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Cosmogenic nuclides constrain surface fluctuations of an East Antarctic outlet glacier since the Pliocene

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ABSTRACT

Understanding past changes in the Antarctic ice sheets provides insight into how they might respond to future climate warming. During the Pliocene and Pleistocene, geological data show that the East Antarctic Ice Sheet responded to glacial and interglacial cycles by remaining relatively stable in its interior, but oscillating at its marine-based margin. It is currently not clear how outlet glaciers, which connect the ice sheet interior to its margin, responded to these orbitally-paced climate cycles. Here we report new ice surface constraints from Skelton Glacier, an outlet of the East Antarctic ice sheet, which drains into the Ross Ice Shelf. Our multiple-isotope (^{10}Be and ^{26}Al) cosmogenic nuclide data indicate that currently ice-free areas adjacent to the glacier underwent substantial periods of exposure and ice cover in the past. We use an exposure-burial model driven by orbitally-paced glacial–interglacial cycles to determine the probable ice surface history implied by our data. This analysis shows that: 1) the glacier surface has likely fluctuated since at least the Pliocene; 2) the ice surface was >200 m higher than today during glacial periods, and the glacier has been thicker than present for ∼75–90% of each glacial–interglacial cycle; and 3) ice cover at higher elevations possibly occurred for a relatively shorter time per Pliocene cycle than Pleistocene cycle. Our multiple-nuclide approach demonstrates the magnitude of ice surface fluctuations during the Pliocene and Pleistocene that are linked to marine-based ice margin variability.

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1. Introduction

Geological records from ice-free areas of Antarctica can provide direct constraints on the sensitivity of the Antarctic ice sheet to past climatic changes. Nunataks that protrude through the ice serve as gauges of past ice sheet thickness change (e.g. Ackert et al., 1999; Stone et al., 2003). The production of *in situ* cosmogenic nuclides in a rock surface can be exploited to quantify whether and when ice previously overrode the area. In locations where this ice was predominantly cold-based, with little or no erosion of the rock surface, multiple-isotope measurements allow the long-term glacial history at the site to be explored (e.g. Balco et al., 2014; Bierman et al., 1999; Corbett et al., 2016; Lilly et al., 2010; Sugden et al., 2005); the nuclides ^{10}Be and ^{26}Al are produced in quartz at a constant ratio during periods of exposure, but the shorter half-life of ^{26}Al (0.716 Ma) relative to ^{10}Be (1.39 Ma) enables faster decay during periods of burial by ice, lowering the ratio of ^{26}Al to ^{10}Be (Lal, 1991). A rock surface with an old apparent exposure age from only a single nuclide indicates the minimum time since first exposed, but exposure may have been constant or intermittent over this time. Multiple-isotope measurements are required to determine if there has been a complex exposure history. A "simple" exposure history could be inferred if exposure ages are consistent between multiple nuclides, indicating constant exposure since first exposed. Whereas, a "complex" exposure history would

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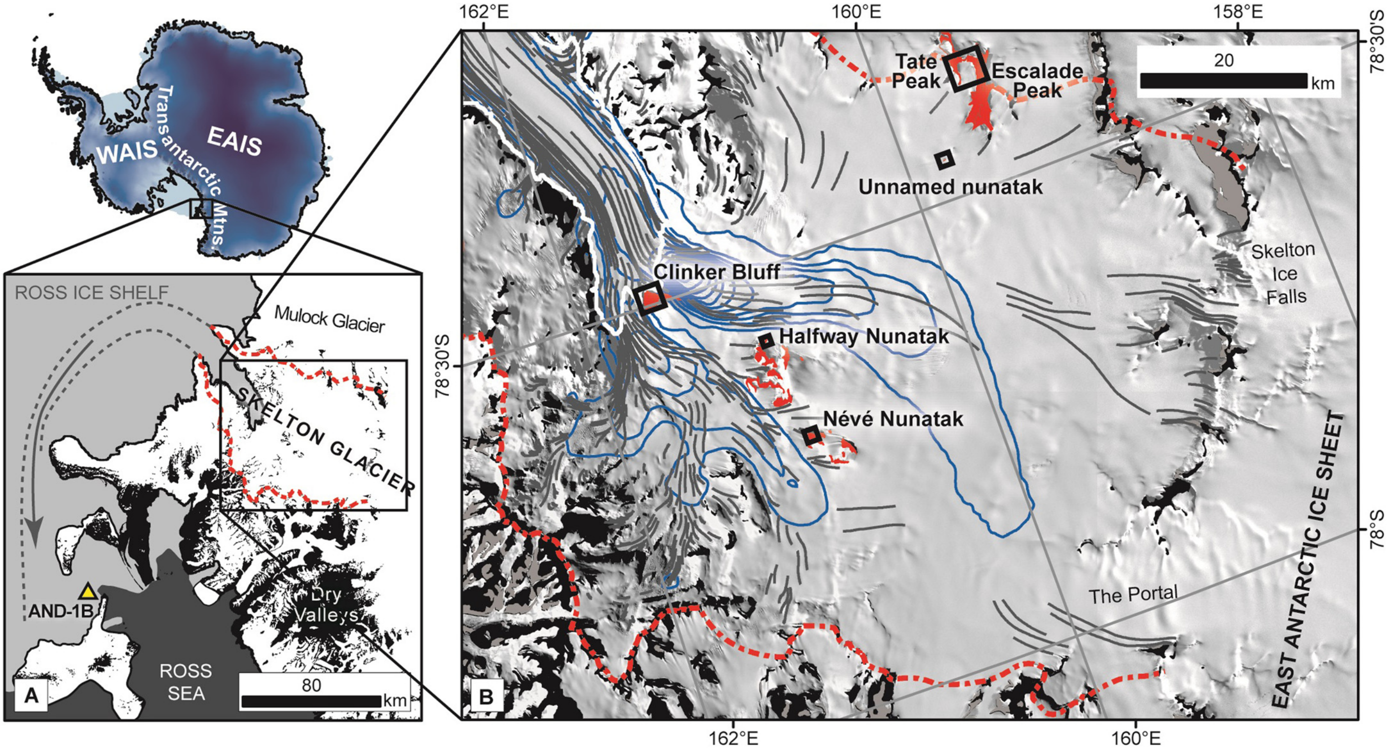

Fig. 1. Study area context. A) Skelton Glacier delivers ice from the East Antarctic Ice Sheet (EAIS) to the Ross Sea and AND-1B core site (yellow triangle; Naish et al., 2009) today, indicated by an arrow, and likely has done since at least the Pliocene (Talarico et al., 2012). Ice-free areas are shown in black. WAIS – West Antarctic Ice Sheet. B) Nunataks targeted for surface-exposure analysis are in red (boxed sample sites are shown in Fig. 2). The catchment boundary of Skelton Glacier (as defined in Jones et al., 2016) is denoted with a red dot-dashed line, while ice flow is highlighted with mapped flow stripes (grey lines) and ice velocity contours (blue lines at 25 ma^{-1} intervals; Rignot et al., 2011). (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

result in exposure ages that are not consistent between multiple nuclides, indicating some period of burial since first exposed.

Multiple-isotope surface-exposure data, collected from near to the interior of the East Antarctic ice sheet (EAIS), have typically provided concentrations and ages consistent with a constant exposure history since first uncovered by ice. These ages show that first exposures were at times during the Pliocene, implying that the ice surface was higher than today in the Pliocene and has not been as high since then (e.g. Balco et al., 2014; Lilly et al., 2010; Yamane et al., 2015). Meanwhile, sediment cores drilled on the continental shelf reveal that large-scale orbitally-paced oscillations of the ice margin occurred through the Pliocene and Pleistocene in marine-based portions of the ice sheet (e.g. drill core site AND-1B; McKay et al., 2012; Naish et al., 2009; Patterson et al., 2014), contemporaneous with local and global environmental changes (Levy et al., 2012). Outlet glaciers link such regions of contrasting ice sheet variability, controlling the flux of ice from the interior to the ice margin. Currently, we lack data constraining the behavior of outlet glaciers prior to the last glacial cycle, in the Pliocene and Pleistocene.

We report new multiple-isotope (^{10}Be and ^{26}Al) surface-exposure data from Skelton Glacier, an outlet of the EAIS. Here ice flows, through the Transantarctic Mountains, from the East Antarctic plateau to the Ross Sea embayment and over the AND-1B drill site (Talarico et al., 2012) (Fig. 1). Skelton Glacier is therefore suitably located to investigate the degree to which past oscillations of the marine-based ice margin that are documented at AND-1B propagated inland. Any past changes near the ice margin should have been expressed upstream as ice surface elevation changes, but the distance upstream and the magnitude of such changes during the Pliocene and Pleistocene is not well understood.

In this paper we determine whether the surface of Skelton Glacier was higher in the past, for how long and by how much it fluctuated, and whether such changes in ice surface elevation can be explained by glacial–interglacial oscillations of the ice margin. We apply an exposure-burial model to robustly evaluate the ice surface history implied by our cosmogenic nuclide data. The results of glacier flowline simulations that were constrained by geological and climatological data, presented in an associated study (Jones et al., 2016, and references therein), are then used to help better understand how glacier surface elevation changes corresponded to shifting ice dynamics under past contrasting climates.

2. Methods

2.1. Study area and sample collection

Six nunataks (Clinker Bluff, Halfway Nunatak, Névé Nunatak, Tate Peak, the Escalade Peak saddle with Tate Peak, and an unnamed nunatak) were targeted to provide spatial coverage of past ice surface changes (Fig. 1). Clinker Bluff, Halfway Nunatak and Névé Nunatak extend upstream from the modern grounding-line, adjacent to and north of the main flow path. Tate Peak, the Escalade Peak saddle and an unnamed nunatak are located to the south of the main flow path of Skelton Glacier, near to the ice divide with Mulock Glacier. The sample sites represent a range of elevations between approximately 2 m and 215 m above the adjacent ice surface, allowing relative changes in the past thickness of Skelton Glacier to be investigated.

The bedrock underlying the Skelton Glacier catchment is comprised of a metasedimentary basement (Skelton Group), overlain by sandstone sedimentary sequences (Beacon Supergroup), which are intruded by dolerite dykes and sills (Ferrar Supergroup) (Gunn and Warren, 1962). Névé Nunatak is made up of dolerite, Clinker Bluff is granite, Halfway Nunatak is comprised of both dolerite and granite, the unnamed nunatak consists of sandstone, and Tate

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