Quaternary Science Reviews xxx (2013) 1–21

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Retreat history of the East Antarctic Ice Sheet since the Last Glacial Maximum

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ARTICLE INFO

Article history:
Received 21 December 2012
Received in revised form
2 July 2013
Accepted 17 July 2013
Available online xxx

Keywords:
Antarctica
Last Glacial Maximum
Ice sheet
Sea level rise

ABSTRACT

The East Antarctic Ice Sheet (EAIS) is the largest continental ice mass on Earth, and documenting its evolution since the Last Glacial Maximum (LGM) is important for understanding its present-day and future behaviour. As part of a community effort, we review geological evidence from East Antarctica that constrains the ice sheet history throughout this period (~30,000 years ago to present). This includes terrestrial cosmogenic nuclide dates from previously glaciated regions, ^{14}C chronologies from glacial and post-glacial deposits onshore and on the continental shelf, and ice sheet thickness changes inferred from ice cores and continental-scale ice sheet models. We also include new ^{14}C dates from the George V Land – Terre Adélie Coast shelf. We show that the EAIS advanced to the continental shelf margin in some parts of East Antarctica, and that the ice sheet characteristically thickened by 300–400 m near the present-day coastline at these sites. This advance was associated with the formation of low-gradient ice streams that grounded at depths of >1 km below sea level on the inner continental shelf. The Lambert/Amery system thickened by a greater amount (800 m) near its present-day grounding zone, but did not advance beyond the inner continental shelf. At other sites in coastal East Antarctica (e.g. Bunger Hills, Larsemann Hills), very little change in the ice sheet margin occurred at the LGM, perhaps because ice streams accommodated any excess ice build up, leaving adjacent, ice-free areas relatively unaffected. Evidence from nunataks indicates that the amount of ice sheet thickening diminished inland at the LGM, an observation supported by ice cores, which suggest that interior ice sheet domes were ~100 m lower than present at this time. Ice sheet recession may have started ~18,000 years ago in the Lambert/Amery glacial system, and by ~14,000 years ago in Mac.Robertson Land. These early pulses of deglaciation may have been responses to abrupt sea-level rise events such as Meltwater Pulse 1a, destabilising the margins of the ice sheet. It is unlikely, however, that East Antarctica contributed more than ~1 m of eustatic sea-

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http://dx.doi.org/10.1016/j.quascirev.2013.07.024

level equivalent to post-glacial meltwater pulses. The majority of ice sheet recession occurred after Meltwater Pulse 1a, between ~12,000 and ~6000 years ago, during a period when the adjacent ocean warmed significantly. Large tracts of East Antarctica remain poorly studied, and further work is required to develop a robust understanding of the LGM ice sheet expansion, and its subsequent contraction. Further work will also allow the contribution of the EAIS to post-glacial sea-level rise, and present-day estimates of glacio-isostatic adjustment to be refined.

1. Introduction

This paper describes the changes that occurred in the East Antarctic Ice Sheet (EAIS) during the Last Glacial Maximum (LGM) and subsequent deglaciation, as part of a collective effort by the Antarctic Climate Evolution (ACE) Programme of the Scientific Committee for Antarctic Research (SCAR) to document the behaviour of Antarctica as a whole during this time. The EAIS is the largest ice sheet on Earth, spanning a vast continental area between the longitudes of ~45°W and ~168°E (Fig. 1), exceeding 2 km in thickness over the majority of its area, and reaching a maximum thickness of >4.8 km near its centre (Lythe et al., 2001; Fretwell et al., 2013). It consists of several domes, and is largely separated from the smaller West Antarctic Ice Sheet in the vicinity of the Transantarctic Mountains. Ice retrieved from Dome C in East Antarctica has been continuously dated to 800,000 years old (Parrenin et al., 2007a). Geological evidence shows that an EAIS has probably persisted, with multiple glacial–interglacial cycles, since its initial formation around 34 million years ago (Barrett, 1996).

It is important to understand the Quaternary history of the EAIS for several reasons:

- The EAIS has a volume of 21.76×10^6 km^3 of grounded ice, equivalent to ~53 m in mean sea-level equivalent (Lythe et al., 2001; Fretwell et al., 2013). Even minor changes in the volume of East Antarctic ice can strongly influence global sea level.
- Ice sheets are one of the key elements of the Earth System. Ice sheets are affected by feedbacks associated with changing atmospheric circulation, planetary albedo and ice elevation (Pollard and DeConto, 2009). They also influence oceanic temperature and circulation through the formation of bottom water, in part beneath ice shelves (Flower and Kennett, 1994).
- Although the EAIS has long been viewed as more stable than the West Antarctic or Greenland Ice Sheets, recent work has cast doubt on this assumption. For example, it may be possible that East Antarctic ice loss contributed to sea-level rise during the Last Interglacial (Pingree et al., 2011).
- The most recent mapping of the bed of the ice sheet (BEDMAP, Fretwell et al., 2013) has now shown that large areas of the EAIS are grounded below sea level and are potentially vulnerable to erosion by ocean currents.
- Present-day observations of ice sheet changes are mostly based on satellite measurements that extend back several decades or less (IPCC, 2007). This period is too short to fully understand natural variability in the ice sheet.
- Deciphering the present-day behaviour of ice sheets using GRACE satellite gravity data requires an understanding of past ice sheet behaviour, because the gravity signal is strongly affected by glacio-isostatic adjustment (GIA) (King et al., 2012).
- The processes governing the response of ice sheets to climate change are imperfectly understood (Joughin and Alley, 2011). Examples of past ice sheet changes provide evidence about where and how fast an ice sheet may respond to environmental forcing.
- Some parts of East Antarctica, especially fast-flowing outlet glaciers (e.g. Totten Glacier, Philippi Glacier) are losing mass at present, while other, especially slower-flowing areas (e.g. in Enderby Land) appear to be gaining mass (Pritchard et al., 2009; Shepherd et al., 2012). Some ice shelves also appear to be losing considerable mass from sub-shelf melting and not just calving (e.g. Totten Ice Shelf, West Ice Shelf) (Rignot et al., 2013). The long-term ice sheet history in these areas might aid in understanding recent ice sheet behaviour.
- Antarctica may have been one of the sources of abrupt sea-level rise events during deglaciation known as 'meltwater pulses.' In particular, an Antarctic contribution has been inferred for Meltwater Pulse 1a (MWP1a) (Clark et al., 2002; Deschamps et al., 2012). Discussion and further study of the geological evidence from East Antarctica is needed in order to identify or rule out possible sources of meltwater pulses.

2. Aims

We aim to describe the marine and terrestrial geological evidence that constrains the history of the EAIS immediately prior to, during and following the LGM. Our specific objectives are to:

1. Summarise evidence for past ice thickness and extent using onshore and offshore records.
2. Compile a table of robust age constraints for glacial features (with an assessment of quality control). This table is available as Supplementary material.
3. Discuss the implications of our findings for understanding the response of the ice sheet to past climate changes, including its possible contribution to global meltwater pulses.

3. Study regions and data sources

The LGM glacial history of East Antarctica is poorly documented (Ingólfsson et al., 1998; Bentley, 1999; Wright et al., 2008). Relatively little of the continental shelf surrounding East Antarctica has been studied (Anderson et al., 2002; Livingstone et al., 2012), and although deglaciated regions occur at both the ice sheet margin and further inland, only a few previous studies provide strong constraints on their glacial history. Ice cores from the interior as well as Law Dome near the ice sheet margin also provide some constraints on past ice sheet thickness (Fig. 1, Table 1).

Ice-free regions, known as 'oases', occupy a small percentage of the overall land area in Antarctica (Fig. 1). Oases typically occur in coastal areas adjacent to large outlet glaciers. Ice-free regions also occur within mountain ranges or on individual mountain nunataks, which extend into the ice sheet interior. We describe the geomorphology of each of these regions, focussing on the features that constrain the maximum ice extent during the LGM and the chronology of deglaciation. For ice sheet chronology, we report only absolute dating methods: Radiocarbon (^{14}C), Terrestrial Cosmogenic Nuclide (TCN) and Luminescence (Optically Stimulated Luminescence – OSL, Infrared Stimulated Luminescence – IRSL) dating. All dates referred to in the text are provided in a Supplementary data