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East Antarctic deglaciation and the link to global cooling during the Quaternary: evidence from glacial geomorphology and ^{10}Be surface exposure dating of the Sør Rondane Mountains, Dronning Maud Land

Yusuke Suganuma [a, b, *], Hideki Miura [a, b], Albert Zondervan [c], Jun'ichi Okuno [a, d]

[a] National Institute of Polar Research, 10-3 Midoricho, Tachikawa, Tokyo 190-8518, Japan
[b] Department of Polar Science, School of Multidisciplinary Sciences, The Graduate University for Advanced Studies (SOKENDAI), Midori-cho 10-3, Tachikawa, Tokyo 190-8518, Japan
[c] GNS Science, National Isotope Centre, Lower Hutt 5010, New Zealand
[d] Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 3173-25 Showa-machi, Kanazawa-ku, Yokohama, Kanagawa 236-0001, Japan

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ABSTRACT

Reconstructing past variability of the Antarctic ice sheets is essential to understand their stability and to anticipate their contribution to sea level change as a result of future climate change. Recent studies have reported a significant decrease in thickness of the East Antarctic Ice Sheet (EAIS) during the last several million years. However, the geographical extent of this decrease and subsequent isostatic rebound remain uncertain. In this study, we reconstruct the magnitude and timing of ice sheet retreat at the Sør Rondane Mountains in Dronning Maud Land, East Antarctica, based on detailed geomorphological survey, cosmogenic exposure dating, and glacial isostatic adjustment modeling. Three distinct deglaciation phases are identified for this sector during the Quaternary, based on rock weathering and ^{10}Be surface exposure data. We estimate that the ice sheet thinned by at least 500 m during the Pleistocene. This thinning is attributed to the reorganization of Southern Ocean circulation associated with global cooling into the Pleistocene, which reduced the transport of moisture from the Southern Ocean to the interior of EAIS. The data also show that since the Last Glacial Maximum the ice surface has lowered less than ca 50 m and that this lowering probably started after ca 14 ka. This suggests that the EAIS in Dronning Maud Land is unlikely to have been a major contributor to postglacial sea-level rise and Meltwater pulse 1A.

1. Introduction

While it is broadly accepted that the Antarctic ice sheets play a major role in the Earth's global climatic system, many questions remain due to the multitude of processes and timescales involved. Climate models (e.g., DeConto and Pollard, 2003; Huber et al., 2004; Pollard and DeConto, 2009) suggest that the main triggering mechanism for Antarctic ice sheet stability is CO_2 concentration in the atmosphere. However, the response of the Antarctic cryosphere to contemporary increases in atmospheric CO_2 remains uncertain. Of particular relevance is the question of how much increase in global mean sea level should be expected from melting of Antarctic ice, under different future global climate scenarios (Bindoff et al., 2007). Reconstructing past variability (stability) of the Antarctic ice sheet will help with finding answers to these questions. At present, the evolution of the West Antarctic Ice Sheet (WAIS) and the larger East Antarctic Ice Sheet (EAIS) through the Neogene and Pleistocene, is not well understood. Recent studies have reported a significant decrease in thickness of the EAIS during the last several million years (e.g., Fogwill et al., 2004; Fink et al., 2006; Huang et al., 2008; Di Nicola et al., 2009, 2012; Strasky et al., 2009; Altmaier et al., 2010; Kong et al., 2010; Lilly et al., 2010; Liu et al., 2010). However, the geographical extent of this decrease and its response and feedback to the global climate remain uncertain. In addition, the nature of the glacio-eustatic rise following the Last Glacial Maximum (LGM), including the extremely rapid sea-level rise event “Meltwater pulse 1A (MWP-1A)”, remains elusive (e.g.,

* Corresponding author. National Institute of Polar Research, 10-3 Midoricho, Tachikawa, Tokyo 190-8518, Japan. Tel.: +81 42 512 0702.
E-mail address: suganuma.yusuke@nipr.ac.jp (Y. Suganuma).

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Clark et al., 2002; Peltier, 2005; Mackintosh et al., 2013). The current lack of data from East Antarctica, especially Dronning Maud Land, makes it difficult to estimate the location(s) of melting ice responsible for this prominent feature of the last deglaciation.

In this study, we focus on the glacial history of the Sør Rondane Mountains in Dronning Maud Land, East Antarctica (Fig. 1). This mountain range provides rare isolated rock outcrops (nunataks) that are distant (ca 150 km inland) from coastal outlet glaciers. Also, there is geomorphological evidence that a large part of these mountains was covered by an expanded ice sheet (e.g., Van Autenboer, 1964; Iwata, 1987; Hirakawa et al., 1988; Aniya, 1989; Hayashi and Miura, 1989; Hirakawa and Moriwaki, 1990; Moriwaki et al., 1991). These facts make the Sør Rondane Mountains a valuable site to investigate elevation changes of the EAIS.

The glacial history of the Sør Rondane Mountains has in some sectors been reconstructed from tills and trimlines (Hirakawa et al., 1988; Moriwaki et al., 1992), using a weathering index (Moriwaki et al., 1991, 1994) and from cosmogenic exposure ages (^{10}Be and ^{26}Al: Nishiizumi et al., 1991, 1998; Matsuoka et al., 2006). Although these pioneering studies have contributed greatly to our understanding of the glacial history of these mountains, they can be improved by using modern methods and apparatus. The first issue is that elevations in previous studies were determined via astronomical positioning. Its level of accuracy is inadequate for the derivation of exposure ages from cosmogenic isotopes because their rates of in situ production strongly depend on atmospheric depth (e.g., Gosse and Phillips, 2001). Global positioning systems (GPS) provide the necessary level of accuracy. Secondary, the refinement of cosmogenic nuclide production scaling models since the late 1990s (e.g., Stone, 2000) was not considered in those previous studies. The more recent models reliably incorporate dependency on geomagnetic location and atmospheric depth (Gosse and Phillips, 2001). Thirdly, the sampling sites are now more carefully chosen and a more precise method is available for sampling rock surfaces (Suganuma et al., 2012). These method improvements help to minimize the impact of erosion and sample shape on cosmogenic exposure ages. The fourth issue is that isostatic rebound of the mountains, due to mass loss with decreasing ice sheet thickness, was not considered in past studies. Glacial isostatic adjustment (GIA) modeling enhances accuracy in estimating changes in thickness and volume of the EAIS (e.g., Lilly et al., 2010). In this study, we advance the research on the glacial history of the Sør Rondane Mountains by combining a new survey of local geomorphological features, with exposure dating of newly sampled rock surfaces using cosmogenic ^{10}Be and with GIA modeling.

2. Study area

The Sør Rondane Mountains emerge as a large group of nunataks covering an area of ca 2000 km^2 within Dronning Maud Land, East Antarctica (Fig. 1). The elevation of the ice sheet surface at the northern side of the Sør Rondane Mountains is about 1000 m, rising to 2500 m in the south. The mountains are mainly composed of low- to high-grade metamorphic rocks and various plutonic rocks that intruded into the metamorphic bedrock (e.g., Shiraishi et al., 1997). The time of the last tectonothermal event of the mountains has been estimated at 500–650 Ma based on sensitive high-resolution ion microprobe U–Pb zircon ages (Shiraishi et al., 2008). The absence of active structures and the lack of Cenozoic volcanism suggest that the Sør Rondane Mountains have been geologically stable over the last 500 Ma.

The current mean annual air temperature at Asuka Station (965 masl), located at the northern margin of the mountain, is −18.4 °C and in summer the air temperature rarely exceeds the freezing point (Matsuoka et al., 2006). Since the elevation of the ice sheet increases toward the south, most of the mountains are assumed to be below the freezing point permanently. It snows throughout the year, but the mountains are essentially snow-free in

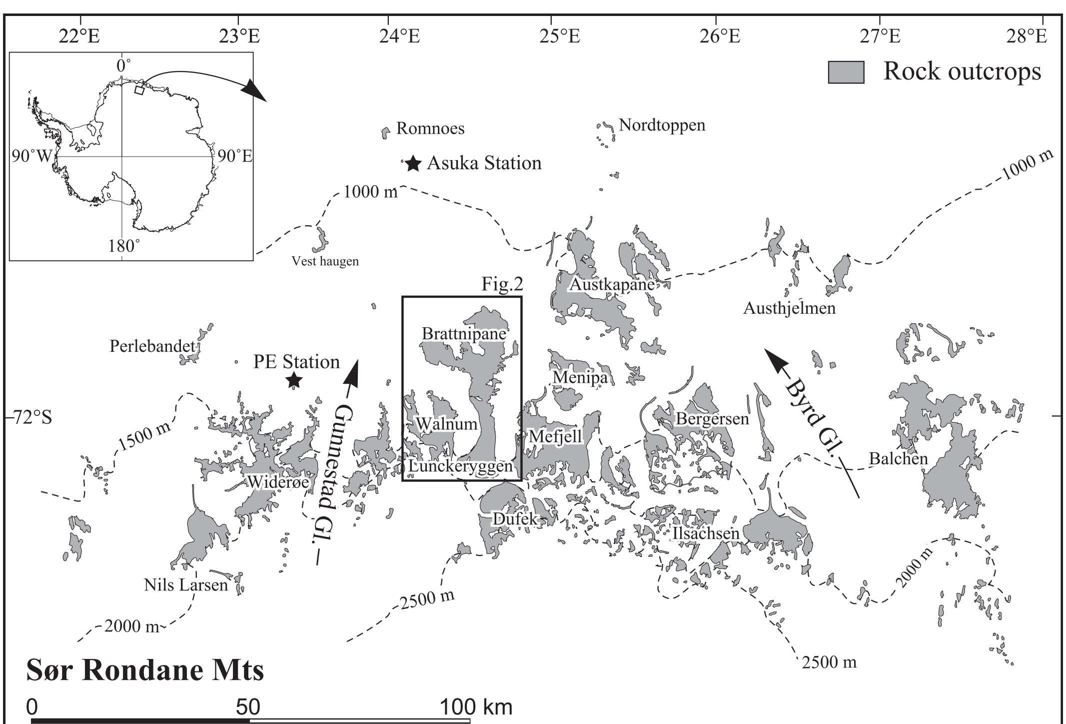

Fig. 1. Location and setting of the Sør Rondane Mountains. The box in the middle marks the location shown in Fig. 2. PE Station = Princess Elizabeth Station.