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RESEARCH ARTICLE

Late Quaternary morphotectonic evolution of Upper Indus valley profile: A cosmogenic radionuclide study of river polished surfaces

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We have studied cosmogenic exposure ages in a set of five samples from the river polished surfaces (1–46 m above present river level) of the Indus river (Ladakh), at maximum discharge yield during August. These ages not only provide an opportunity to unravel the complex morphotectonic history of the Upper Indus valley, but also yield estimates of river incision rates during down-cutting of bedrocks. The three lower surfaces, 21 m, 6 m and 1 m above the river level have monotonically decreasing cosmic ray exposure ages of 22, 15 and 3 ka BP, suggesting that the river has been cutting the bedrocks initially (22–15 ka) at high rate of 2 mm yr⁻¹ which reduced to 0.3–0.4 mm yr⁻¹ since 15 ka BP. The latter is at par with the reported values of exhumation rate for the Ladakh region. The present data together with similar data from the Indus valley west of Skardu, reported earlier, give a better understanding of the so far poorly understood interplay of regional exhumation, incision rate and the role of climate in the morphotectonic evolution of the Upper Indus valley.

THERE exists sufficient geological evidence to suggest that Tibet and the adjoining regions of Ladakh

witnessed appreciable changes in local and regional climates during the Late Pleistocene–Holocene. These are related to the advances and retreats of the mountain glaciers, and the high altitude (> 5 km) and the middle latitude (33°–38° N) 'continental glaciers' in Tibet. Moraines, which mark the former limits of alpine glaciers present in Tibet region, are present in Gilgit–Ladakh region as well^{1–4}. Recent studies on oxygen isotopic data from the core samples of Dunde ice cap from Tibet⁵ and the magnetic susceptibility of loess and interbedded soils in central China⁶ serve as a proxy measure of palaeoclimate of the region.

All the Himalayan rivers are in their 'early' to 'immature' stages of development, and show erosional as well as depositional features characteristic of river rejuvenation with every pulse of uplift in the Himalaya⁷. Wadia⁸ suggested that the major rivers like Indus, Satluj, Ganga and Brahmaputra remained nearly confined to their channels, but worked certainly at an accelerated rate of erosion in response to uplift of the region near their source. The down-cutting (incision) of the rivers kept pace with the uplift of the mountain chains, resulting in deep valleys. He reported existence of about 5,000 m deep valley profile of Indus in Gilgit carved by the river, as evident from erosional features and fluvial

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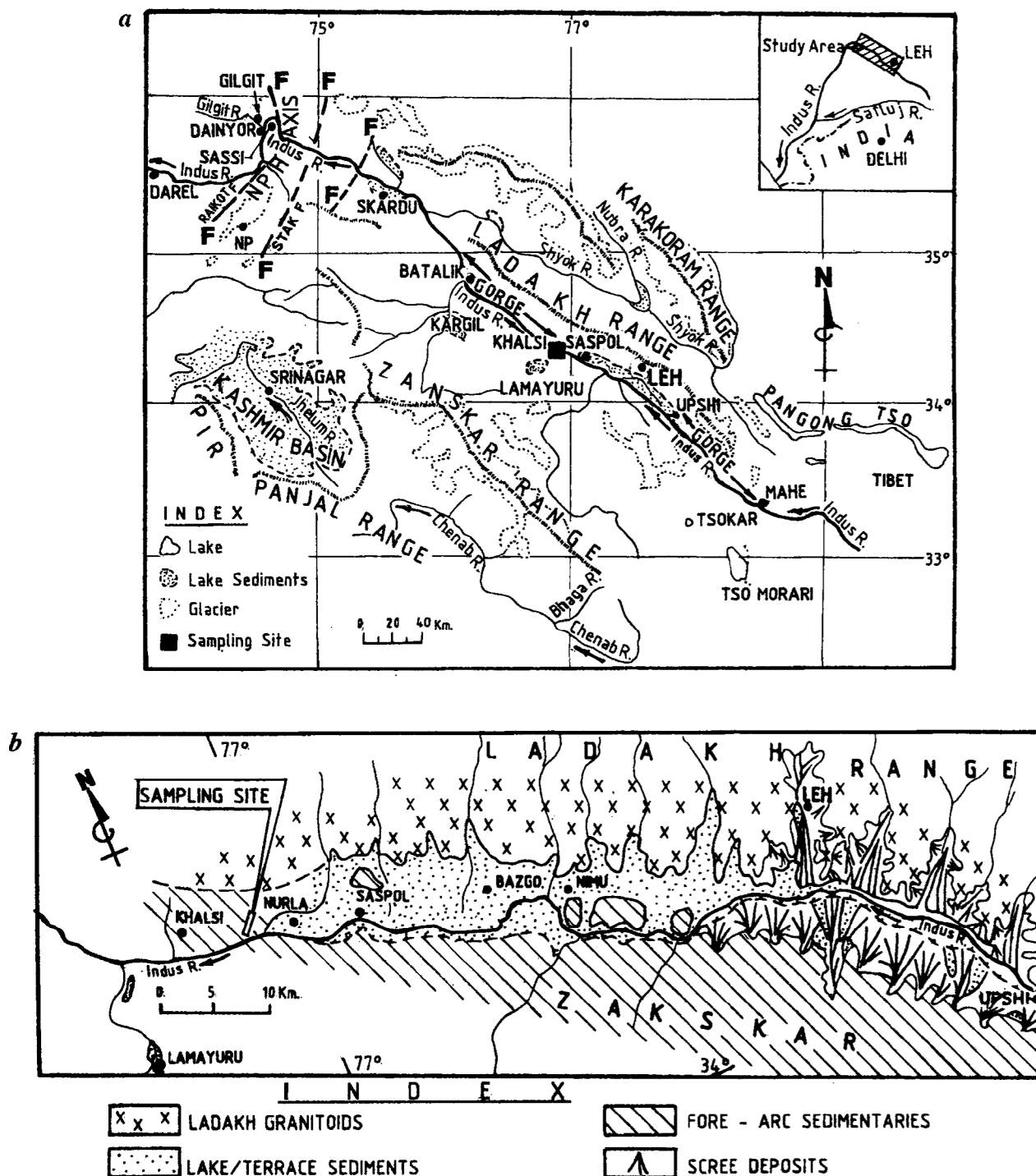


Figure 1. *a*, Sketch map of the Upper Indus valley showing longitudinal profile of the Indus river and location of various places. *b*, Sketch map of the Leh basin between Khalsi and Upshi showing geology of the area: Ladakh magmatic arc (Ladakh granitoids), fore-arc sedimentaries and the youngest terrace/lake deposits of the Leh basin.

terrace deposits. Presently, estimates of precise erosion rate in the Himalayas are virtually non-existent but there are now a few data on the incision rates from the Indus river, west of Skardu downstream of Khalsi⁹.

This paper presents exploratory data on the cosmogenic exposure ages based on ¹⁰Be and ²⁶Al radio-

nuclides in a set of five samples from the river polished surfaces in the Upper Indus valley near Khalsi, Ladakh. This study provides direct information on incision rates during down-cutting of the bedrocks and the formation of the terraces, and a plausible scenario for the palaeoclimate of the region and its interplay with the

a



b



Figure 2. *a*, View of the sampling site in the Upper Indus valley showing topography and the geology of the area. LG, Ladakh granitoids of the magmatic arc; FBS, Fore-arc basin sedimentaries; Oph., Obducted ophiolites; LSD, Lamayuru continental slope deposits; TD, Younger terrace/lake deposits; KH, Khalsi; SS, Sampling site. *b*, Horizontally lying terrace/lake deposits on eroded bedrock surface of folded fore-arc basin sedimentaries near Nimu (Ladakh) upstream of sampling site. A sharp 20 m deep cut by the Indus river below the terrace/lake deposit is a conspicuous feature upstream of the sampling site, indicative of the second stage down-cutting, after the lake was drained off. TD, younger terrace/lake deposits; FBS, Fore-arc basin sedimentaries.

post-collision tectonic activity-induced uplift. We discuss our results along with those obtained by Burbank *et al.*⁹, also based on studies of cosmogenic exposure, using radionuclides (^{10}Be , ^{26}Al), in river polished surfaces, from the Nanga Parbat–Haramosh region, 150 km downstream of our sampling site (Figure 1).

Experimental method and results

We sampled the upper 10–15 cm thick layers of *in situ* river polished surfaces from the Upper Indus valley between Nurla and Khalsi (Lat. $34^{\circ}18'\text{N}$; $76^{\circ}56'\text{E}$), 50 km West of Leh (Figures 1, 2*a*). The river-water polish, still retained by the sampled surfaces, obviously suggests that these locations somehow escaped subsequent valley erosion. The flow of water in the Upper Indus valley from Tibet to Gilgit is dominated by ice-melt rather than the monsoon rains, as in the Lower Indus valley south of Gilgit. Our samples were collected from the right bank of the Indus river, i.e. the south facing profile, which has no soil, vegetation or snow cover at present and are assumed to have received same intensity of cosmic ray irradiation. Unpaired terraces and lake sediments at about 20 m above the river level (Figure 2*b*) are present upstream of Khalsi from Nurla to Upshi, which were deposited in the Leh basin. Such unpaired terraces are quite common along many of the Himalayan rivers where meandering streams rapidly erode a valley fill, while shifting its loops in both longitudinal and cross-valley profiles. The rock exposed at the sampling site is a hard, green sandstone (with occasional quartz veins) of the fore-arc sedimentary basin filled with Ladakh magmatic arc-derived sediments¹⁰. A

total of five samples were analysed from 3165 m, 3155 m, 3140 m, 3125 m and 3120 m altitudes.

The upper few centimeters of the polished surface were chipped off in the laboratory, crushed to 100–150 μm fraction, and repeatedly treated with warm HF and HNO_3 solution to obtain a 99%+ quartz fraction. Subsequently, the enriched quartz fraction was dissolved in HF with 1.5 mg of Be carrier and 0.5 mg Al carriers¹¹. The chemical procedures for extraction of ^{10}Be and ^{26}Al from quartz have been described in detail elsewhere^{12–14}. The ^{10}Be and ^{26}Al measurements were performed at the Center for Mass Spectrometry at Lawrence Livermore National Laboratory, USA. The results are presented in Table 1 together with calculated apparent exposure ages. Errors introduced into the calculated age, due to geometric corrections and changes in blocking angle ($< 30^{\circ}$), are likely to be insignificant. Within the uncertainties of measurements, the $^{26}\text{Al}/^{10}\text{Be}$ ratios in our samples (Table 1) are close to the ratio at production, as would be expected for relatively short exposure age of the measured samples, compared to ^{10}Be and ^{26}Al half-lives¹⁴.

The cosmogenic (^{10}Be and ^{26}Al) data from Khalsi suggest relatively short exposure durations (less than 25 ka) for the lower three samples. The 1 m level terrace was cut about 3 ka BP. The corresponding mean ages for the 6 m and 21 m levels are 15.5 ka and 22.5 ka BP. In contrast, the upper level samples (36 m and 46 m) show relatively lower exposure ages of 7 ± 2 ka and 15 ± 2 ka, respectively. One would normally expect exposure ages to increase with altitude and on this basis, the 36 m and 46 m samples are anomalous. The considerably lower exposure ages of upper level samples can

Table 1. ^{10}Be and ^{26}Al concentrations and exposure ages of Indus river terrace samples from Khalsi, Ladakh

Sample code	Altitude (m)	Elevation* (m)	Concentration 10^6 atoms/g quartz		Exposure age (ka)			Incision rate	
			^{10}Be	^{26}Al	^{10}Be	^{26}Al	Mean	mm/yr	(period)
LG-738	3165	46	0.48 ± 0.08	3.70 ± 0.19	$13 \pm 2^{**}$	16 ± 1	14.5 ± 2.4		
LG-739	3155	36	0.27 ± 0.08	1.66 ± 0.08	$7 \pm 2^{**}$	7 ± 0.3	7.0 ± 2.0	1.3 ± 0.43	(57–64.5 ka)**
LG-740	3140	21	0.77 ± 0.07	5.87 ± 0.29	20 ± 2	25 ± 2	22.5 ± 2.9	2.14 ± 0.48	(15.5–22.5 ka)
LG-741	3125	6	0.69 ± 0.10	2.93 ± 0.15	18 ± 3	13 ± 1	15.5 ± 2.8	0.43 ± 0.14	(3–15.5 ka)
LG-742	3120	1	0.08 ± 0.02	0.91 ± 0.05	2 ± 0.5	4 ± 0.2	3.0 ± 0.8	0.33 ± 0.09	(0–3 ka)

*Above the present river level.

**See text for a discussion of the measured short exposure age for the 3155 m and 3165 m sample. As noted in the text, the estimated exposure ages from the 46 m and 36 m samples do not give true ages since these surfaces were polished. Possibly these surfaces were polished 65 ka and 57 ka BP respectively.

be explained due to these surfaces having been shielded by sediments. The presence of lake sediments at 20 m above the river level on the already cut and polished bedrock along the sides of the valley profile, upstream of the sampling site, strongly supports such a possibility (Figures 1, 2 b). However, we must state that at present there are no sediments on the surfaces sampled.

The Nanga Parbat–Haramosh Axis (NPHA) bounded by faults is considered to be one of the rare areas on the earth which has undergone extremely rapid exhumation ($4\text{--}6\text{ mm yr}^{-1}$), as evident from the mineral chronothermometers, during the Late-Quaternary^{15,16}. In contrast, the Kohistan and the Ladakh regions on either side of the NPHA exhumed at relatively much slower rate ($0.3\text{--}0.4\text{ mm yr}^{-1}$), and are related to the post-collision tectonic activity continuing in the Himalayan region^{15,17}.

Discussion and conclusion

The extensive moraines and tills, and associated fluvio-glacial and glacio-lacustrine deposits from Hindi and Gilgit in the Hunza–Gilgit valley, and between Sassi and Darel in the Indus valley west of the NPHA dated between 60 and 30 ka (with a few up to 139 ka), suggest that the westernmost part of the Ladakh region (Karakoram ranges, Nanga Parbat–Haramosh mountains and Zaskar ranges surrounding the Indus valley) had an extensive glacial cover during the Late Pleistocene^{2–4}. It is also suggested that the maximum penultimate glaciers at peak were much more extensive than those of the last glaciation stage (LGS) in the Karakoram^{2,18}. Further, within the last glaciation, the most extensive glaciers in the Karakoram–Zaskar region preceded the LGS of Tibet region by 20 ka or more. A close climatic correlation based on the pollen record from Tsokar (Ladakh)¹⁹, isotopic data from the Dunde ice core (Tibet)⁵, and magnetic susceptibility data from Central China⁶ evidently suggest regionality of climate in the Ladakh–Tibet region during the past 40 ka BP. Two warming events (~ 32 ka and 22 ka) in the Ladakh–Tibet region

are evident from the oxygen isotopic data, total dust particles, and SO_4^{2-} and Cl^- contents from the Dunde ice core records from Tibet and pollen data¹⁹ from Tsokar, Ladakh (Figure 3). The estimated temperature variations of $4^\circ\text{--}6^\circ\text{C}$ during last 40 ka and $4.2^\circ\text{--}6.5^\circ\text{C}$ during the period of LGS (pre-15 ka) in the Tibetan plateau are in good agreement with temperature estimates for other high mountainous regions in the tropics in both the hemispheres²⁰. In view of the above, any warming event causing an increase of $4^\circ\text{--}6^\circ\text{C}$ around 22 ka and 32 ka in the Tibetan region would be sufficient to increase melt-water and sediment supply, and hence the down-cutting capacity and the higher incision rate of the Indus river, as estimated from the cosmogenic exposure age data from Khalsi and Skardu–Sassi areas.

With the preceding discussion in mind, we consider the following as a plausible scenario for the evolution of the Upper Indus valley, based on cosmogenic exposure ages, which is consistent with the geological and climatic evidence for the Ladakh–Tibet region. Quite clearly the history of cutting/polishing of the upper two surfaces (46 m, 36 m) have been at variance with the lower three (21 m, 6 m, 1 m), which are consistent with a continuous river bed-cutting during the past 22 ka BP, resulting in a total cut of about 20 m. The measured lower exposure ages of 14.5 ka and 7 ka for the upper level (46 m, the 36 m) surfaces can be understood in a number of ways. Obviously, these surfaces did not receive cosmic ray irradiation continuously since they were polished because of the shielding for quite some time, possibly by lake sediments of Leh basin observed upstream of Khalsi. To us it appears that the extensive moraines (60–30 ka) of the glaciers, descending from the Karakoram–Zaskar ranges and the Nanga Parbat–Haramosh mountains into the valley, most probably dammed the Indus river around 50 ka, however, the possible role of active faults across Indus as in the NPHA (Figure 1 a) cannot be ruled out. Damming of the Indus river is known from the geological and historic records²¹, however, the period over which such natural dams existed is a matter of controversy and depends upon

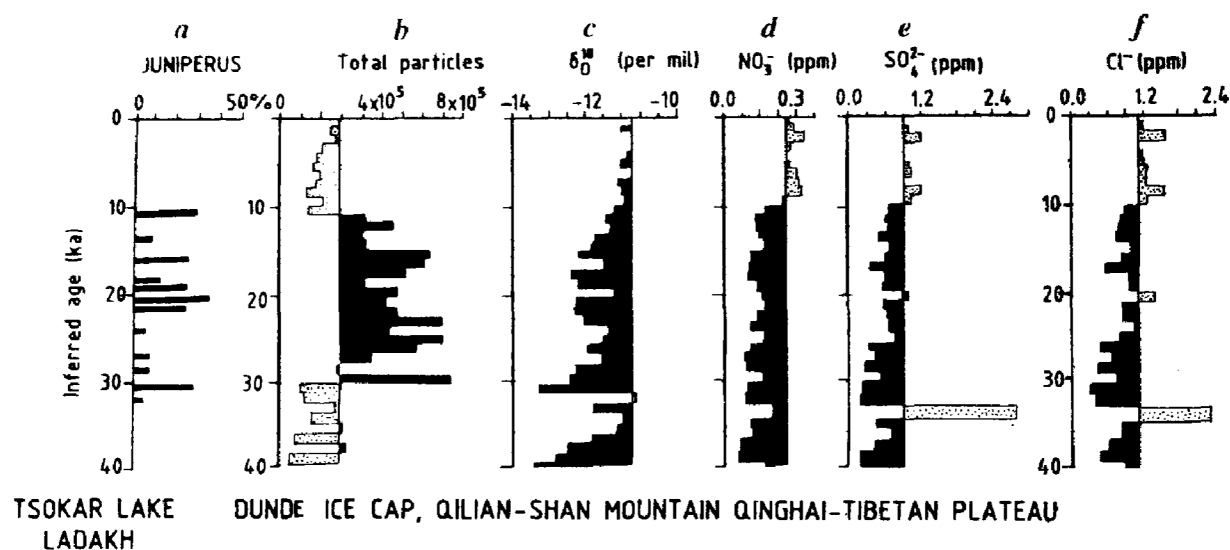


Figure 3. A comparative diagram showing (a) Juniper (%) variation in core TP6 from Tsokar lake (Ladakh) after Bhattacharyya²⁰; (b) dust concentrations ($\geq 2.0 \mu\text{m}$); (c) $\delta^{18}\text{O}$ value; (d) NO_3^- contents; (e) SO_4^{2-} contents and; (f) Cl^- contents in the cores from Dunde ice cap (Tibet) after Thompson *et al.*⁵. A sharp increase/decrease in various data sets is conspicuous and suggestive of short duration warm-arid events around 32 ka and 22 ka in Ladakh-Tibet region and continuously warm-arid climate since the beginning of the Holocene.

the climatic factors and water and sediments inflow. Incidentally, the ^{14}C dating of the organic debris (35.5 ± 0.6 ka) in the white chalky bands, lower part of the sequence²² and the charcoal pieces (> 40 ka) from 3.5 m above the base of the two hundred metre thick fluvio-lacustrine sequence of the Lamayuru basin²³ suggest that the damming of the stream (a tributary of Indus downstream of Khalsi; see Figure 1a) resulting in the formation of this basin also took place around 50 ka.

Damming of the Indus river, together with abrupt change in the gradient of the Indus river from 7.5 m/km upstream of Upshi to 2.3 m/km between Upshi and west of Leh, resulted in the development of the Leh basin where thick (~ 50 m) accumulation of the lake sediments took place. A few meters thick layer of the Leh basin sediments still covers the Indus bedrock surfaces upstream of the sampling site at Khalsi and lies at 20 m height above the present river level (Figure 2b). Such sediments possibly covered the upper level (46 m, 36 m) surfaces at Khalsi till the recent past, limiting their ages to the exposure duration of 14.5 ka and 7 ka reached before their burial by the sediments of the Leh basin. In this case, the actual time since when the 46 m and the 36 m surfaces were cut and polished at Khalsi would work out to be 64.5 ka and 57 ka respectively. It may be of interest to mention that similar exposure ages (60–67 ka) have been reported by Burbank *et al.*⁹ for the strath-1 (located at an elevation of 185 m) from west of Skardu, 150 km downstream of Khalsi, thus supporting 50 ka as the tentative timing for the damming of the Indus river and development of the Leh basin.

The second stage continuous down-cutting of the bedrocks below the lake sediments by the Indus river is evident from Figure 2b and the exposure age of the lower level (21 m, 6 m, 1 m) surfaces from Khalsi. These bedrock surfaces were initially cut and polished from 21 m to 6 m level at a much faster rate (2 mm yr^{-1}) between 22.5 ka and 15.5 ka period, corresponding to a short duration warming event in Tibet-Ladakh region around 22 ka (Figure 3). In contrast, a monotonic slow cutting ($0.3\text{--}0.4 \text{ mm yr}^{-1}$) of the bedrock by the Indus river since 15.5 ka BP is at par with the exhumation rate, at which the Ladakh region has been uplifting. The exposure chronology and the two-stage evolution of the Indus valley profile near Khalsi, deciphered from the cosmogenic nuclide data, suggest that the dammed lake on Indus resulting in the formation of the Leh basin drained off around 22 ka BP.

To conclude, the present study based on cosmogenic exposure ages of the river polished surfaces from various heights near Khalsi, together with similar data along the 100 km long stretch of the Indus river from the downstream (Skardu-Sassi area), clearly bring out that the extremely rapid incision rates for short duration around 32 ka ($> 12 \text{ mm yr}^{-1}$) in Skardu-Sassi area and ~ 22 ka ($> 2 \text{ mm yr}^{-1}$) in Khalsi area, where the monsoon influence is the least, are due to the combined effects of climate-induced melt-water supply, and the continued post-collision tectonic uplift, rather than exclusively to the tectonics as suggested by Burbank *et al.*⁹.

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