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Intermittent glacial sliding velocities explain variations in long-timescale denudation

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ABSTRACT

Quantifying controls on glacial erosion over geologic timescales is central to understanding the role of Cenozoic climate change on the development of modern mountain belts, yet the mechanisms that produce the distinct relief and topography visible in glaciated regions remain poorly constrained. We test the hypothesis that commonly assumed glacial sliding parameterizations control denudation rates over geologic timescales. We do this by modeling glacier dynamics over a glacial–interglacial cycle and compare with a dense dataset of (U–Th)/He thermochronometer derived denudation rates from the southern Coast Mountains, BC. Results indicate zones of rapid Quaternary erosion correspond to locations where the model predicts the highest averaged sliding velocities. The results are consistent with the hypothesis that sliding influences the rate of glacial erosion. Regression between sliding predicted by the model and erosion rates shows a statistically significant correlation ($r^2 = 0.6$). The coefficient of the regression (10^{-5}) is smaller than previous estimates based on data from much shorter timescales. The model results also reveal that for a specific location, active subglacial sliding, and hence erosion, occurs for only ~10–20% of a glacial–interglacial cycle, suggesting high temporal variations in erosion rates. This intermittency of erosion requires instantaneous erosion rates to be greater than long term averages, explaining how timescale averaging can impact estimates of glacial erosion rates.

1. Introduction

In many mountainous landscapes Late Cenozoic climate change caused a transition from fluvial to glacial erosion processes (Brozović et al., 1997; Egholm et al., 2009; Herman et al., 2013). Understanding and quantifying this response is a focus of many glacial landscape evolution studies (Pedersen and Egholm, 2013; Tomkin, 2009; Yanites and Ehlers, 2012); however, quantifying the controls on glacial erosion remains elusive (Koppes et al., 2015). This results from a number of issues that obviate direct measurements of glacial erosion, including limited observations beneath active glaciers and a paucity of techniques for measuring rates of erosion in glacially modified terrain.

Empirical and theoretical evidence suggests that glacial sliding controls subglacial erosion, but testing this claim is limited to short timescales (Herman et al., 2015; Humphrey and Raymond, 1994), arguments based on simple topographic relationships such as the height of hanging valleys (Amundson and Iverson, 2006), or inferences from topographic reconstructions based on rock-cooling histories in New Zealand (Shuster et al., 2011). Koppes et al. (2015), found that mean annual temperature, as opposed to glacial sliding, is the dominant control on century to decadal sediment flux out of temperate glaciers. Climate variability further confounds a quantitative analysis of sliding velocity and erosion rates as glaciers have consistently expanded and retreated in response to changing climate. The findings of previous studies combined with the variability of climate over the timescale of landscape evolution require an integrated modeling-data approach towards assessing the controls on glacial erosion over geologic timescales.

We utilize a natural experiment in the glaciated southern Coast Mountains, British Columbia, Canada (Fig. 1) where spatial and temporal variations in Quaternary denudation have been documented over a 60 × 60 km region (Fig. 1B) (Densmore et al., 2007; Ehlers et al., 2006; Olen et al., 2012; Shuster et al., 2005). Our approach involves quantifying and averaging glacial sliding through an entire glacial–interglacial cycle (both 40 ky and 100 ky) using a glacial model and comparing these results with long-term rates of Quaternary erosion. This comparison provides an evaluation of

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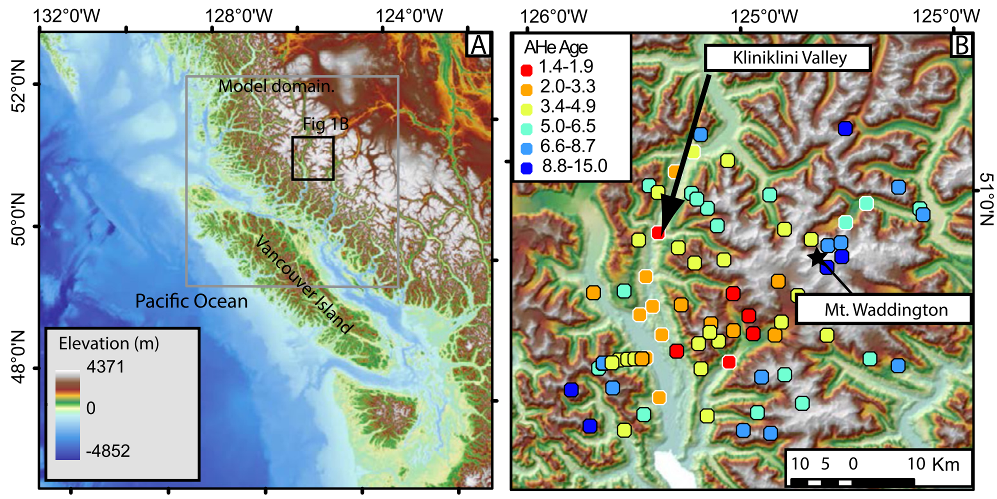

Fig. 1. Map of the southern Coast Mountain region in British Columbia, Canada showing combined digital elevation and bathymetric models (A). Black boxes indicate model domain (see Fig. 3) as well as study area. (B) Map of the distribution of apatite (U–Th)/He ages in the study area. White outline indicates the locations for the regression analysis in Fig. 6. The extent of Fig. 1B is the same for Figs. 4 and 5.

glacial erosion models used in modern landscape evolution models of mountain topography development.

2. Field area

The glacially sculpted landscape of the southern Coast Mountains of British Columbia provides a natural laboratory to explore the long-term (10^5–10^6 yrs) controls on glacial landscape evolution (Densmore et al., 2007; Ehlers et al., 2006; Shuster et al., 2005). During the Last Glacial Maximum in British Columbia, ice expanded from confined alpine glaciers to form the Cordilleran Ice Sheet (Clague and James, 2002). The maximum ice sheet thickness occurred at ∼14 ka, reaching thicknesses up to 2 km. Although constraints on the western extent of the ice sheet are limited due to submergence of terminal moraines off the coast, there is enough evidence to reconstruct the general distribution of ice and flow directions during the LGM (Clague and James, 2002). Such an ice sheet likely existed in prior glacial periods, but constraints on the specific extent and thickness of these events are missing. Nonetheless, expanding and retreating alpine and ice sheet glaciers have carved deep glacial valleys into this region over the last 2 million years.

A dense dataset of 79 apatite (U–Th)/He thermochronology ages collected within a 60 × 60 km region provide constraints on long-term patterns of glacial erosion. Apatite (U–Th)/He data record rock cooling from ∼60–90 °C to the Earth's surface (Ehlers and Farley, 2003) and correspond to shallow crustal depths of ∼2–4 km. These data record the latest phase of denudation in the Coast Mountains, which is largely glacially driven (Shuster et al., 2005). Thermochronometers provide a spatially averaged denudation rate over lateral distances akin to the closure temperature depth (e.g. ∼2–4 km for apatite (U–Th)/He) meaning that individual samples record the denudation history of the area surrounding each sample. Topographic warping of isotherms can limit the utility of using a simple age as a quantitative marker for erosion (Olen et al., 2012). Using a 3-D thermokinematic model and linear inverse technique, Olen et al. (2012) constrain the denudation rates across the Mt. Waddington region, accounting for the warping and advection of isotherms. The thermochronometer ages and denudation rates of this region (Fig. 1B) exhibit a large spatial variability in mineral cooling ages. This variability provides an opportunity to explore the controls on glacial landscape evolution and test the hypothesis that glacial sliding largely drives erosion. Because the erosion of the landscape occurs throughout a glacial–interglacial period, we use a glacial model to assess if sliding velocities, integrated over the entire cycle, can explain the spatial variability in denudation calculated from thermochronometer data.

3. Methods

3.1. Model

The distribution of glacial sliding velocity through a glacial–interglacial period is modeled using a shallow-ice approximation (SIA) for glacial mechanics with a constriction factor to account for topographic effects on ice flow (Braun et al., 1999). The ICE model (Herman and Braun, 2008) was used and adapted (Yanites and Ehlers, 2012) to include processes important to glacial mass balance and mechanics in the southern Coast Mountains including orographic precipitation (Roe et al., 2003), snow avalanching (Kessler et al., 2006), and iceberg calving (Van Der Veen, 1996). The model is run at time steps of 0.01 yr. Model inputs are topography, periodic climate variations, and glacial mechanical properties. For topography, we use a DEM in which estimates for the thickness of modern glacial ice in the region of Mt. Waddington has been removed (Clarke et al., 2009). Observations of exposed bedrock in many valley bottoms suggest that interglacial alluvial fill is minimal in the study area (Fig. 1B). Furthermore, the exhumation indicated by the thermochronology suggests that any accumulated sediment is evacuated by advancing ice to allow for bedrock erosion (Densmore et al., 2007; Ehlers et al., 2006; Shuster et al., 2005). The DEM used in this study was combined with bathymetry from the Canadian Hydrographic Service and resampled to ∼700 m resolution (Fig. 1A) for the model simulations.

The effect of orographic precipitation on the glacial mass balance in southern British Columbia were accounted for with a moist-advection precipitation model (Roe et al., 2003). The model uses the integrated Clausius–Clapeyron relationship that incorporates a wind component that accounts for the horizontal transport of hydrometeors (Roe et al., 2003)

$$-\nabla \cdot F = \left(\alpha_0 + \alpha_1 \bar{\nu} \frac{dz}{dx}\right) e_{sat}(T_s) \quad (1)$$

where $-\nabla \cdot F$ is the vertical convergence of water moisture, α_0 is the convergence in the absence of topography, $\bar{\nu}$ is the wind velocity, dz/dx is the surface slope, and the coefficient α_1 partitions the moisture between the air column and intercepting topography (Roe et al., 2003). The term $e_{sat}(T)$ is the saturation vapor pressure