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Research paper

Glacial erosion and sediment dispersion from detrital cosmogenic nuclide analyses of till

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Abstract

Field evidence based on sedimentology, geomorphology, and sediment provenance, supported by thermo-mechanical ice sheet model simulations, are used to classify the thermal regime of paleo-ice cover in northern central Baffin and evaluate the spatial and temporal variability of those conditions. A new means to identify paleo-glacier polythermal conditions from the measurement of terrestrial in situ cosmogenic nuclides (TCN) in till was developed to test the assertion that glacial erosion and till production are partially controlled by the thermal regime at the base of a glacier. Concentrations of cosmogenic ^{10}Be and ^{26}Al in 19 till samples from north central Baffin Island reflect the spatial pattern of areas classified as warm-based or cold-based (end member) systems. An ice sheet simulation of bed conditions produces the same pattern. The $^{26}Al/^{10}Be$ ratio is also used to confirm the long cold-based ice burial histories of surfaces that have not been significantly eroded. The data suggest that till and regolith near the current terminus of the Oliver Glacier preserve a record of >3 Ma of continuous glacial cover. In three localities resembling intermediate cases (i.e., where field observations yield conflicting interpretations of basal thermal regime), the TCN concentrations and $^{26}Al/^{10}Be$ reveal that the surface experienced a combination of cold-based ice burial and glacial erosion. When coupled with a high-resolution ice sheet model, the ^{10}Be concentrations in till provide a more robust means of establishing the temporal and spatial variability in glacial erosion, and can be an important new tool for mineral exploration in glaciated terrain.

Keywords: Cosmogenic; Glacial; Erosion; Warm-based; Cold-based; Ice; Drift prospecting; TCN; Till production; Glacial erosion; Basal thermal regime

1. Introduction

Glacial erosion of basal material and the movement and deposition of entrained basal detritus is linked to the basal thermal regime of the ice (Boulton, 1972; Hallet, 1979, 1996; Alley et al., 2003), which mainly depends on the distance from the ice divide, the air temperature signal, and the underlying bed topography. Glaciers are cold-based when the basal temperature is lower than the pressure-melting point. Thin, cold-based ice inhibits glacial erosion and may protect regolith (bedrock, saprolite, surficial materials) from periglacial processes (Sugden, 1978). Warm-based ice (i.e., the basal temperature is greater than the pressure-melting point) creates a mobile water layer that helps induce glacial erosion. Thick ice lowers the pressure-melting point and effectively insulates geothermal heat from cold air temperatures, so thin ice caps are often cold-based. Heat is also produced by frictional or strain heating, prevalent in areas with converging ice flow. Except near the ice sheet or glacier terminus, ice velocities generally

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increase with distance from the ice divide, owing to the advection or "downwelling" (Marshall and Clark, 2002) of cold surface ice at the ice dome. Basal sliding velocity is enhanced by increased basal water that can result from raising the ice temperature above the pressure-melting point.

Beneath a polythermal ice sheet, the basal thermal regimes and associated glacial erosional and depositional processes vary spatially (Paterson, 1994) and temporally. The bed of an ice sheet may remain frozen or melted during an entire glaciation, or could have alternated between melting and freezing (Boulton, 1972). Climate-induced changes in ice thickness and glaciological or climatic shifts in ice dispersal centres can induce temporal variations in thermal regime and contribute to the spatial variation in erosional and depositional processes (Moores, 1990). In regions with high-altitude coastal highlands, warm-based conditions persist in fiords with thicker and faster flowing ice, and cold-based conditions persist on summit plateaus with thin ice caps and in regions under ice divides or ridges where net velocity approaches zero.

Basal thermal regime, physical properties of the bedrock and regolith, transport distance and distance from the ice centre are reflected in the textural characteristics of basal tills (Shilts, 1993). Basal tills from cold-based ice have short transport distances ("short-distance tills") and have less silt than tills from warm-based ice ("long-distance tills") because the latter are subjected to more comminution. "Short-distance tills" generally contain clasts that are angular, locally derived, and rarely striated. Fine-grained, silt-rich tills with striated, subrounded, and facetted clasts ("till stones") and a wide variety of clast lithologies are indicative of "long-distance tills" associated with warm-based conditions. The decrease in particle size fraction and increase in clast lithology variation with ice-transport distance has been well-documented (Shilts, 1976). Areas of cold-based ice cover can be difficult to differentiate from areas that have not been glaciated because cold-based ice cover leaves only scant, cryptic evidence of glaciation, such as lateral meltwater channels (Dyke, 1993) and tills with angular clasts. The temporal variation in the thermal regime can be inferred from the presence of palimpsest and preserved landforms (e.g., Kleman, 1994).

Our motivation for measuring ^{10}Be and ^{26}Al in tills as a record of glacial erosion originates from the many studies in polar landscapes which reveal that TCN concentrations in bedrock and boulders are often excessive for the duration of post-glacial exposure (Fabel et al., 2002; Stone et al., 2003; Briner et al., 2003; Marquette et al., 2004; Briner et al., 2005). The excess concentration observed in some areas is normally attributed to the retention (inheritance) of TCN concentration produced prior to the last glaciation. Inheritance has been documented in till (Nishiizumi et al., 1989; Balco, 2004) and in late-glacial glaciolacustrine and glaciomarine deltas on Baffin Island (Hilchey, 2004). Although inheritance is common in polar and high-latitude temperate regions, $<3\%$ of moraine boulders contain discernible amounts of inherited TCN in alpine environments (Gosse and Phillips, 2001; Putkonen and Swanson, 2003). This would imply that glaciers in alpine environments erode more deeply than ice sheet and ice cap systems.

The purpose of this paper is to demonstrate that TCN can be used to fingerprint basal thermal regimes and reveal spatial variations in glacial erosion under ice sheet and ice cap systems. We demonstrate that the variations are not solely dependent upon landscape position (elevation) or physical properties of the underlying bedrock and regolith. We first use geomorphological and sedimentological observations to classify and select regions in northern Baffin Island where end-member cold-based or warm-based conditions persisted through most of the last glacial cycle. We test the hypothesis that basal thermal regime is a primary control on the spatial and temporal variability in glacial erosion using the following experiments: (1) compare the ^{10}Be concentrations in tills at 19 sites with different geomorphic and glacial geological characteristics; (2) measure the ratio of ^{26}Al/^{10}Be to establish that low erosive sites (tills with high ^{10}Be concentration) have recorded long durations of exposure with burial; and (3) compare our interpretations of TCN concentration to simulations from a thermo-mechanical ice sheet model.

2. Physiography of the study area

The study area is situated to the north and east of the Barnes Ice Cap, north central Baffin Island (Fig. 1). It is a glaciated, rugged, treeless barren with extant ice caps and outlet glaciers, sporadic to complete glacial drift cover, lakes, abandoned meltwater channels, felsenmeer, and raised glaciolacustrine sediments. The study area comprises three large physiographic zones which broadly correspond to bedrock lithologies and probably reflect their resistance to erosion (Little et al., 2004). The Davis Highlands zone in the north is a fiord-dissected elevated plateau composed of metamorphosed Archean rocks of the Mary River Group where relief can exceed 1700 m. The Ice Bound Lakes region of this highland has small, decaying cold-based ice caps and ice patches (Andrews et al., 1976). Toward the southwest, the Baffin Uplands is a low relief plain that begins at the heads of the fiords and generally slopes to the southwest from >900 to <300 m (Ives and Andrews, 1963). The Baffin Uplands consists of moderately metamorphosed Proterozoic siliciclastic and carbonate units dissected by deep (>300 m) valleys. Large lakes, extensive bogs, flat rolling till plains, and subdued non-metamorphosed carbonate and siliciclastic bedrock ridges characterize the lower Lancaster Plateau (Fig. 1). In the study area, the Lancaster Plateau is a graben defined by the Central Baffin Fault.

3. Glacial history of the study region

The overall pattern of deglaciation has been interpreted by Ives and Andrews (1963), Hodgson and Haselton