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Research paper

Geological scatter of cosmogenic-nuclide exposure ages in the Shackleton Range, Antarctica: Implications for glacial history

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A B S T R A C T

We use cosmogenic $^{26}Al/^{10}Be$ ratios in rocks from the Shackleton Range, Antarctica to investigate geological scatter, a challenge that faces exposure-age studies in Antarctica. Examining the scatter helps reveal the long-term lowering of Slessor Glacier, an outlet glacier of the East Antarctic Ice Sheet (EAIS) which flows into the Weddell Sea embayment. 144 ^{26}Al and ^{10}Be exposure ages from 72 samples are related to bedrock or clast sample characteristics and geomorphological measures of weathering, slope and stability. We explore this noisy dataset by using Principal Components Analysis (PCA) to identify patterns in the data. Despite noise, there exist correlations between age and degree of weathering and age and elevation above the adjacent ice surface. Clasts with young exposure ages have more complex exposure histories than those with old exposure ages. In terms of glacial history we show that (a) warm-based ice covered the upper slopes of the Shackleton Range millions of years ago and that the uplands have been mainly free of ice for more than 800 ka, (b) that Slessor Glacier's surface elevation was c. 150 m above present at c. 270 ka and c. 700 ka.

1. Introduction

Cosmogenic-nuclide exposure age dating has opened up new horizons into the glacial history of Antarctica (Balco, 2011). It has produced a body of field evidence dotted around the continent which makes it possible to identify the trajectory of change of the ice sheet over time scales of several centuries to millions of years. This deeper knowledge of the behaviour and longer-term trajectory of the ice sheet helps in assessing the significance of current geophysical measurements of change (Ivins and James, 2005; Whitehouse et al., 2012). In turn this helps refine glaciological models that are necessary to assess future ice-sheet change in a warming world.

Many exposure-age studies in Antarctica have revealed a wide scatter of ages (Ackert et al., 2007; Bentley et al., 2010; Bromley et al., 2010; Mackintosh et al., 2007; Stone et al., 2003; Storey et al., 2010; Todd et al., 2010). In many studies the aim has been to track thinning of the ice since the LGM as a means of improving the understanding of both ice-sheet behaviour and its effect on global sea-level change. Faced with what is termed "geological scatter" (cf. Balco, 2011), it is commonly assumed that the ice has emplaced some erratics with prior exposure – i.e. a boulder exposed for some time has been picked up by an overriding glacier and deposited elsewhere. On this basis anomalies may be identified, excluded from the analysis, and the interpretation of glacier thinning is based on the youngest clasts at any altitude (Bentley et al., 2010; Stone et al., 2003). In other cases it is argued that clasts accumulate on the ice surface in blue-ice ablation areas and have a scatter of ages before they are deposited (Ackert et al., 2011; Fogwill et al., 2012). In still other situations it can be shown that an exposed surface has been overridden by cold-based ice and survived the period of burial without disturbance, sometimes with deposition of occasional erratics (Briner et al., 2006; Sugden et al., 2005).

There is also the issue of the subsequent weathering of a moraine. Hallet and Putkonen (1994) showed how erosion of a moraine leads to a scatter of ages younger than the age of the

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moraine. In a high-altitude part of the McMurdo Dry Valleys, Antarctica, Swanger et al. (2011) showed how clast size reduced from the glacier margin over a series of progressively older moraines which had been exposed for millions of years; the implication is that weathering breaks down the clasts and produces a scatter of younger ages mixed with the original older ages. In such cases the oldest exposure ages most closely date the moraine emplacement. There are also studies of ancient till surfaces in the high parts of the Dry Valleys, often with tundra polygons, which demonstrate that surfaces lower slowly through erosion and this leads to surface exposure ages that are younger than the original till deposit (Margerison et al., 2005; Morgan et al., 2011; Schafer et al., 1999). In some cases it is possible to determine the geomorphic process (e.g., moraine degradation or inheritance) that controls the exposure age distribution from a single moraine using statistical methods (Applegate et al., 2012).

This study of the Shackleton Range contributes to the debate about the significance of geological scatter in several ways. First, it comes from a new location in Antarctica. There are relatively few cosmogenic-nuclide studies from the Atlantic-facing Weddell Sea embayment. Second, the 72 samples related to one outlet glacier is one of the densest multi-nuclide datasets in Antarctica, and thus there is potential to unravel the multiple processes affecting geological scatter and learn the long-term glacial history. But there is one important cautionary note. The samples were selected in transects from the glacier margin to test a different hypothesis about thinning since the LGM. Thus we only sampled the freshest-looking, least-weathered samples at each location. To minimise the effects of the effect of weathering and disturbance we restricted our sampling to brick-sized clasts with long axes of 10–20 cm, preferably with glacial faceting indicating subglacial erosion (Hein et al., 2011). This sampling strategy means that our results will emphasize the youngest samples on the slopes.

The paper arises from the study of the elevation changes of the Slessor and Recovery glaciers, outlets of the East Antarctic Ice Sheet, during the Last Glacial Maximum (LGM) (Fig. 1). An initial paper suggested that the outlet glaciers had not thickened significantly during the LGM (Hein et al., 2011). Indeed only six out of 70 clasts revealed exposure ages younger than 50 ka, and these rocks were all on or at the glacier margin. The remaining 64 samples from the slopes overlooking Slessor Glacier display puzzling relationships and the ^{10}Be surface exposure ages range from 110 ka to 1.6 Ma. There is no simple relationship between the scatter of ages and altitude above the glacier margin, suggesting that many different processes are at work both prior to clast deposition and afterwards. We explore such processes to gain an insight into the deeper glacial history of the mountains and the implications for exposure-age dating in Antarctic polar environments. This paper contributes 59 new ^{26}Al exposure ages and 2 repeat ^{26}Al/^{10}Be measurements to the original dataset, making a total of 144 ^{26}Al and ^{10}Be exposure ages from 72 rock samples (Hein et al., 2011).

2. Field area and approach

The Shackleton Range consists of basement rocks and in the context of the wider Transantarctic Mountains is unusual in that it is not capped by Beacon Supergroup sediments consisting mainly of sandstones (Kerr and Hermichen, 1999). The mountains boast a west-facing escarpment rising 700–800 m above the Filchner Ice Shelf which bounds a plateau which rises to ∼1800 m before

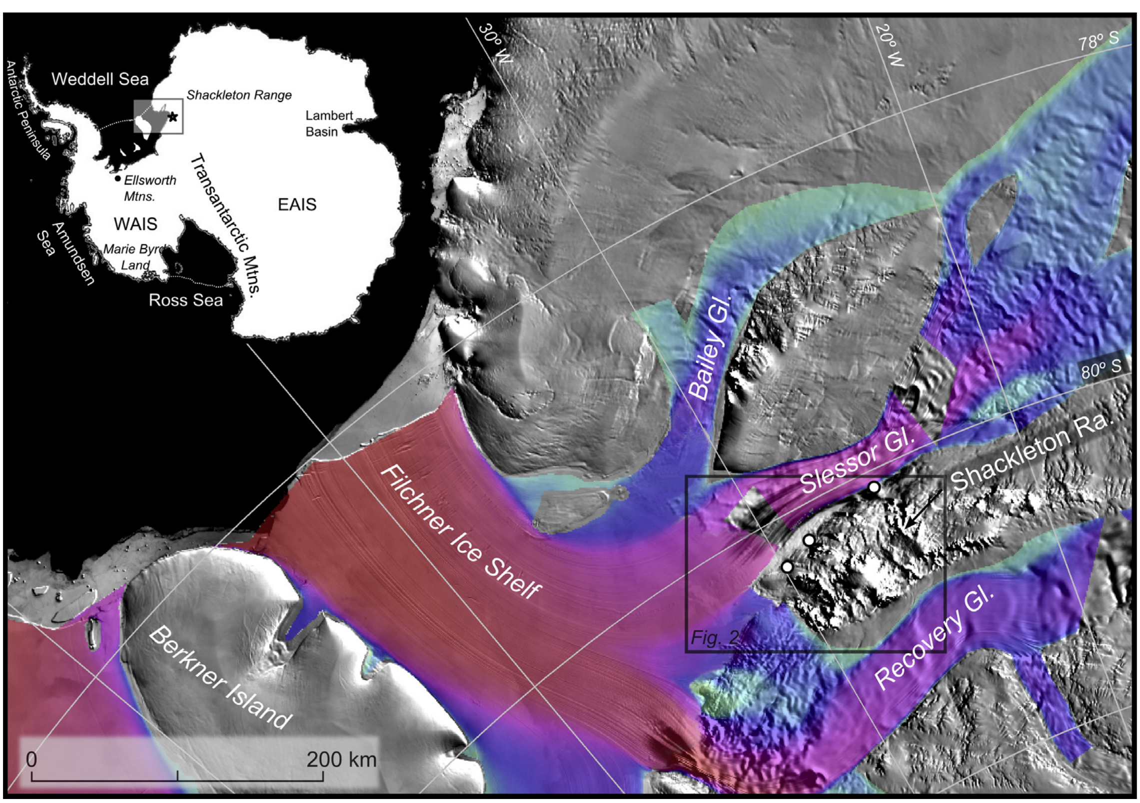

Fig. 1. The eastern Weddell Sea showing ice velocities for three major ice streams feeding the Filchner Ice Shelf; warm colours indicate fast flow-rates of up to 1500 m a^{-1} (red), reducing to<100 m a^{-1} (green) as illustrated by the progressively cooler colours (after Joughin and Bamber, 2005). The sample locations in the Shackleton Range are circled. After MODIS Mosaic of Antarctica image map (Haran et al., 2005) (figure adapted after Hein et al., 2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)