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Emergence of the Shackleton Range from beneath the Antarctic Ice Sheet due to glacial erosion

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A B S T R A C T

This paper explores the long-term evolution of a subglacial fjord landscape in the Shackleton Range, Antarctica. We propose that prolonged ice-sheet erosion across a passive continental margin caused troughs to deepen and lower the surrounding ice-sheet surface, leaving adjacent mountains exposed. Geomorphological evidence suggests a change in the direction of regional ice flow accompanied emergence. Simple calculations suggest that isostatic compensation caused by the deepening of bounding ice-stream troughs lowered the ice-sheet surface relative to the mountains by ~800 m. Use of multiple cosmogenic isotopes on bedrock and erratics (^{26}Al, ^{10}Be, ^{21}Ne) provides evidence that overriding of the massif and the deepening of the adjacent troughs occurred earlier than the Quaternary. Perhaps this occurred in the mid-Miocene, as elsewhere in East Antarctica in the McMurdo Dry Valleys and the Lambert basin. The implication is that glacial erosion instigates feedback that can change ice-sheet thickness, extent, and direction of flow. Indeed, as the subglacial troughs evolve over millions of years, they increase topographic relief; and this changes the dynamics of the ice sheet.

1. Introduction

We explore the long-term evolution of the Shackleton Range, a massif in the Weddell Sea sector of the Transantarctic Mountains (Fig. 1). The massif is bounded by the Slessor and Recovery outlet glaciers that drain the East Antarctic Ice Sheet. If deglaciated, the massif would comprise a fjord landscape, with Slessor and Recovery glaciers now filling troughs excavated below sea level. Fjord landscapes in the Northern Hemisphere are characteristic of passive continental margins bounding the North Atlantic and are especially well developed in Norway (Holtedahl, 1967), northeast Greenland (Bretz, 1935), and Baffin Island (Løken and Hodgson, 1971). Here most fjords exploit preexisting river valleys and dissect relatively flat uplands. Their origin is thought to primarily reflect interplay between ice-sheet dynamics and topography (Kessler et al., 2008), while their morphology is also affected by the pattern of basal thermal regime (Briner et al., 2008; Kleman et al., 2008) and of rock strength (Augustinus, 1992; Swift et al., 2008). In the Northern Hemisphere, the interpretation of long-term evolution is based mainly on inferences from landscape form. The advantages of studying such a landscape in the Antarctic is that the glacial processes are there to see and that a long history of ice-sheet glaciation extends back tens of millions of years rather than the shorter glacial episodes of the Northern Hemisphere.

There is a long-held view that the erosion of troughs through passive continental margins leads to the progressive emergence of intervening uplands from beneath an ice sheet. The transition from dissected coastal mountains to inland plateau landscapes around existing and former Northern Hemisphere ice sheets has been interpreted as showing that, during the course of glaciation, outlet glaciers establish lower and shallower ice-sheet surface gradients as they deepen and extend their troughs (e.g., Fig. 10.12 in Sugden and John, 1976). The deeper the trough and the more it extends inland, the lower the resulting ice-sheet surface will be and the greater the extent of exposed surrounding uplands. In many locations, and indeed in the Shackleton range, local plateau ice caps can build up on the exposed mountains. A contributing factor to emergence is isostatic recovery achieved as a result of the substitution of the rock volume of a trough by less dense ice. This latter process can account for the uplift of adjacent massifs by hundreds of metres (Kerr and Gilchrist, 1996; Stern et al., 2005; Jamieson et al., 2008). A further implication is that the process of erosion itself introduces feedbacks that affect the dynamics of the ice sheet, even its oscillations (Tomkin, 2003; Hein et al., 2011).

In view of the interaction of ice sheets with independent tectonic, sea level, and climatic controls, quantifying the role of glacial erosion in the emergence of uplands is difficult. However, evidence elsewhere in East Antarctica suggests that ice in mountainous areas was thicker

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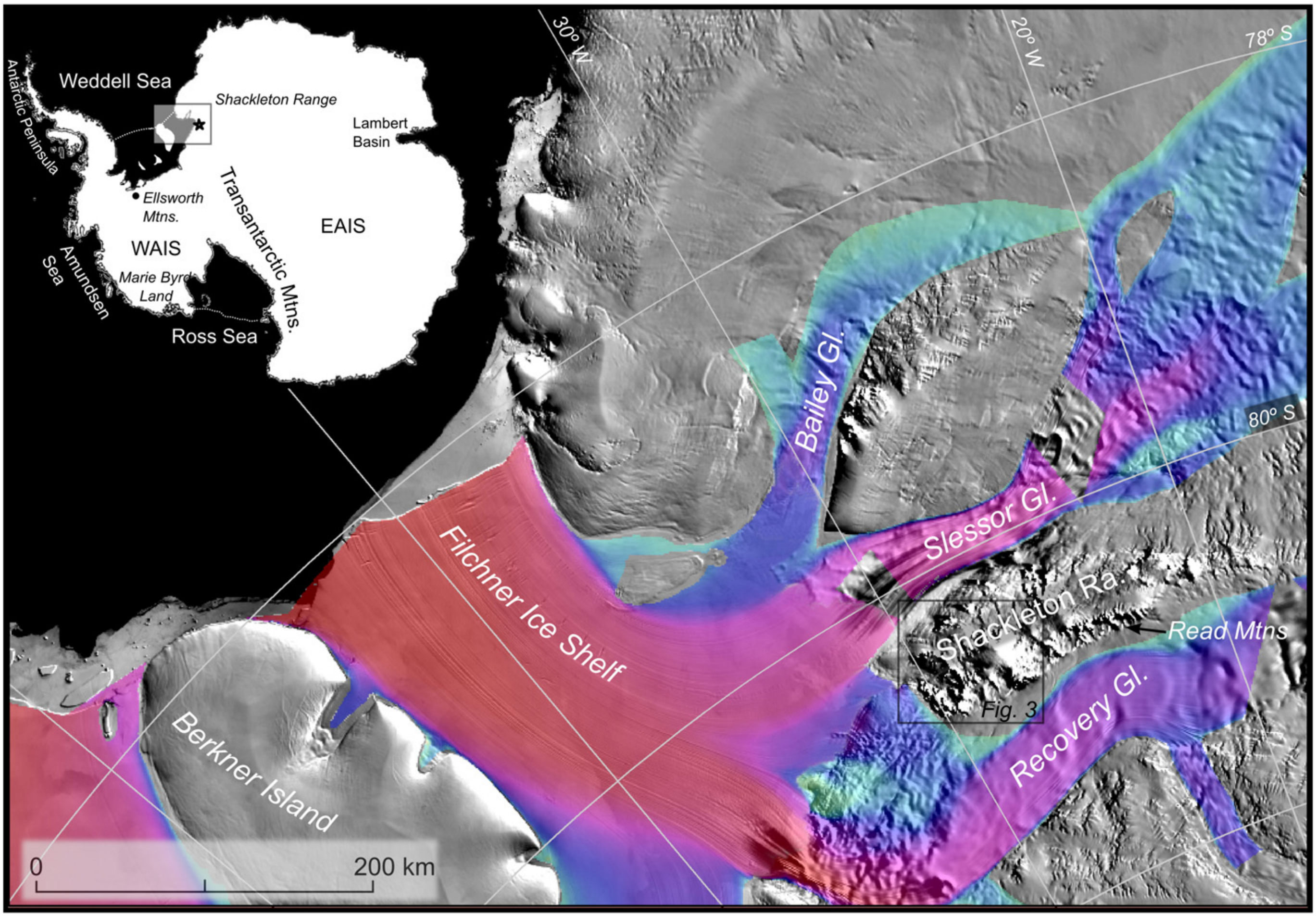

Fig. 1. The Shackleton Range in Antarctica, situated between the Slessor and Recovery outlet glaciers of the East Antarctic Ice Sheet, overlooks the Filchner Ice Shelf that floats above the deep submarine Thiel trough. Map shows the location of the geomorphology map in Fig. 3 and the Read Mountains. The red colours indicate fast ice flow up to 1500 m/y. After Joughin and Bamber (2005).

at an early stage, and this can be interpreted as partly reflecting rock exposure as a result of glacial erosion. For example, an ice sheet roughly 1000 m thicker than present overrode the topography of the Dry Valleys and Convoy mountain blocks in southern Victoria Land (Sugden and Denton, 2004). The $^{40}Ar/^{39}Ar$ ages of volcanic ashes suggest that this occurred at ~14 Ma and that the mountains have been largely free of an ice sheet since (Marchant et al., 1993). Cosmogenic nuclide analyses in Queen Maud Land imply that the mountains have emerged from beneath the ice sheet in the last 1–4 Ma (Altmaier et al., 2010). Glaciomarine deposits on the flanks of the Lambert Glacier are pre-late Miocene and late Miocene in age and have been uplifted by 500 and 200 m, respectively (Hambrey et al., 2007). Further, low temperature thermochronology has been used to argue that the Lambert trough was deepened 1.6–2.5 km during the early stages of Antarctic ice-sheet glaciation (Thomson et al., 2013). It is possible that these landscape changes result from the lowering of the ice-sheet surface in response to the progressive deepening of adjacent glacial troughs, although other explanations cannot be ruled out. In the case of the Shackleton Range we can isolate the role of glacier erosion with more confidence.

2. The Shackleton Range

The Shackleton Range is part of the Transantarctic Mountains that extends over 3000 km across Antarctica (Fig. 1 inset). The mountain block extends 200 km from east to west and 75 km from north to south (Fig. 2). The bounding Slessor Glacier to the north is 50 km wide and in places the bed is 2000 m below sea level (Fretwell et al., 2013). Recovery Glacier to the south is 70 km in width and in the vicinity of the western Shackleton Range, the trough is ~2000 m below sea level. The high velocities and low gradients of both glaciers have been argued to show that they currently flow on sediment (Bamber et al., 2006; Rippin et al., 2006). Local glaciers flow radially from an ice cap centred on the massif (Skidmore and Clarkson, 1972). In the main ice-free areas, numerous small wind-drift glaciers accumulate on the western lee slopes of topographic highs.

The Shackleton mountain block is eroded wholly into basement rocks, mainly shales, sandstones, and gneiss (Höfle and Buggisch, 1995; Stephenson, 1966). This contrasts with most of the Transantarctic Mountains, including the adjacent blocks of Whichaway Nunataks to the south and the Theron Mountains to the north, which are capped by Beacon Supergroup sediments, mainly sandstones (Kerr et al., 2000). In common with most of the Transantarctic Mountains the gross morphology is of fault-bound mountain blocks with a coastal escarpment and a plateau surface that in the east disappears beneath the East Antarctic Ice Sheet. In the Shackleton Range, the Read Mountains on the southeastern flank of the massif at ~1800 m are the highest summits (see Fig. 1 for location). The western front of the mountain block comprises an escarpment rising 700–800 m above the Filchner Ice Shelf. Offshore, beneath the ice shelf, is the Thiel trough with a depth of over 1500 m extending northward to the Filchner trough in the Weddell Sea (Makinson and Nicholls, 1999). Water depths are 900 m within 25 km of the summit of Mt. Provender at 950 m, the northwest point of the range. This morphology is typical of a passive continental margin, and erosion of the mountains would have followed