the fraction of trunk drainage network located above the ELA for a given ΔELA.

Discharge estimates were based on 4-yr average rainfall rates derived from Tropical Rainfall Measuring Mission (TRMM) data[27] and summed over the upstream drainage area for each point down a river profile. Channel slopes were computed as a running average over a 10-km-length reach centred on each point down the river profile using SRTM30 data.

We characterized inferred long-term (10^5–10^6 yr) erosion by projecting locations of published mineral (that is apatite, zircon (U-Th)/He, and biotite $^{40}Ar/^{39}Ar$) cooling ages[13] onto the longitudinal profiles of the Parlung and Yarlung Tsangpo.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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METHODS

Moraine dam mapping and ELA reconstruction. Moraine dams were identified from LANDSAT ETM+ satellite images on the basis of a suite of morphologic characteristics, including the presence of glaciers in headwaters and concomitant occurrence of impounded lakes. The single, sharp and mostly vegetated crests indicate little modification by post-depositional surface processes[28], while ruling out deposition as landslide debris during catastrophic emplacement because of a lack of characteristic morphology[29]. There are also numerous remnants of terminal moraines that appear to have been truncated by fluvial erosion along narrow bedrock gorges, particularly on the Yigong and the Yarlung Tsangpo. Moreover, the proximity of modern glaciers to mainstem rivers suggests that additional glacial dams probably occurred in numerous locations where scant or no direct morphologic evidence speaks to their former presence. We have not included such tentatively identified potential glacial dams in our regional map (Fig. 1). Therefore, the number of moraine dams mapped in Fig. 1 provides a minimum estimate of the overall effects of glacial damming.

In the absence of data on former glacier surface topography, we used TSAM to reconstruct ELAs necessary to produce the advances preserved in conspicuous moraine ridges and loops. TSAM uses the arithmetic mean of the elevation difference between the highest summit peak and the lowest terminal moraine position for each catchment (for a thorough discussion of this and alternative methods of reconstructing former ELAs, see ref. 30). It is ideal for reconstructing former ELAs at a regional scale from 3 arcsec Space Shuttle Topographic Radar Mission (SRTM3) digital elevation data. These data suffer from local data gaps in this region of high local relief and have been merged with SRTM30 data to provide a nominal grid-cell resolution of $\sim$80 m.

In order to calibrate our TSAM results, we obtained the locations of present ELA from the literature[16–19] and measurements from LANDSAT and LANDSAT ETM+ imagery at the end of the monsoon season. The annual ELAs on these images are closely approximated by clearly detectable, conspicuous colour differences between ice and firn cover. The monsoonal temperate glaciers of southeast Tibet are very sensitive to climatic change, as small temperature changes lead to substantial response in the glacier mass balance[17]. We compared multitemporal satellite images to confirm a negative mass balance for 20 of the larger glaciers between 1987 and 2001.

TSAM helps approximate the steady-state ELA for a given glacier. Given that the field-derived positions of the ELA were acquired during a period of negative mass balance, we can assume that these values somewhat, although probably slightly, overestimate the position of the steady-state ELA. Comparison of measured modern ELA positions versus TSAM-derived modern ELA positions reveals that TSAM systematically overestimates measured ELA by $\sim$200 m, and is less reliable for determining ELA on debris-covered glaciers and those prone to surging in the study area[17]. Nonetheless, TSAM provides conservative (that is, minimum) estimates with respect to necessary conditions for river blocking, as surging will more readily impound rivers with climatic changes involving even less ELA depression.

We focused on glaciers issuing from mostly steep tributary basins with areas between 10 and 260 km^2 and a total relief of between 1.2 and 5.4 km. In order to account for potential erosional censoring of moraine dams, especially at sites with limited geomorphic evidence of former blockage, we also used TSAM to estimate the minimum ΔELA required to advance glacier snouts to tributary junctions, and thereby block mainstem rivers.

Estimating fluvial erosion potential. We extracted river-long profiles and active channel widths from the SRTM3 data and Landsat ETM+ images (monochromatic band 8 at 15-m resolution), respectively. We also mapped the length of the Yigong and Parlung Tsangpo either impounded or aggraded upstream of present and former terminal moraine positions, as well as the ice-covered region upstream of the tributary. Because of the available DEM resolution, we used an upstream area $>$10 km^2 to automatically delineate and measure the length of major river branches. This roughly corresponds to the length of fluvial channels, as the transition from debris-flow dominated colluvial channels to fluvially incised bedrock rivers typically occurs at drainage areas of 1–10 km^2 (ref. 31). While this transition arguably varies between individual catchments, there is documented evidence that debris flows are frequent geomorphic agents in many of the lower-order tributary basins[32]. We then calculated the cumulative elevation distribution (hypsometry) of this drainage network, that is, excluding all low-order channels and hillslopes, for both the Yigong and Parlung Tsangpo in order to estimate the fraction of trunk drainage network located above the ELA for a given ΔELA. We note that this value does not necessarily reflect the fraction of landscape that was covered by glaciers; we are here interested in reconstructing the potential geomorphic effects of glaciers on river systems rather than the total extent of Pleistocene glaciation.

Discharge estimates were based on 4-yr average rainfall rates derived from TRMM data[27] and summed over the upstream drainage area for each point down a river profile. We have chosen this approach to include the effects of the regional precipitation gradient across the Tsangpo-Brahmaputra catchment. Channel slopes were computed as a running average over a 10-km-length reach centred on each point down the river profile using SRTM30 data.

Finally, we characterized inferred long-term (10^5–10^6 yr) erosion by projecting the locations of published mineral (that is apatite, zircon (U-Th)/He, and biotite ^{40}Ar/^{39}Ar) cooling ages[13] onto the nearest locations of the river-long profiles of the Parlung and Yarlung Tsangpo. We chose this approach in order to test whether the locations of the reconstructed glacier fluctuations and their effect on retarding fluvial bedrock incision would be detectable in the long-term development of the Tibetan plateau margin.

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