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The million-year evolution of the glacial trimline in the southernmost Ellsworth Mountains, Antarctica

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ABSTRACT

An elevated erosional trimline in the heart of West Antarctica in the Ellsworth Mountains tells of thicker ice in the past and represents an important yet ambiguous stage in the evolution of the Antarctic Ice Sheet. Here we analyse the geomorphology of massifs in the southernmost Heritage Range where the surfaces associated with the trimline are overlain by surficial deposits that have the potential to be dated through cosmogenic nuclide analysis. Analysis of 100 rock samples reveals that some clasts have been exposed on glacially moulded surfaces for 1.4 Ma and perhaps more than 3.5 Ma, while others reflect fluctuations in thickness during Quaternary glacial cycles. Modelling the age of the glacially moulded bedrock surface based on cosmogenic ^{10}Be, ^{26}Al and ^{21}Ne concentrations from a depth-profile indicates a minimum exposure age of 2.1–2.6 Ma. We conclude that the glacially eroded surfaces adjacent to the trimline predate the Last Glacial Maximum and indeed the Quaternary. Since erosion was by warm-based ice near an ice-sheet upper margin, we suggest it first occurred during the early glaciations of Antarctica before the stepped cooling of the mid-Miocene at ∼14 Ma. This was a time when the interior Antarctic continent had summers warm enough for tundra vegetation to grow and for mountain glaciers to consist of ice at the pressure melting point. During these milder conditions, and subsequently, erosion of glacial troughs is likely to have lowered the ice-sheet surface in relation to the mountains. This means that the range of orbitally induced cyclic fluctuations in ice thickness have progressively been confined to lower elevations.

1. Aim

The aim is to examine the geomorphology of the three most southerly mountain massifs in the Heritage Range, part of the Ellsworth Mountains in Antarctica. The mountains protrude through the Antarctic Ice Sheet and feature a glacial trimline reflecting thicker ice than at present. The advantage of the sites in the southern Heritage Range is that, unlike most locations in the higher parts of the Ellsworth Mountains, here the ice-scoured bedrock adjacent to the trimline is overlain by glacial deposits with the potential of constraining its age and evolution.

2. Background

The Ellsworth Mountains, discovered by Lincoln Ellsworth in 1935, form a rugged range 350 km long and 80 km wide on the landward boundary of the Filchner–Ronne Ice Shelf in the Weddell Sea embayment (Fig. 1). The range runs NNW–SSE and the eastward flowing Minnesota Glacier separates the Sentinel Range to the north from the Heritage Range in the south. The Sentinel Range rises abruptly above the ice sheet and on its western side is an escarpment leading to a succession of peaks exceeding 3500 m and including the highest mountain in Antarctica, Mount Vinson at 4897 m. The Heritage Range is lower with peaks below 2500 m. The topography is dominated by a blend of longitudinal mountain ridges separated by glacier-filled basins with ice overspilling from the main ice sheet dome to the west. The southernmost massifs

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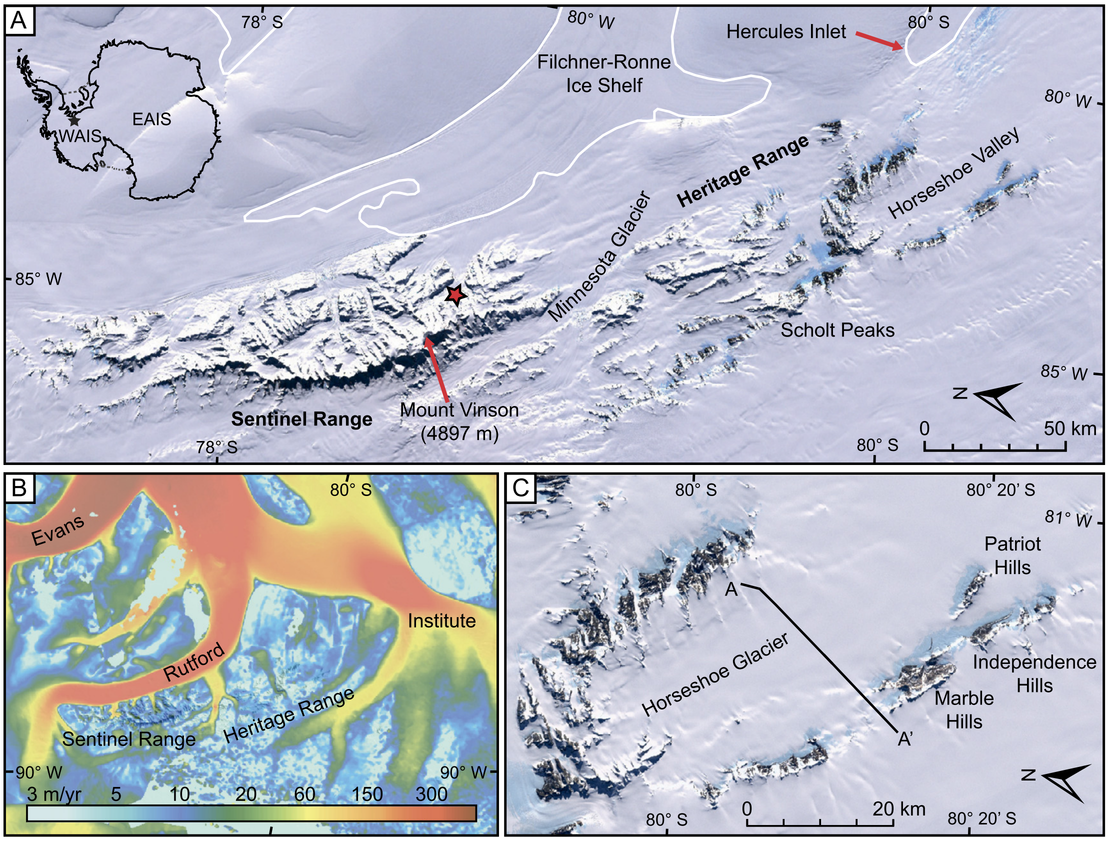

Fig. 1. (a) Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat Image Mosaic (LIMA) imagery of the Ellsworth Mountains showing the location of the Sentinel and Heritage ranges north and south of Minnesota Glacier and Mt. Vinson (4897 m), the highest peak in Antarctica. The location of the photograph in Fig. 2 is marked by a star. (b) Ice flow in the vicinity of the Ellsworth Mountains. The image shows satellite-derived surface ice flow velocities (m/yr) and the main ice streams (after Rignot et al., 2011). (c) The Marble, Patriot and Independence Hills and Horseshoe Glacier in their glaciological setting, showing the location of the radargram in Fig. 9.

of Marble Hills with the highest summit of Mt. Fordell (1670 m), Independence Hills with Mount Simmons (1590 m) and the Patriot Hills (1246 m), are surrounded by ice flowing into and along Horseshoe Glacier towards the southeast and east (Fig. 1c). The Heritage Range, unlike the Sentinel Range, experiences katabatic winds that sweep north-westwards across the main ridges and create blue-ice ablation areas on glaciers in their lee (Hein et al., 2016a). Upward glacier flow compensating for the surface ablation brings debris to the glacier surface and its margin. It is this latter process that explains the debris cover and marginal moraines of the mountain-foot glaciers of the southernmost massifs.

The Ellsworth Mountains consists of a conformable sequence of folded Cambrian to Permian sediments. Cambrian conglomerates and limestones are the dominant rocks of the Heritage Range, while younger quartzites underlie the high peaks of the Sentinel Range (Webers et al., 1992). The mountain block as a whole is thought to be a microplate that, prior to its separation around 140 million years ago, was part of what is now the East Antarctic continental plate (Storey et al., 1988; Fitzgerald and Stump, 1991). Glaciation is thought to have modified a pre-existing fluvial topography, the latter demonstrated by the dendritic pattern of valleys and the preservation of landscapes with rolling slopes around Mt. Vinson (Rutford, 1972). Many summits in the Sentinel Range and higher parts of the Heritage Range have been sculpted by alpine glaciers to form a landscape of horns, arêtes and sharp spurs (Denton et al., 1992).

A glacial trimline representing a higher elevation ice sheet has been described and mapped throughout the Ellsworth Mountains (Denton et al., 1992). It stands 400–650 m above the present ice sheet on the western side of the mountains and 1300–1900 m above the present surface of the Rutford Ice Stream to the east. The elevation of the trimline reflects the gradients of the present ice sheet surface and falls from the divide near the mid Sentinel Range towards the north, to the east towards the Weddell Sea, and to the south towards the Heritage Range (Fig. 1b). Denton et al. (1992) argued that this regionally consistent pattern shows that the trimline is an ice-marginal feature rather than an englacial thermal boundary. Although the latter possibility of a thermal boundary within the ice sheet has been used to explain an upper limit of glacial erosion beneath former ice sheets in the shield areas of northern mid-latitudes (Kleman et al., 1997), it would not explain the regionally consistent trimline elevation in the rough terrain of the Ellsworth Mountains. The trimline separates a glacially moulded and often striated bedrock surface from upper sharp mountain crests with fragile rock pinnacles (Fig. 2). The striations form two groups. One set of finely spaced, oxidised striations is associated with moulded and streamlined rock surfaces. These striations are typical of glacial abrasion beneath warm-based ice. Other striations that may cut through the oxidised set are discontinuous and irregular and typical of overriding cold-based ice. The age of the trimline and the glaciated surfaces beneath it have been controversial since its discovery. On the basis of the preservation of the striations and the nature of the drift, some have argued that the trimline represents the surface of a thicker West Antarctic Ice Sheet during the Last Glacial Maximum (LGM) (e.g. Rutford et al., 1980). Others have noted the great age of weathered striations in the Transantarctic Mountains and the difficulty of creating warm-based ice at the upper margin of an ice sheet during Antarctic climates of the last few million years (Denton et al., 1992). In this latter case the trimline could be millions of years old.

The contrasting views spill over into adjacent scientific fields. Early estimates of ice mass loss in West Antarctica based on the