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Meteoric ^{10}Be as a tracer of subglacial processes and interglacial surface exposure in Greenland

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ABSTRACT

In order to test whether sediment emerging from presently glaciated areas of Greenland was exposed near or at Earth's surface during previous interglacial periods, we measured the rare isotope ^{10}Be contained in grain coatings of sediment collected at five ice marginal sites. Such grain coatings contain meteoric ^{10}Be (^{10}Be$_{met}$), which forms in the atmosphere and is deposited onto Earth's surface. Samples include sediment entrained in ice, glaciofluvial sediment collected at the ice margin, and subglacial sediment extracted during hot water drilling in the ablation zone. Due to burial by ice, contemporary subglacial sediment could only have acquired substantial ^{10}Be$_{met}$ concentrations during periods in the past when the Greenland Ice Sheet was less extensive than present.

The highest measured ^{10}Be$_{met}$ concentrations are comparable to those found in well-developed, long-exposed soils, suggesting subglacial preservation and glacial transport of sediment exposed during preglacial or interglacial periods. Ice-bound sediment has significantly higher ^{10}Be$_{met}$ concentrations than glaciofluvial sediment, suggesting that glaciofluvial processes are sufficiently erosive to remove tracers of previous interglacial exposures. Northern Greenland sites where ice and sediment are supplied from the ice sheet's central main dome have significantly higher ^{10}Be$_{met}$ concentrations than sites in southern Greenland, indicating greater preglacial or interglacial landscape preservation in central Greenland than in the south. Because southern Greenland has more frequent and spatially extensive periods of glacial retreat but nevertheless has less evidence of past subaerial exposure, we suggest that ^{10}Be$_{met}$ measurements in glacial sediment are primarily controlled by erosional efficiency rather than interglacial exposure length.

1. Introduction

For ice sheets, such as the Greenland Ice Sheet, the links between climate forcings, ice sheet response, and resultant sediment fluxes have generally not been well resolved (Bierman et al., 2016). Past interglacial periods, such as the mid-Holocene and marine isotope stage (MIS) 5e, had reduced global ice volumes compared to present (Lisiecki and Raymo, 2005), but it remains uncertain how much of the ice volume change came from changes to the Greenland Ice Sheet (e.g. Stone et al., 2013). The sediment flux from erosion under glaciers and ice sheets is highly variable, with some regions experiencing considerable erosion (Hallet et al., 1996) and others experiencing very little (Bierman et al., 1999). Over the Quaternary period, substantial volumes of sediment have fluxed from the Greenland Ice Sheet to the oceans and shelf, although the total volume and chronology is not well constrained (Laine, 1980; Molnar, 2004). Modeling efforts can produce variable results depending on the assumed climate forcings (Goelzer et al., 2013) and have only limited constraint from the offshore sediment record (Dowdeswell et al., 2014). New approaches for assessing past changes in ice sheet extent and erosive response are needed.

Here, we seek to add new constraints on the past exposure history and erosive behavior of the Greenland Ice Sheet by measuring isotopic and geochemical tracers of previous surface exposure. Our study is based on the premise that analyses of previously exposed sediment at the present-day glacial margin can

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identify up-glacier regions where the ice sheet was previously absent and subsequent erosion was insufficient to fully remove such tracers from the landscape and thus from the ice sheet's sediment load. Meteoric ^{10}Be (^{10}Be$_{met}$) is the primary tracer we employ; it is a long-lived cosmogenic isotope that is easily incorporated into the grain coatings of sediment and accumulates during periods of surface exposure (Graly et al., 2010; Pavich et al., 1984). We also report organic carbon and total nitrogen measurements as indicators of soil formation and thus surface exposure (Barjes, 1996). We measured the stable isotope composition of water in the ice surrounding some of our samples in order to infer sediment entrainment mechanisms and therefore erosional processes (Sugden et al., 1987).

2. Background

2.1. Glacial-interglacial history

The Greenland Ice Sheet is assumed to have responded to the same climate forcings that cause global glacial-interglacial cycles (Huybrechts, 2002), but the differences between Greenland's response and global average response are not known (Schaefer et al., 2016). According to the marine benthic stable isotope record, global ice volume was less than the mid-Holocene level for only ~40,000 of the past 2.1 million years (Bintanja and van de Wal, 2008). This brevity of past interglacial global ice volume lows is independently confirmed by a variety of paleoclimatic indicators, such as speleothems, pelagic dust flux, and coastal highstand features (e.g. Grant et al., 2014; Rohling et al., 2017). In some cases, these records suggest even briefer interglacial highstands than the marine benthic stable isotope record implies (Rohling et al., 2010). This corresponds with a comparable lack of evidence of extended surface exposure after ~1.8 Ma in East Greenland's offshore record (Bierman et al., 2016). However, other evidence suggests the Greenland Ice Sheet may have been more responsive to climatic optima than the global records suggest. Measurement of ^{10}Be and ^{26}Al in cores of the sub-ice rock below the GISP2 ice core are consistent with either numerous or extensive periods of interglacial exposure in central Greenland, beginning in the mid-Pleistocene (Schaefer et al., 2016). Organic carbon and meteoric ^{10}Be in the basal sediment of the GISP2 core suggest preservation of a well-developed preglacial or interglacial soil in central Greenland (Bierman et al., 2014). Mid to later Pleistocene climatic optima are suggested by the presence of boreal-forest remains in sub-ice sediment from southern Greenland (Willerslev et al., 2007).

2.2. Meteoric ^{10}Be systematics

High concentrations of ^{10}Be$_{met}$ are generally found in the chemically weathered portions of well-developed soils. ^{10}Be$_{met}$ forms in the atmosphere from the spallation of nitrogen and oxygen by cosmic rays and has production rates on the order of 10^6 atoms·cm^{-2}·a^{-1}; it differs in production location from *in situ* ^{10}Be, which forms from atomic spallation within mineral lattices and has depth integrated production rates at sea level on the order of 10^3 atoms·cm^{-2}·a^{-1} (Lal and Peters, 1967). Once formed, ^{10}Be$_{met}$ sorbs to aerosol particles and is transported by atmospheric circulation, eventually coming to Earth through wet or dry deposition (Graly et al., 2011; Heikkilä et al., 2008). In general, ^{10}Be$_{met}$ strongly adsorbs to sediment (You et al., 1989) and accumulates within the soil column (Pavich et al., 1984). However, Be is mobile, moving between adsorbed, clay, oxide, or oxyhydroxide phases with evolving soil chemistry (Bacon et al., 2012; Barg et al., 1997), typically following clay illuviation to accumulate in greatest concentrations within the B-horizon at depths < 2–3 m (Graly et al., 2010). In deep continental regolith, appreciable concentrations of meteoric ^{10}Be are found to depths of 10–20 m (Brown et al., 1988).

If similar deeply weathered regolith formed in preglacial Greenland, any regolith remaining after glaciation likely contains at least some ^{10}Be$_{met}$. In contrast, the duration of brief interglacial periods (<10 ka) is insufficient for substantial clay illuviation or transport of ^{10}Be$_{met}$ beyond the top meter of the soil profile (Harden et al., 2002; Pavich and Vidic, 1993). Though the systematics of ^{10}Be$_{met}$ in soils have been mostly studied in the mid-latitudes, ^{10}Be$_{met}$ data from high latitudes also show long-term transport of the isotope to depth (Ebert et al., 2012). High latitude flux of ^{10}Be$_{met}$ to marine sediment has been measured in glaciomarine settings near Greenland and Antarctica, though its relationship to terrestrial soil concentrations is complicated by the scavenging of ^{10}Be$_{met}$ from ocean water (Simon et al., 2016; Sjunneskog et al., 2007; Yokoyama et al., 2016).

Past studies have analyzed ^{10}Be$_{met}$ concentrations in terms of a total soil inventory that uses the total abundance of the isotope within a soil column to assess surface ages and erosion rates (e.g. Pavich et al., 1986). The ^{10}Be$_{met}$ inventory is related to soil exposure age via:

$$N = \frac{q}{\lambda}\left(1 - e^{-\lambda t}\right) \quad (1)$$

where N is the inventory measured in atoms·cm^{-2}, t is the exposure period in years, λ is the ^{10}Be disintegration constant of $5.0 \cdot 10^{-7}$ yr^{-1} (Korschinek et al., 2010), and q is the average annual flux (atoms·cm^{-2}·a^{-1}) of ^{10}Be$_{met}$ atoms into the soil profile.

Holocene ^{10}Be$_{met}$ deposition rates in central Greenland are approximately $3.5 \cdot 10^5$ atoms·cm^{-2}·a^{-1} based on measurements of ^{10}Be$_{met}$ in ice cores (Finkel and Nishiizumi, 1997). In eastern and southern Greenland, Holocene ^{10}Be$_{met}$ fluxes are up to 2 times larger, primarily due to higher mean annual precipitation (Sturevik-Storm et al., 2014). Eemian (MIS 5e) deposition rates were 30% higher; ~$4.2 \cdot 10^5$ atoms·cm^{-2}·a^{-1} is recorded in the NEEM core, in north-central Greenland (Sturevik-Storm et al., 2014). The Eemian ^{10}Be$_{met}$ data plot along the same accumulation-flux trend that is seen in the Holocene data, strongly suggesting that the increase in ^{10}Be$_{met}$ deposition is precipitation controlled. We do not know how closely the ^{10}Be$_{met}$ deposition rates of previous interglacial periods resembled mid-Holocene or Eemian fluxes.

Because ^{10}Be$_{met}$-bearing aerosols and dust are deposited on the ice sheet (Baumgartner et al., 1997), glacial ice is also a potential source of ^{10}Be$_{met}$ to the subglacial environment. In the ice sheet ablation zone, surface meltwater is routed to the bed and forms high discharge, erosive streams (Alley et al., 1997). Such streams are likely to erode and transport the subglacial sediment they encounter, and therefore are not likely to be a major source of ^{10}Be$_{met}$ to subglacial sediment. In regions where surface melt water does not readily reach the bed, basal melt is the only source of subglacial water. With geothermal heat fluxes implying basal melt rates of ~5 mm·a^{-1} (Greve, 2005), ice density of 0.9 g·cm^{-1}, and Pleistocene ^{10}Be$_{met}$ concentrations in ice of ~$4 \cdot 10^4$ atoms·g^{-1} (Finkel and Nishiizumi, 1997), the flux of ^{10}Be$_{met}$ from basal melt is approximately $1.8 \cdot 10^4$ atoms·cm^{-2}·yr^{-1}. This is more than an order of magnitude lower than the interglacial ^{10}Be$_{met}$ flux from precipitation at the ice sheet surface documented in ice cores. Because surface ^{10}Be$_{met}$ primarily runs off in erosive meltwater streams that would remove sediments that acquire the isotope and basal ^{10}Be$_{met}$ is fluxed to the bed in minimal quantities, we conclude that ^{10}Be$_{met}$ in sub-ice sediment will predominately accumulate during interglacial surface exposure or else be inherited from preglacial regolith (Fig. 1).