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Late Miocene ice sheet elevation in the Grove Mountains, East Antarctica, inferred from cosmogenic ^{21}Ne–^{10}Be–^{26}Al

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ABSTRACT

The Grove Mountains, lying in the interior of East Antarctica, consist of 64 nunataks. Geomorphic characteristics of the nunataks suggest that past ice sheet elevations have overtopped the summits of the Grove Mountains. Cosmogenic ^{21}Ne, ^{10}Be and ^{26}Al dating yields surface exposure ages of five bedrock samples taken from the crest of Mount Harding, a typical nunatak in the Grove Mountains. Using multi-nuclide fitting, we have calculated the time that the ice sheet retreated below the crest of Mount Harding; all data point to the late Miocene, ~6.3 Ma ago. The results provide the first land-based evidence of the elevation of the East Antarctic Ice Sheet in the Grove Mountains in Late Miocene, which reached 2300 m, 200 m higher than the current ice sheet level. The higher than current ice sheet elevations during the late Miocene together with contemporaneously higher temperatures in the Southern Ocean suggest that moisture transport plays an important role in ice sheet expansion in the interior of East Antarctica.

1. Introduction

The Antarctic Ice Sheet (AIS) contains about 3×10^7 km^3 of ice, equaling nearly 61% of the fresh water on Earth. The ice sheet in East Antarctica rests on a major land mass and contains 83% of total ice in Antarctica. Hence any changes of ice volume in East Antarctica fundamentally affect global sea levels; total melting of ice in Antarctica would lead to ~70 m of global sea level rise (Alley et al., 2005).

Glaciation of Antarctica is believed to have begun 34 Ma ago in conjunction with the opening of the Southern Ocean and declining global CO_2 levels (DeConto and Pollard, 2003). A major expansion of the East Antarctic Ice Sheet (EAIS) followed during the middle Miocene (Flower and Kennett, 1994; Shevenell et al., 2004). This scenario largely relies on the $\delta^{18}O$ value in benthic foraminifer and Mg/Ca data in deep-sea sediments and sea-level records from the passive continental margin (Shevenell and Kennett, 2007). Benthic foraminifer $\delta^{18}O$ variations reflect the combined effects of global ice volume and deep-ocean temperatures, and Mg/Ca ratios provide direct indicators of ocean temperature (Lear et al., 2000). A mismatch of the global water balance, however, shows significance to acquire independent ice volume data (DeConto et al., 2008). Nevertheless, field evidence of the thickness of the EAIS in the past is largely absent. Currently ice cores reveal the climate history in Antarctica as long as 800,000 years (Lüthi et al., 2008). To study the extent and thickness of the AIS before this time, we have to seek for glacial geological and geomorphological evidence of former ice expansion.

Erosion rates in Antarctica are extremely low, which permits preservation of landforms for millions of years (e.g., Brook et al., 1995; Fogwill et al., 2004). The cosmogenic nuclides ^{10}Be and ^{26}Al can often establish exposure histories within 5 million years, since the half lives of ^{10}Be and ^{26}Al are 1.387 Ma and 0.705 Ma, respectively. For pre-Pliocene exposure histories, multiple nuclides ^{21}Ne–^{10}Be–^{26}Al show special merits to reduce uncertainties associated with the exposure histories (Nishiizumi et al., 2005).

In an earlier study, we determined bedrock exposure ages in the Grove Mountains, East Antarctica, with the cosmogenic nuclides ^{10}Be and ^{26}Al (Huang et al., 2008). The ^{10}Be-inferred minimum exposure ages for the crests of the Zakharoff Ridge and Mount Harding, two typical nunataks in the Grove Mountains, are 2.0 Ma and 3.89 Ma, respectively. In this study we attempt to date the uncovering of the crest of Mount Harding by the EAIS, using the multiple nuclides ^{21}Ne–^{10}Be–^{26}Al. With such an approach we hope to provide independent measurements of EAIS elevations in the past and to eventually shed light on the mechanisms of glaciation in East Antarctica.

2. Geological setting

The Grove Mountains lie in Princess Elizabeth Land in the interior of East Antarctica (Fig. 1a), cover an area of ~3200 km^2, and include 64

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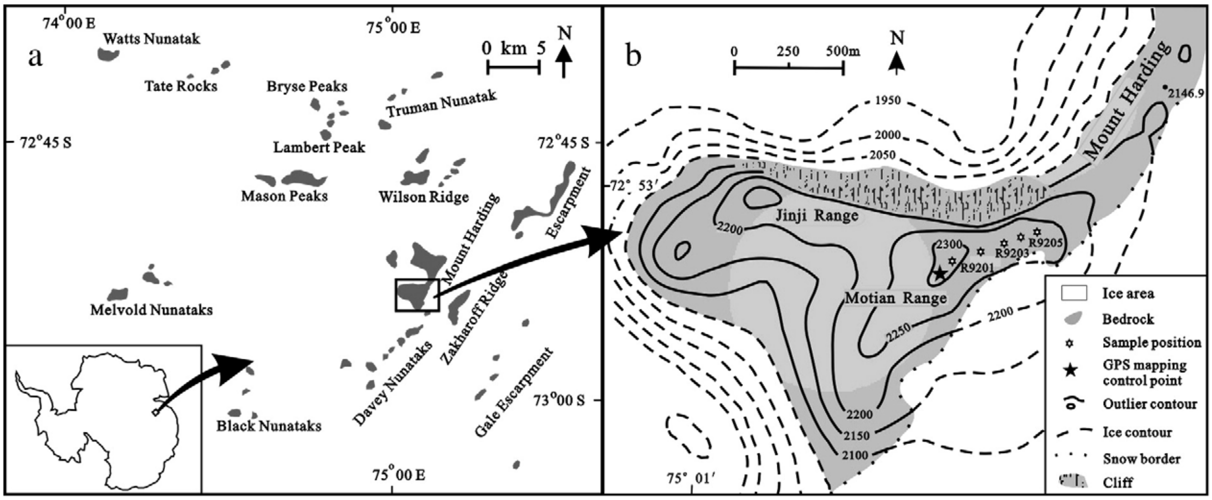

Fig. 1. Map of the Grove Mountains showing sample locations at Mount Harding. After Huang et al. (2008).

nunataks. They stand 440 km away from the Larsemann Hills, where Zhongshan Station lies. These nunataks consist mainly of upper amphibolite to granulite facies metamorphic rocks, syn-orogenic to late orogenic granite, and post tectonic granodioritic aplite and pegmatite. The absence of active structures and earthquakes, and the lack of Cenozoic volcanism suggest that this region has been tectonically stable since at least the Late Mesozoic Era (Liu et al., 2010).

The 64 nunataks can be divided into five ranges forming ridge-valley topography with a NNE trend. The regional ice flows north-westwards, perpendicular to the ridges and away from the central part of the EAIS. The stoss slopes of nunataks in the Grove Mountains are smooth and their bedrock faces show glacial striation. The side and lee slopes usually form cliffs, also indicating glacial abrasion. Thus past ice sheet elevations have overtopped the summits of the Grove Mountains.

Mount Harding, a typical nunatak in the Grove Mountains, consists of north and south ends (Fig. 1a). The south crest measures 2300 m, 200 m higher than the current ice sheet level. The central segment of the ridge-line between the two summit crests descends progressively until it reaches the ice surface at a central col. The five samples studied in this work were taken from the granulite bedrock surface of the south end crest (Fig. 1b). The sample thickness is ≤3 cm. Topographic cosmic ray shielding corrections for the samples are negligible.

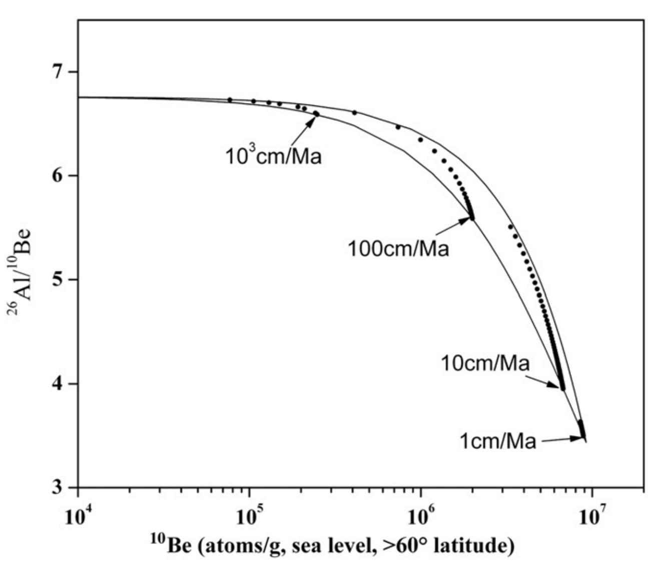

Fig. 2. Theoretical diagram of $^{26}Al/^{10}Be$ ratios vs. ^{10}Be concentrations for exposure histories reaching equilibrium between production and steady-state erosion. The upper line represents changes of concentration ratios of the two nuclides with time in conditions of $\varepsilon = 0$, the lower line consists of endpoints of various evolution curves for different erosion rates. The dotted lines show exposure histories with constant erosion rates of 10^3 cm/Ma, 100 cm/Ma, 10 cm/Ma and 1 cm/Ma.

3. Methods

3.1. Cosmogenic nuclide theory

Material exposed to cosmic rays will inevitably contain small amounts of cosmogenic nuclides produced by nuclear interactions between high energy cosmic ray particles and target nuclei within the material. The concentration of cosmogenic nuclides depends on the exposure time and erosion rate (Lal, 1991), and can be expressed as:

$$N = \frac{P}{(\lambda + \rho\varepsilon/\Lambda)}\left[1 - e^{-(\lambda + \rho\varepsilon/\Lambda)T}\right] + N_0 e^{-\lambda T} \quad (1)$$

where N is the concentration of cosmogenic nuclides (atoms/g), P is the production rate (atoms/g ·yr), T is the exposure age (yr), ε is the erosion rate (cm/yr), λ is the decay constant of the nuclide (for a stable nuclide $\lambda = 0$), ρ is the rock density (g/cm^3), Λ is the absorption mean free path of cosmic-ray nucleons (g/cm^2), and N_0 represents any initial concentration of the nuclide that accumulated before exposure.

Researchers typically use this equation to calculate either exposure age or erosion rate, assuming either zero erosion or that long-term exposure has reached steady-state with erosion. For many actual geological cases, however, these two assumptions are not satisfied. For these cases, calculated exposure ages are minimal and erosion rates are maximal.

If the concentrations of two cosmogenic nuclides can be obtained, Eq. (1) can in principle provide both the exposure age and the erosion rate. A limited number of papers in the literature derive exposure ages and erosion rates using this method (Bierman et al., 1999; Nishiizumi et al., 2005; Alvarez-Marrón et al., 2008). This is mainly because uncertainties with the obtained exposure ages and erosion rates are usually large. By using concentrations of more than 2 cosmogenic nuclides, uncertainties associated with the sample exposure history can be significantly reduced.

A theoretically calculated diagram showing the ratio of two nuclide concentrations versus one of the nuclide concentrations further helps to clarify sample exposure histories (Lal, 1991). For example, in the $^{26}Al/^{10}Be$ vs. ^{10}Be diagram (Fig. 2), the upper line represents changes of concentration ratios of the two nuclides with time in the condition of $\varepsilon = 0$, the lower line consists of endpoints of various evolution curves for