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Quantification of subaerial and episodic subglacial erosion rates on high latitude upland plateaus: Cumberland Peninsula, Baffin Island, Arctic Canada

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ABSTRACT

Long-term rates of subaerial and episodic subglacial erosion by predominately cold-based ice cover are determined for tors on weathered plateaus on Cumberland Peninsula. By measuring terrestrial cosmogenic nuclide concentrations in differentially weathered surfaces on a given tor, we reconstruct the complex exposure and erosion history involving recurring cold-based ice cover. The style and rate of subaerial and subglacial erosion at multiple tor sites on Cumberland Peninsula are assessed with a Monte Carlo approach that computes plausible exposure histories based on a proxy record of global ice volume. Constant subaerial erosion rates by weathering are low (<2 mm ka^{-1}), corroborated by nuclide concentrations measured on two tors located on coastal ridge crests that have likely never been glaciated. Summit plateaus intermittently covered by cold-based ice throughout the Quaternary have experienced episodic subglacial erosion by plucking of fractured bedrock with rates between 1 and 16 mm ka^{-1}. Variation of episodic erosion rates is associated with topographic position of the sampled tors and bedrock fracture density. Most of the tors were last glacially plucked in pre-ultimate glaciations, not during the Wisconsinan glaciation. Furthermore, the new approach provides evidence for the extent of ice coverage during the late Wisconsinan, which is significant if no erratics are available for exposure dating. Despite late Pleistocene intervals of ice cover and glacial plucking, tor-studded landscapes of Cumberland Peninsula are of considerable antiquity.

1. Introduction

The erosion history of both upland surfaces and valleys must be known to directly determine temporal and spatial variability in rates of relief generation, sediment flux to oceans, and isostatic uplift over 10^3–10^6-year timescales. For high-latitude dissected coastal plateaus, the relatively high proportion of upland plateaus requires that even slow erosion of these surfaces may contribute a first-order control (Dowdeswell et al., 2010; Steer et al., 2012) owing to polythermal ice and periglacial processes during glaciations and extensive regolith development during warm periods (von Blanckenburg, 2005). In these regions, rates and styles of valley incision by streams and glaciers has been analysed (e.g., Davis et al., 1999; Staiger et al., 2005; Briner et al., 2008; Kessler et al., 2008). However, determining the exhumation rates of upland plateaus at timescales shorter than those determined from thermochronometry has been difficult, because the rates are slow and the controlling processes do not operate continuously in a changing climate. The spatial distribution of terrestrial cosmogenic nuclides (TCN) measured in bedrock surfaces, boulders, and till cover on summit plateaus provides insight into some of the controlling process, such as distribution of weakly-erosive, cold-based ice cover, (e.g., Bierman et al., 1999; Marsella et al., 2000; Marquette et al., 2004; Briner et al., 2006; Staiger et al., 2006; Lilly et al., 2010), but the rate of episodic erosion processes has remained intractable. Because episodic erosion rates may significantly exceed gradual erosion rates (Small et al., 1997; Muzikar, 2008, 2009), determining rates of sporadic erosion is crucial for constraining rates of landscape lowering and the evolution of high-latitude highland plateaus.

The concentration and ratio of TCN vary predictably with depth below bedrock surfaces and can be used to measure episodic rates of erosion. By using twin or triplet samples from adjacent bedrock surfaces that share a common exposure history (e.g., ice cover,

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subaerial erosion), climate, and lithological properties but exhibit contrasting degrees of weathering because of plucking, it is possible to determine the long-term average total erosion rate (episodic and constant gradual erosion) from glacial and other processes. In this paper, we describe a new approach using TCN from such differentially weathered surfaces to examine the nature and determine the rates of subaerial and subglacial erosion that prevail on weathered upland plateaus. For this purpose, we collected samples from tors — conspicuous towers of coarsely fractured bedrock protruding metres to decametres above regolith cover (e.g., blockfields) or till plains. The differentially plucked tors provide an opportunity to collect samples at different depths without the need for drilling, and to use the TCN concentrations and ratios to establish the most probable timing of last plucking and therefore maximum limiting age of last ice cover. Constrained by a climate time-series, a Monte Carlo method is used to generate variable histories of ice cover, horizontal fracture densities (thickness of joint blocks), subaerial erosion rate, and timing of subglacial plucking, with which the TCN data can be modelled to provide a probability distribution of solutions of episodic erosion rates. The results are used to relate the rate of plucking (i.e., sudden removal of a joint block at the base of a glacier used here synonymously with quarrying), abrasion, and subaerial weathering history on different summits to the extent and style of glacierization, variation in bedrock properties, and regional and local topography. The inferred rate of total erosion is compared with long-term sediment flux to the ocean and exhumation histories determined by low-temperature thermochronology. The measured TCN concentrations reveal that episodic subglacial erosion by quarrying is slow yet amounts to a tenth of the erosion rates incising fiords and valleys over the Quaternary.

2. Previous studies of episodic erosion

Geomorphic processes are often dominated by episodic erosion events that are controlled by climate, tectonic processes, lithology, or autogenic cyclicities (e.g., Womack and Schumm, 1977). It is difficult to quantify the long-term (10^3–10^6 years) rate of erosion attributed to episodic processes, even if they may exceed steady rates (Small et al., 1997; Muzikar, 2008, 2009). For instance, landscapes dominated by wasting processes have infrequent but high-volume erosion events that equal or exceed incremental bedrock and soil denudation rates over longer timescales (Kirchner et al., 2001; Niemi et al., 2005; Antinao Rojas, 2009).

Glacial plucking, or quarrying, is an episodic process of block-style erosion and has been shown to be primarily controlled by fracture spacing and the roughness of the glacier bed (Anderson, 2014). Smaller blocks are more likely to be quarried, so that landscapes with higher fracture density are lowered more rapidly (Dühnforth et al., 2010; Goodfellow et al., 2014). With additional knowledge or assumptions of the glacial history, the rate of plucking has been estimated using TCN in bedrock surfaces (Macchiaroli, 1995; Phillips et al., 2006; Jansen et al., 2013; Fujioka et al., 2015). The rate of glacial quarrying was first and most often determined by assuming that a single plucking event occurred during the last glaciation (Macchiaroli, 1995). Most of the previous studies focussed on quarrying and abrasion by warm-based valley glaciers or ice sheets (Briner and Swanson, 1998; Davis et al., 1999; Colgan et al., 2002). However, on eroded bedrock surfaces in glaciated regions, TCN concentrations are often a mixed signal of exposure during interglacial intervals, shielding during one or more glaciations, single or multiple episodic plucking during some glaciations, and gradual erosion of the surface by subglacial abrasion or subaerial processes (e.g., Nishiizumi et al., 1991; Small et al., 1997; Bierman et al., 1999; Fabel et al., 2002; Stroeven et al., 2002; Briner et al., 2006; Phillips et al., 2006; Lilly et al., 2010). Quantification of low erosion rates on plateaus is important, because low-relief, high-elevation surfaces are often used as reference points for estimates of total glacial erosion in adjacent valleys assuming that the plateaus remained nearly unaltered throughout the Quaternary (Small and Anderson, 1998).

3. Glacial dynamics of the study area

Cumberland Peninsula on Baffin Island is particularly interesting because it provides a detailed record of the interactions of the northeastern polythermal Laurentide Ice Sheet (LIS), a mostly cold-based Penny Ice Cap, and alpine polythermal glaciers on the eastern half of the peninsula (Fig. 1) and their influences on the bedrock landscape (Andrews and Dugdale, 1971; Miller, 1973; Boyer and Pheasant, 1974; Miller and Dyke, 1974; Andrews et al., 1976; Sugden and Watts, 1977; Anderson, 1978; Dyke, 1979; Watts, 1979; Dyke et al., 1982; Steig et al., 1998; Bierman et al., 1999; Davis et al., 1999; Marsella et al., 2000; Kaplan et al., 2001; Miller et al., 2002; Margreth, 2015). The extent of ice cover on weathered plateaus during the last (Wisconsinan) glaciation has been extensively debated (Sugden and Watts, 1977; Dyke et al., 1982; Steig et al., 1998; Bierman et al., 1999, 2001; Wolfe et al., 2001). Miller et al. (2002) reconciled the previous contradictory maximum (Flint, 1943) and minimum (Ives, 1978) ice cover models with an intermediate level of ice cover. A 'Goldilocks' conceptual model recognizes the preservation of undisturbed pre-Wisconsinan sediments in tarns (Wolfe, 1996; Wolfe and Härtling, 1996; Wolfe et al., 2000) and the advanced weathering degree of plateaus and pre-Wisconsinan sediments suggesting ice-free conditions for at least the last glaciation in some regions (Steig et al., 1998). The Goldilocks model also seemed consistent with the interpreted glacial modification of tors (Sugden and Watts, 1977; Watts, 1979) and TCN concentrations measured on erratic boulders scattered on the plateaus and on weathered bedrock surfaces of tors (Bierman et al., 1999; Marsella et al., 2000), which indicate the highlands were covered by predominately cold-based ice during the last glaciation. However, although coverage of tors at some time by cold-based ice could be revealed by measuring the concentration of two radionuclides with differing decay rates (Bierman et al., 1999; Marsella et al., 2000; Kaplan et al., 2001), the exact timing of the last ice cover could not be uniquely determined from these data alone. In other words, while previous interpretations of $^{26}Al/^{10}Be$ data have demonstrated that highly weathered surfaces were covered by ice, they were not able to reveal when. This is also a shortcoming of previous tests of the 'Nunatak Hypothesis' (Gosse et al., 2006). An estimate of the most probable timing of the last ice cover on the plateau summits would be most useful, and a quantitative assessment of what controls the rate of glacial modification is required to quantify the landscape response to climate change.

4. Methods

The new approach to determine the rate of episodic quarrying and the timing of last plucking is based on TCN concentrations measured in nearby differentially weathered bedrock surfaces. Although it has been specifically developed for tors on weathered plateaus, the method could also be applied to interglacial scarp retreat during felsenmeer development on highland summits. In addition, parts of the method could be adapted for studying other episodic erosion processes, such as rockfall, toppling, and coastal cliff retreat of medium to coarsely fractured rock. In general, the question of timing of last plucking or long-term rate of erosion requires multiple parametric constraints for which limited or no data are available. The challenge is to reduce the degrees of