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Asymmetrical erosion and morphological development of the central Ladakh Range, northern India

Jason M. Dortch [a,*], Lewis A. Owen [a], Lindsay M. Schoenbohm [b], Marc W. Caffee [c]

[a] Department of Geology, University of Cincinnati, Cincinnati, OH 45221, USA
[b] Department of Chemical and Physical Sciences, University of Toronto, Mississauga, Canada ON L5L 1C6
[c] Dept of Physics/PRIME Laboratory, Purdue University, West Lafayette, IN 47906, USA

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ABSTRACT

Variations in erosion were quantified across the topographically and morphometrically asymmetrical central Ladakh Range in NW India to elucidate erosion and sediment transfer processes across space and time and to gain insight into how mountains erode and evolve. Morphometric analysis and ^{10}Be cosmogenic nuclide analysis of 14 fluvial sediment samples from active channels in six catchments conducted across the mountain range constrains 100 ka timescale erosion rates for catchments on the northern side of the mountain range and are between 56 ± 12 and 74 ± 11 m/Ma, while catchments on the southern side of the mountain range to between 20 ± 3 and 39 ± 8 m/Ma for the last ~300 ka. Maximum elevation from swath analysis across the range shows a strong correlation with the ELAs of 382 contemporary glaciers. The higher erosion rate to the north likely relates to tectonic tilting of the central Ladakh Range and to active rock uplift on the northern side of the range along the Karakoram Fault. Morphometric analysis shows that the maximum and average elevations increase at nearly the same rate on a catchment-scale across the central Ladakh Range, with higher elevation on the northern side. This suggests that greater erosion on the northern side of the range is not keeping pace with rock uplift. Moreover, long-term denudational unloading does not play a significant role in the tectonic tilting of the central Ladakh Range.

1. Introduction

Researchers have hypothesized that erosional unloading can influence rate and style of tectonic deformation (Molnar and England, 1990; Brozovic et al., 1997; Hodges et al., 2001, 2004; Zeitler et al., 2001; Hodges, 2006) but this hypothesis remains controversial and rates of erosion and sediment transfer need to be quantified to help test these models (Broecker and Denton, 1990; Zeitler et al., 2001; Burbank et al., 2003). Yet, few studies have provided data quantifying the erosion rate across a mountain range, partially because of the lack of adequate methods to determine rates on geomorphic timescales (10^0 to 10^6 years). However, the development of terrestrial cosmogenic nuclide (TCN) methods now provides a means to determine the spatial and temporal variation in erosion (Lal and Arnold, 1985; Bierman, 1994; Bierman and Steig, 1996; Granger et al., 1996; Portenga and Bierman, 2011). To provide some of the first data on erosion rates across a high range in the Himalaya and to begin to test tectonic-climate-erosion models, we undertook a study of the central Ladakh Range, located in the Transhimalaya of northern India, using field mapping, remote sensing and ^{10}Be TCNs. The asymmetric morphology of the central Ladakh Range suggests that erosional unloading affects rock uplift on the northern side of the range, but our results indicate otherwise.

The central Ladakh Range is an ideal study area because the mountain range is easily accessible, of moderate size, and has contrasting styles of deformation, unroofing history, and geomorphology on its northern and southern sides (Fig. 1). The Indus-Tsangpo Suture Zone (ITSZ) bounds the range along its southern margin, which is essentially inactive; whereas the more active Karakoram Fault and Shyok Suture Zone (SSZ) bound its northern side (Rex et al., 1988; Dunlap and Wysoczanski, 2002; Kirstein et al., 2006). Based on thermochronology data from zircon and apatite (U–Th/He) and apatite fission-track methods (AFT), Kirstein et al. (2006, 2009) argued that the central Ladakh Range has been tectonically tilted southward, which results in higher elevations on the northern side of the mountain range during the Late Paleogene (Fig. 2; Table 1). Using morphometric analysis of digital elevation models (DEMs), Jamieson et al. (2004) showed that catchments on the southern side of the central Ladakh Range are significantly shorter, narrower, and have a lower mean elevation than the equivalent catchments on the northern side of the range.

In principle, the tectonic tilting should cause enhanced erosion of northern catchments compared to the southern catchments. Moreover,

* Corresponding author at: Department of Chemical and Physical Sciences, University of Toronto, Mississauga, 3359 Mississauga Rd. N., Mississauga, Canada ON L5L 1C6. Tel.: +1 905 828 5397; fax: +1 905 828 5425.
E-mail address: jason.dortch@utoronto.ca (J.M. Dortch).

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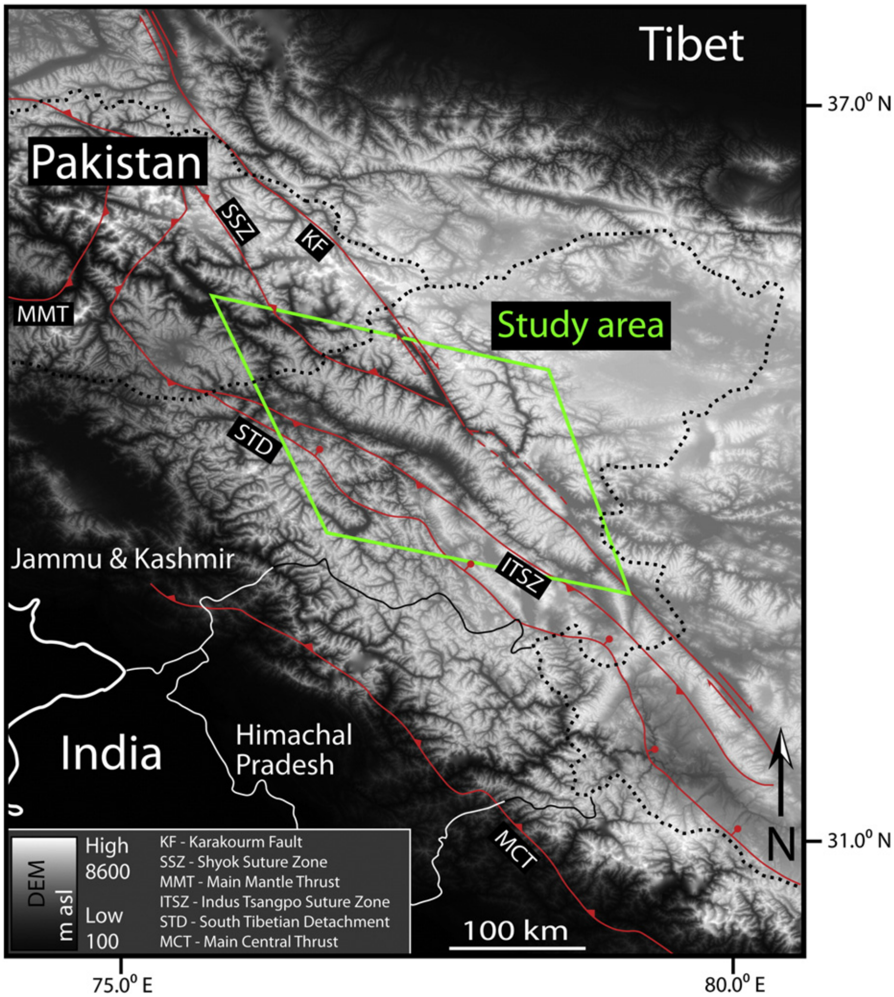

Fig. 1. Shuttle Radar Topography Mission (SRTM) DEM for the NW India Himalaya. The Karakoram Fault (KF) bounds the northeastern edge of the study area. Major faults (from Hodges, 2000) shown in white (red in online version) are (from NW to SW): SSZ — Shyok Suture Zone; ITSZ — Indus-Tsangpo Suture Zone; STD — South Tibetan Detachment; and MCT — Main Central Thrust.

higher erosion on the northern side of the range is expected to create positive feedback between incision, relief, glaciation, and mass movement – inducing denudational unloading and causing the rivers to be in disequilibrium – while the rivers in the southern catchments should aggrade in their lower reaches to advance toward a state of dynamic equilibrium.

In this study, we aim to test these ideas by comparing catchment-wide erosion rates, long valley profiles, equilibrium-line altitude's (ELAs), and basin statistics across the central Ladakh Range using ^{10}Be TCN method, and morphometric analysis. Ultimately, we conclude that asymmetric erosion across the central Ladakh Range is not pervasive enough to influence tectonic processes, which precludes a denudational unloading scenario.

2. Study area background

The Ladakh and adjacent ranges are a consequence of the collision of the Indian and Eurasian continental lithospheric plates starting at ~50 Ma, which resulted in ~2000 km of crustal shortening (Dewey et al., 1989; Johnson, 2002). This collision produced the world's largest and highest orogenic plateau, the Himalayan–Tibetan orogen (Yin and Harrison, 2000; Searle and Richard, 2007). Some of the crustal shortening and thrust and strike-slip faulting are still active (Hodges et al., 2004; Vannay et al., 2004; Bojar et al., 2005).

Located in the Transhimalaya, the Ladakh Range is primarily composed of Cretaceous, continental-arc, plutonic rocks (Searle, 1991). A wide band (≤10 km) of Khardung volcanics comprises the very northern edge of the Ladakh Range (Dunlap et al., 1998).

The inactive ITSZ marks the southern boundary of the Ladakh Range. The Shyok Suture Zone (SSZ) bounds the NW side of the range and is relativity inactive. Rex et al. (1988) suggested that the SSZ was reactivated in the late Tertiary, calling it the Main Karakoram Thrust. The active Karakoram Fault, principally a dextral strike-slip fault, bounds the northeastern side of the range. The Karakoram Fault is a >750–km-long, continental-scale structure that has offset the Indus River ~150 km; however, the evolution and displacement rate along the fault remain hotly debated (Searle et al., 1998; Searle and Owen, 1999; Brown et al., 2002, 2005; Chevalier et al., 2005; Searle and Richard, 2007; Robinson, 2009a,b). Dunlap et al. (1998) showed two periods of oblique, transpressional motion along the Karakoram Fault from 7 to 8 Ma and from 13 to 17 Ma using ^{40}Ar/^{39}Ar methods. Apatite (U–Th/He) and apatite fission-track thermochronometers have yielded Oligocene to Pliocene ages, with progressively younger ages northward across the central Ladakh Range (Choubey, 1987; Sorkhabi et al., 1994; Clift et al., 2002; Schlup et al., 2003; Kirstein et al., 2006, 2009). Based on amphibole thermobarometry data, Kirstein (2011) suggested that rapid cooling (exhumation rate at 0.4 km/Ma) occurred by ~29 Ma on the southern margin and ~22 Ma in the middle of the central Ladakh Range. The most recent phase of exhumation (0.43–0.65 km/Ma) occurred on the northern side of the range since 1517 Ma with the removal of >4 km of material since ~7 Ma (Kirstein, 2011).