In review *(Geology)*: Alpine landscape evolution dominated by cirque retreat

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Abstract

Despite the abundance in alpine terrain of glacially dissected landscapes, the magnitude and geometry of glacial erosion can rarely be defined. In the eastern Kyrgyz Range, a widespread unconformity exhumed as a geomorphic surface provides a regional datum with which to calibrate erosion. As tectonically driven surface uplift has progressively pushed this surface into the zone of ice accumulation, glacial erosion has overprinted the landscape. With as little as 500 m of incision into rocks underlying the unconformity, distinctive glacial valleys display their deepest incision adjacent to cirque headwalls. The expansion of north-facing glacial cirques at the expense of south-facing valleys has driven the drainage divide southwards at rates up to 2 to 3 times the rate of valley incision. Existing ice-flux-based glacial erosion rules incompletely model expansion of glacial valleys via cirque retreat into the low-gradient unconformity remnants. Local processes that either directly sap cirque headwalls or inhibit erosion down-glacier appear to control, at least initially, alpine landscape evolution.

Introduction

The remarkable coincidence of glacial snowlines with average height of high mountains suggests that glaciation may exert primary control on mountain-range elevation, irrespective of tectonic rates (Broecker and Denton, 1990; Brozovic et al., 1997; Montgomery et al., 2001; Spotila et al., 2004). Thus the topographic evolution that accompanies the transformation of nascent, unglaciated landscapes to highly glaciated ones is a key to unraveling the erosional component of a climate–erosion feedback system (Molnar and England, 1990). Comparative geomorphic studies support contentions that glaciation enhances valley erosion and topographic relief (Brocklehurst and Whipple, 2002; Kirkbride and Matthews, 1997; Montgomery, 2002; Small and Anderson, 1998). Observations of planimetric cirque expansion (Federici and Spagnolo, 2004; Olyphant, 1981) and truncated glacial valleys (Brocklehurst and Whipple, 2002) indicate cirque retreat could play a competing role by expanding valleys horizontally and removing high topography. The significance of cirque retreat in limiting mountain range height, however, has not been conclusively established.

For tectonically active mountain ranges undergoing surface uplift, their progressive penetration into the zone of glaciation can provide a proxy for transformation of landscapes during the well-documented late Cenozoic cooling (Shakleton and Opdyke, 1973). Growth of the Tien Shan (Fig. 1, inset), when combined with its unique geologic history, establishes a natural laboratory to investigate glacial valley erosion and cirque retreat. Basement-cored uplifts of the northern Tien Shan exhume resistant Paleozoic plutonic and metamorphic bedrock from beneath unconsolidated Cenozoic non-marine sedimentary strata. A regionally extensive, pre-Cenozoic low-relief unconformity separates these units (Chediya, 1986). In the arid environment of central Asia, significant areas of this exhumed unconformity form geomorphic surfaces that appear little modified by fluvial erosion, and instead faithfully delineate the geometry of range-scale folding (Burbank et al., 1999). When surface uplift causes ranges to intersect the local Pleistocene glacial equilibrium-line altitude (ELA), however, glacial erosion may cause significant incision of the Paleozoic rocks underlying the unconformity. Reconstruction of this datum over glaciated topography thus enables reliable estimation of the magnitude of glacial bedrock erosion.

Late Cenozoic uplift of the Kyrgyz Range provides a structurally well-controlled experiment from which to measure sequential glacial landscape evolution. Uplift occurs via hangingwall folding and slip on a reverse fault system that emplaces resistant Paleozoic quartzite, metaconglomerate, granitic, and metavolcanic rocks northward over Miocene through Quaternary foreland-basin strata. Bedrock thermochronology supports erosion rates of ~1 km/Myr from 3 Ma to present in the central, highest part of the range (Bullen et al., 2001). Detrital apatite fission-track ages from foreland-basin strata and modern rivers indicate progressively less exhumation in the eastern Kyrgyz Range (Bullen et al., 2003), consistent with preservation of exhumed, tilted remnants of the unconformity on over _ of the easternmost 50 km of its south-facing slope (Fig. 1). These observations support an eastward propagation or an eastward-declining rate of coeval rock and surface uplift that has progressively elevated the range crest into the zone of glaciation above the local Pleistocene ELA.

Glacial Erosion of the eastern Kyrgyz Range

Exhumation of the pre-Cenozoic unconformity as a geomorphic surface underpins the quantification of erosion. Swath topographic profiles (Fig. 2) reveal minimal topographic relief development on its unglaciated south-facing slope. Maximum elevations of these areas are defined by low relief, upland surfaces with concordant elevation and southward tilt preserved between larger, incised drainages that descend from the range crest (Fig. 3). These surfaces merge with outcrops of the unconformity beneath Cenozoic strata at the base of the range. A fourth-order polynomial surface with curvature of <1°/km fit to the distribution and tilt of mapped remnants defines a continuous envelope over the south-facing slope of the range (Fig. 4). This envelope captures the mapped unconformity within ±100 m (1σ), over >1500 m of structural relief. Tilting of the restored unconformity surface increases both with elevation and from east to west, consistent with a gradient of slip over a curviplanar reverse fault at depth.

Comparison of three adjacent catchments incised into the south-facing slope of the Kyrgyz Range reveals details of the form of initial glacial erosion and the continuity of interfluvial geomorphic surfaces (Fig. 5). All three streams descend at steep (>8°) slopes incised <600 m into the tilted unconformity preserved at concordant undissected interfluves. The fluvial part of each valley is analogous to a half-pipe, with uniform valley width and fairly uniform incision. In contrast, the glaciated parts of these catchments display significant widening and deepening with the greatest incision at their glaciated headwaters. Adjacent glaciated catchments show a similar pattern of maximum incision at their headwaters (Fig. 4).

North-facing glaciated catchments of the eastern Kyrgyz Range consist of high-elevation, gently sloped U-shaped valleys linked to steep, V-shaped canyons that descend to the range-bounding reverse fault (Fig. 1). Absence of preserved remnants of the unconformity near the fault limits precise estimation of incision of these catchments. To conservatively evaluate glacial incision by north-facing catchments, the slopes of north-facing glaciated valleys are examined with respect to slope of the adjacent, south-dipping unconformity surface preserved at the range crest (Fig. 4). The difference of these slopes defines a ratio of valley length to valley incision (0.3–0.4) that is significantly less than the average slope (0.8 ± 0.1 (1σ), n=66) of cirque headwalls along the range crest.

The presence and extent of glaciation in north-facing catchments corresponds to changes of trend and elevation of the range crest. Outside of the zone of glaciation, the range crest tracks ~5 km south of the trace of the range-bounding reverse fault, the range shape reflects growth of the underlying geologic structure (e.g. Fig. 2a), and peak elevations climb steadily from 2400 m near the Chu River in the east to 3400 m at the first glaciated catchment. Within the zone of glaciation, peak elevations stabilize at ~4000 m elevation and the position of the range crest shifts systematically southward relative to the range front in proportion to the degree of Late Pleistocene ice cover (e.g. Figs. 2b through 2d).

Discussion

The gradient in rock uplift of the eastern Kyrgyz Range permits along-strike space-for-time substitution of observations of incision of the range by glaciers. Because the range is rising above an active reverse fault at approximately 1 km/Ma, glaciation of the eastern range tip is likely to have occurred sequentially during the Pleistocene. Although each valley has a unique incision history, spatial trends of landscape evolution that are shared among several adjacent valleys may represent temporal trends within an individual valley. Much of the transformation of the Kyrgyz Range into its glacially sculpted form involves competition between adjacent catchments that drives migration of drainage divides over time. Exhumation of the pre-Cenozoic unconformity as a geomorphic surface datum affords a unique opportunity to quantify the degree of glacial incision that accompanies progressive changes in valley form.

Rapid formation of gently sloped upland U-shaped valleys accompanies initial glacial erosion of the eastern Kyrgyz Range. Glaciers on south-facing slopes accomplish this by widening and eroding their valleys deeper than adjacent fluvial valleys, evidenced by incision and valley-width maxima near the range crest (Fig. 5). Approximately 0.5 km of incision into the unconformity surface forms these characteristically glaciated valleys, consistent with low erosion depths required to obtain stable glacial valley cross-sections in numerical simulations (Harbor, 1992).

Systematic, relative southward migration of the drainage divide of the eastern Kyrgyz Range shows that cirque retreat also accompanies initial glacial erosion. Expansion of north-facing valleys via glacial cirque retreat provides a consistent explanation for these spatial trends of landscape evolution with progressive rock uplift above the local ELA (Fig. 6): (1) range crest elevation stabilizes at ~4000 m with the onset of erosion by glaciers; (2) further uplift and tilting of the range is accompanied by southward relative migration of the drainage divide; and (3) the pre-Cenozoic unconformity is preserved as a geomorphic surface at the range crest. Peak heights remain constant along trend and the range crest preserves remnants of the exhumed unconformity because the divide has shifted southward with progressive uplift and glacial erosion (Fig. 2). In effect, during initial glacial erosion, the range crest remains more or less pinned to the intersection of the 4000-m contour line with the tilted unconformity. This explanation requires that a competitive advantage for cirque erosion exists for north-facing catchments over their south-facing counterparts and that glacial erosion of the Kyrgyz Range occurs, at least initially, by a combination of cirque retreat and glacial valley incision.

Alternative origins for southward migration of the divide include differential fluvial incision, exposure of lithologies that resist glacial erosion, or formation in place of the present divide by range-scale folding. Range-scale folding may be ruled out as an explanation because peaks and ridges north of the present divide are locally at the same elevation or higher than the exhumed unconformity preserved at the divide (Figs. 1, 2c, and 2d). This geometry requires that the structural axis of the Kyrgyz Range trends north of the present drainage divide in the zone of glacial erosion. Metasedimentary rocks that underlie the glaciated area strike transverse to valleys and dip steeply, inconsistent with lithologic control of valley floor elevation. It is also unlikely that the present low-gradient upland valleys formed entirely by glacial incision of steeper fluvial valleys (c.f. Brocklehurst and Whipple, 2002) because the valley heads terminate at uneroded remnants of the unconformity. Only headward erosion of low-gradient glaciated valleys by cirque retreat could maintain this geometry at the range crest (Fig. 6). To estimate the total amount of cirque retreat and valley incision requires additional knowledge of the divide position that developed by range-scale folding and fluvial incision prior to glaciation. A tentative reconstruction of the original divide position across the easternmost four glaciated catchments indicates between 0.9 and 4.4 km of cirque retreat with only 0.4 to 1.3 km of valley incision (Fig. 4). Further extrapolation of the pre-glaciation divide suggests that >10 km cirque retreat dominates erosion of north-facing valleys.

Evidence for substantial headward expansion of catchments via cirque retreat in the Kyrgyz Range, the Sierra Nevada (Brocklehurst and Whipple, 2002), and potentially elsewhere (Olyphant, 1981) compels a closer examination of the resulting valley form. The immediate cause of cirque retreat is the collapse of steep headwalls at the expense of adjacent low-relief uplands. Processes that sap the cirque walls at the head of the glacier ultimately determine the retreat rate. Because the ratio of valley length to valley incision (0.3–0.4) in the headwaters of north-facing catchments is 2 to 3 times less than the slope of adjacent cirque headwalls (0.8 ± 0.1), sapping by valley incision alone is unlikely to cause the observed retreat. Rather, erosion localized at the base of cirque headwalls is required to propagate cirque retreat across the range at a rate 2 to 3 times greater than the glacial valley incision rate. Incision maxima developed at the heads of south-facing glaciated valleys (Fig. 4) are consistent with a localized sapping process at cirque headwalls.

Because cirque headwalls form within the glacial accumulation zone, modeling cirque erosion via ice-flux based rules (Hallet, 1979, 1996) predicts in greater downstream valley incision than erosion of the cirque floor: a prediction incompatible with observations from the Kyrgyz Range. This may be reconciled if subglacial water pressure fluctuations within cirques locally enhance erosion (Hooke, 1991), or if development of glacial bedforms, such as terminal moraines and overdeepenings, restricts pressure fluctuations and erosion down-glacier (Alley et al., 2003). It is also possible that the integrated residence time of vestigial cirque glaciers under average Quaternary conditions (Porter, 1989) has been sufficient to tip the balance of erosion in favor of cirque incision and consequent headward retreat. Such erosion is consistent with preferred erosion of north-facing catchments, where shading of glacier surfaces lowers the local ELA by ~200 m.

Conclusion

Analysis of the configuration and gradient of glacial valleys in the eastern Kyrgyz Range indicates that cirque retreat dominates initial glacial erosion. This erosion is quantified in the context of a progressively tilted pre-Cenozoic unconformity that is exhumed as a geomorphic surface. This cirque retreat may be incompatible with existing ice-flux-based glacial erosion rules, and highlights a need to understand erosional processes localized within cirques in order to predict alpine landscape evolution. Cirque retreat can effectively bevel across an elevated alpine plateau and keep pace with moderate rock uplift rates, as documented here for the Kyrgyz Range where retreat rates are at least 2 to 3 times greater than the accompanying valley incision rate. Although cirque retreat may not be as significant in all alpine settings (White, 1970), results from the Kyrgyz Range support the contention that glacial valley incision combined with cirque retreat into interfluves may be a viable mechanism whereby glaciers simultaneously erode at high rates and limit alpine relief.

Figures

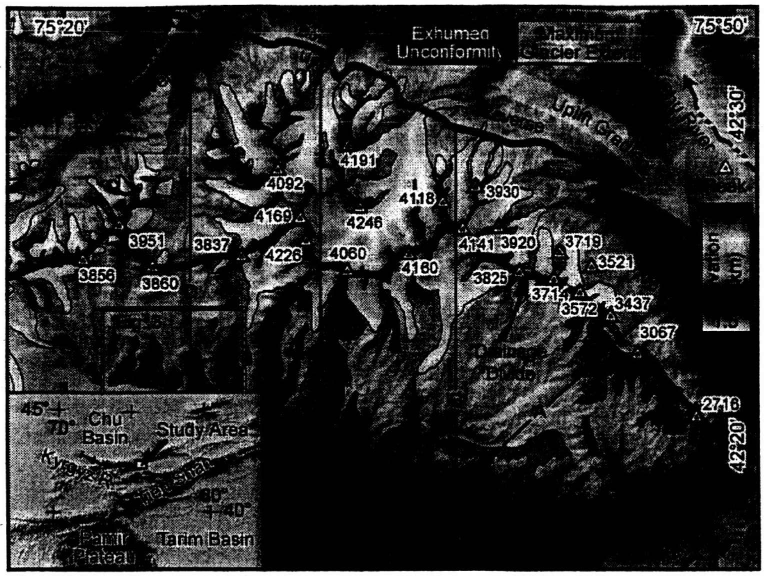

Figure 1. Exhumed pre-Cenozoic unconformity and maximum glacial extent in the eastern Kyrgyz Range. Present-day drainage divide shown as line of peaks (elevations in meters) connected by heavy gray solid line. A-D are center lines of swath profiles in Fig. 2. Inset: shaded relief map of central Asia with Kyrgyz Range crest as hatched line.

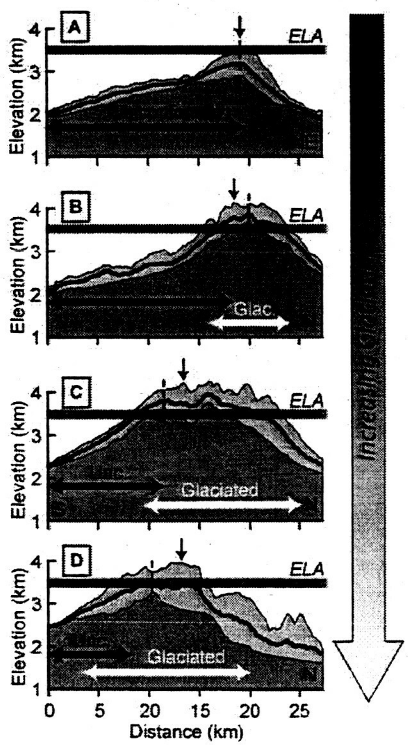

Figure 2. Topographic swath profiles across the easternmost Kyrgyz Range. Each profile samples topography from a 5-km-wide swath centered on profile lines shown on Figure 1. Light gray band depicts range of minimum and maximum topography, with mean values shown as thicker central line. Horizontal black arrow depicts extent of geomorphic surfaces formed by exhumed remnants of the pre-Cenozoic unconformity. ELA is last glacial maximum equilibrium-line altitude. White arrow is extent of last maximum glaciation. Glaciated areas correspond to areas of higher relief and erosional removal of the pre-Cenozoic unconformity at the range crest. Extent of glaciation is inversely proportional to northward position of drainage divide, illustrated by vertical dashed lines. Highest elevation of the range crest shown by downward arrows.

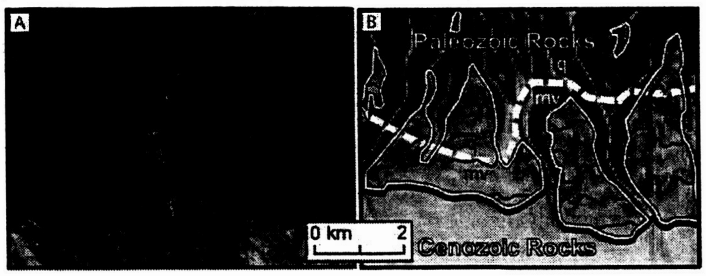

Figure 3. A. ASTER scene of geomorphic surfaces formed by exhumed pre-Cenozoic unconformity on south slope of the Kyrgyz Range. Surfaces are visible as medium albedo with intricate dendritic stream network. B. Interpreted slope map of area shown in A. Steeper slopes (darker gray) correspond to valley sides. White solid lines outline surface remnants mapped from analysis of the SRTM topography, ASTER, and Corona imagery (not shown). Elevation contours at 100-m intervals (black lines) show minimal local relief formed by incision of geomorphic surfaces. White dashed line shows folded Paleozoic contact (truncated by the unconformity) between metavolcanic rocks (mv.) and quartzite (q).

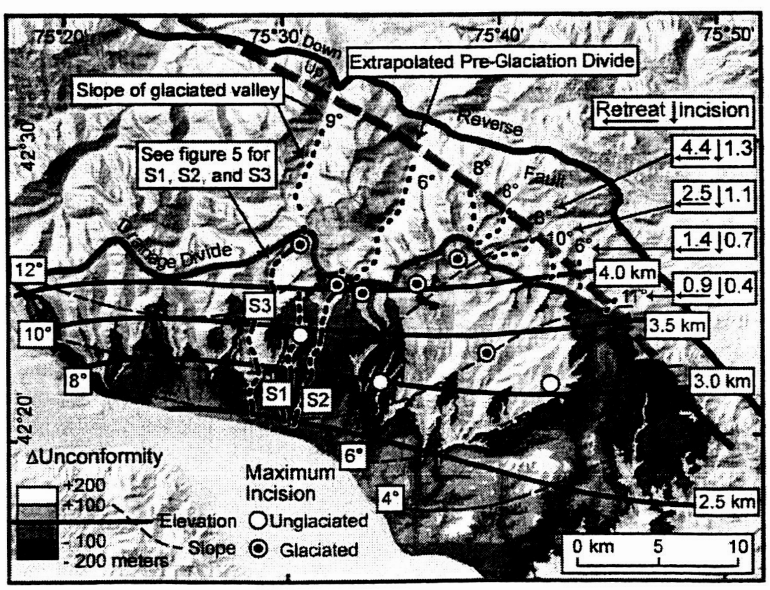

Figure 4. Contours of reconstructed pre-Cenozoic unconformity elevation (solid lines) and slope (dashed lines) overlain on a shaded relief image of the Eastern Kyrgyz Range derived from SRTM topography. ΔUnconformity depicts elevations within 100 m and 200 m from modeled unconformity and compares well with its mapped exhumed remnants on Fig. 1. Dotted lines show gradients of north-facing glacial valley floors. Pre-glaciation divide extrapolated along front of prominent faceted spur ridges that separate glaciated valleys.

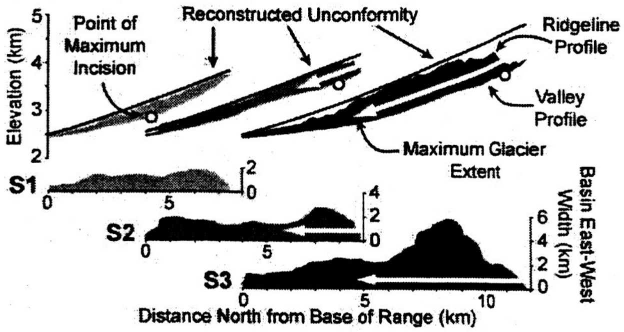

Figure 5. Valley profiles, incision beneath the reconstructed unconformity, and catchment width from three adjacent south-facing streams with varying amounts of glaciation. See Fig. 4 for catchment locations. In the absence of glaciation, incised valleys (S1) are shaped like half-pipes with uniform width. Glacial erosion corresponds to incision maxima at cirque floors and widening of catchments in the zone of ice accumulation, supporting valley expansion via cirque retreat.

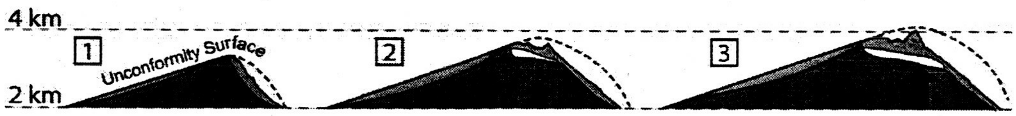

Figure 6. Landscape evolution of the eastern Kyrgyz Range with progressive rock uplift. Compare to Figs. 2a through 2c. Light and dark gray represent ridgeline and valley elevation, respectively. Dashed line shows extrapolation of folded unconformity surface over north slope of range. 1. Range form prior to glacial erosion with divide controlled by fluvial erosion and range-scale structural fold axis. 2. Initial glacial erosion of north-facing valley causes southward divide migration relative to fold axis. Unconformity surface is preserved on south-facing slope at range crest. 3. Further range uplift accompanied by additional cirque retreat and expansion of north-facing valley. Note peak of northern ridgeline is higher than unconformity preserved at the drainage divide.

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