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Pliocene erosional pulse and glacier-landscape feedbacks in the western Alaska Range

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ABSTRACT

Pliocene–Pleistocene glaciation modified the topography and erosion of most middle- and high-latitude mountain belts, because the evolution of catchment topography controls long-term glacier mass balance and erosion. Hence, characterizing how erosion rates change during repeated glaciations can help test hypothesized glacier erosion-landscape feedbacks across a range of settings. To better understand how glaciations and landscapes coevolve on geologic timescales, I quantify erosion rates in the glaciated western Alaska Range with low-temperature thermochronometric data and modeling. Zircon (U–Th)/He and apatite fission track data suggest mountain-building was underway by the early Miocene. In contrast, lower-temperature apatite (U–Th)/He age-elevation and grain age-kinetic data indicate that erosion accelerated coincident with regional Pliocene glaciation ca. 4 Ma. Furthermore, erosion rates calculated within an eroding half-space indicate slow erosion at a rate $\leq$0.3 km/m.y. before 4.2 Ma, an initial pulse of rapid erosion at a rate of 1.0–1.6 km/m.y. during 4.2–2.9 Ma, and more moderate erosion at a rate of 0.4–0.7 km/m.y. since 2.9 Ma. The initial erosion pulse suggests a significant transient landscape adjustment to the introduction of efficient glacial erosion. The subsequent decrease in Pleistocene erosion rates is consistent with a negative feedback between continuing glaciation and glacier size/erosivity: If glacial erosion outpaces rock uplift, glacier erosion decreases over time as topography, mass balance, valley gradients, and ice flux are reduced. These findings imply that in areas of moderate rock uplift rates, the onset of local Plio–Pleistocene glaciation may have been punctuated by an initial pulse of rapid landscape change, after which change became more gradual.

1. Introduction

Oscillating climate, cooling, and glaciation in Pliocene–Pleistocene time is proposed to have created a state of geomorphic disequilibrium responsible for increased rates of erosion and sediment accumulation that are observed globally (Molnar, 2004; Herman et al., 2013). Glacial erosion had an expanded role in the middle and high latitudes during this time and various studies discern an increase in erosion rates whose timing is latitudinally variable (Herman et al., 2013; De Schepper et al., 2014). Even where evidence for a first-order increase in Plio–Pleistocene glacial erosion is clear, however, the second-order evolution of erosion rates since the increase is more difficult to ascertain. Data that characterize how erosion rates vary over the course of repeated glaciations are thus needed to evaluate how glaciations and landscapes coevolve on geologic timescales.

Changes in erosion rates due to Plio–Pleistocene glaciation are not uniform in time or space (Shuster et al., 2011; Valla et al., 2011; Herman and Brandon, 2015; Yanites and Ehlers, 2016), owing partly to complex feedbacks between topography, climate, glaciation, and erosion on geologic timescales (Yanites and Ehlers, 2012). Changes in catchment topographic evolution (Pedersen and Egholm, 2013), moisture flux (Herman and Brandon, 2015), and glacier thermal regime (Koppes et al., 2015) can significantly modulate the size, extent, and erosivity of glaciation. Observations and modeling suggest a spectrum of glacial erosion behavior that ranges from more erosive "buzzsaw" conditions across an entire landscape (e.g., Brozović et al., 1997) to selective preservation of "Teflon" peaks and plateaus above the polar limit (e.g., Ward et al., 2012). Modeling of erosive valley glaciers under an idealized climate pattern suggests that the long-term evolution of topographic factors like relief, hypsometry, valley gradients, and rock uplift rates control glacier mass balance and erosion rates on geologic timescales (MacGregor et al., 2000; Anderson et al., 2012; Yanites and Ehlers, 2012).

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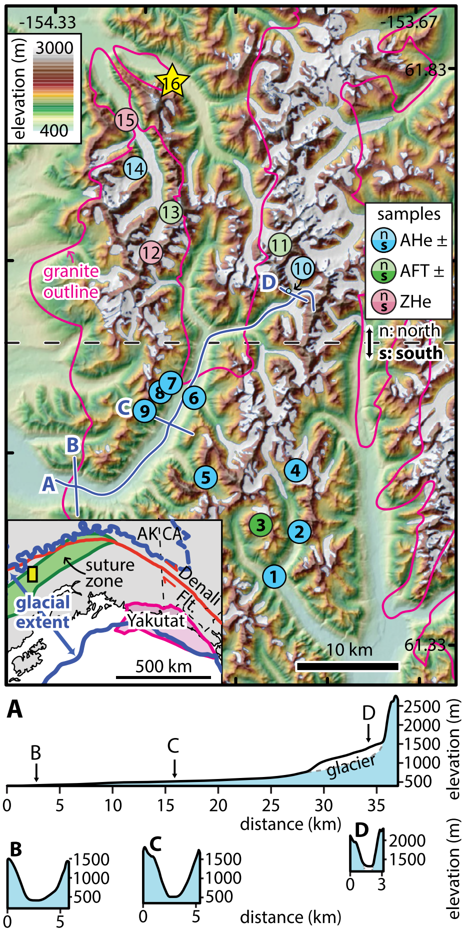

Fig. 1. Western Alaska Range samples for thermochronometer age-elevation transect and modeling (numbered circles; Figs. 2, 4, 5) and age-kinetic model (yellow star; Fig. 3). Topographic long (A) and cross-valley profiles (B–D) portray glacial landscape. Inset shows tectonic and glacial setting of study area (yellow box). Collision of the Yakutat microplate (magenta) has driven mountain building in the weak Alaska Range suture zone (green). Plio–Pleistocene glaciers have repeatedly covered the region (blue: max extent; Kaufman et al., 2011). AK – Alaska, CA – Canada. See Fig. S1 for cooling ages alongside map.

Measuring glacial erosion rates on geologic timescales presents some challenges. For example, advancing glaciers tend to recycle sediment deposited during prior retreat cycles. This makes it difficult to quantify sediment yields or, alternatively, use isotopic proxies extending beyond one or a few glacial cycles, especially in the terrestrial realm (Jaeger and Koppes, 2016). Longer Plio–Pleistocene glacial records can exist in sedimentary basins, however these integrate over large areas including unglaciated regions and can be fragmentary. In addition, autogenic or tectonic basin processes can mute glacial signals, and because basins tend to be far removed from source areas, it may be impossible to relate glacier dynamics to landscape forcing. Alternatively, low-temperature thermochronometry provides a means to measure continuous, long-term erosion rates from known bedrock locations in glacial landscapes (e.g., Shuster et al., 2011; Valla et al., 2011; Christeleit et al., 2017), providing an indirect measure of landscape forcing. Here, I employ thermochronometry in a high-latitude area of moderate rock uplift to quantify both the onset of accelerated Pliocene erosion and how erosion rates evolved during glaciation.

2. Setting

I investigate the exhumation history of the Revelation Mountains, at the western end of the >600-km-long Alaska Range in southcentral Alaska (Fig. 1). Oligocene collision of the Yakutat microplate with the southern Alaska margin drove deformation in distal regions. Bedrock and detrital thermochronometer data indicate that exhumation was focused in a weak Mesozoic suture zone and propagated along the entire length of the Alaska Range between 30 and 18 Ma (Benowitz et al., 2014; Lease et al., 2016; Finzel et al., 2016; Haeussler et al., 2008). In contrast, the variable space-time pattern of middle to late Miocene Alaska Range exhumation suggests independently evolving histories influenced by local structures (Fitzgerald et al., 1993; Benowitz et al., 2014; Lease et al., 2016). Increased Pliocene exhumation is limited to high-relief, glacier-covered regions (Benowitz et al., 2011; Lease et al., 2016).

The Pliocene initiation of large-scale glaciation in interior Alaska and the Alaska Range is constrained by proxy records. Increasing fluxes of Alaska Range detritus and glacial meltwater to the Bering Sea suggest the initial development of Alaska Range glaciers between 4.2 to 3.3 Ma, and growth of progressively larger glaciers between 3.3 to 2.5 Ma (Horikawa et al., 2015) that occurred during 9 °C of sea-surface temperature cooling (Yamamoto and Kobayashi, 2016). These glaciers are recorded by changes in Nd and Pb isotopes, clay minerals, C_{37} alkenones, and sea-ice related diatoms (Horikawa et al., 2015), as well as glacially-derived loess in interior Alaska (Westgate et al., 1990). Although initial alpine glaciation in the Gulf of Alaska to the south is coeval with mountain building at ∼6 Ma, a major expansion with tidewater glaciation occurred at 3–3.5 Ma with subsequent intensifications (Lagoe et al., 1993; Gulick et al., 2015). Alaska Range glaciations are consistent with global evidence for high-latitude Pliocene glaciations (De Schepper et al., 2014) and an increase in global ice volume between 3.6 and 2.4 Ma during the gradual initiation of Northern Hemisphere Glaciation (Mudelsee and Raymo, 2005).

Valleys of the Revelation Mountains have incised into strong Paleogene granites of the Alaska Range batholith (Fig. 1). Mountain peaks are consistently 3000 to 2300 m in elevation, modern glaciers have a mean elevation of ∼1500 m, and local base level is at ∼400 m. Valleys display mature glacial forms, with wide U-shaped cross profiles, gently-sloping longitudinal profiles, steps at tributary junctions, rapid downstream valley widening, and steep cirque headwalls (Fig. 1A–D).

3. Methods

I determined the erosional history of the Revelation Mountains with low-temperature thermochronometry. I utilized the elevational dependency of apatite (U–Th)/He [AHe], apatite fission track [AFT], and zircon (U–Th)/He [ZHe] cooling ages, which have effective closure temperatures of ∼60 °C, ∼110 °C, and ∼180 °C, respectively (Reiners and Brandon, 2006). The 10^6 yr integration time for the thermochronometers averages multiple glacial cycles. Eleven AHe, 8 AFT, and 9 ZHe ages are reported from samples ranging in elevation from 520 to 2060 m. The (U–Th)/He analyses were performed at the University of Colorado and the fission-track analyses were performed at GeoSep Services (see Supplementary Material and U.S. Geological Survey Data Release (Lease, 2018) for complete analytical details). The fission-track ages reported in this study have large uncertainties because of the low number of spontaneous track counts, which precluded meaningful statistical analysis of track lengths.

The late Miocene–Holocene cooling history was quantified with inverse modeling of the well-characterized AHe mean age-elevation transect (see Supplementary Material for complete modeling details). In addition, modeling was conducted on a sample situated north of the relief transect where AHe grain ages covary with kinetic data and indicate residence in the AHe partial retention zone (Reiners and Farley, 2001). In both cases, Monte Carlo