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Abstract

Limited information on the East Antarctic Ice Sheet (EAIS) geometry during Marine Isotope Stage 3 (MIS 3; 60-25 ka) restricts our understanding of its behaviour during periods of climate and sea level change. Ice sheet models forced by global parameters suggest an expanded EAIS compared to the Holocene during MIS 3, but field evidence from East Antarctic coastal areas contradicts such modelling, and suggests that the ice sheet margins were no more advanced than at present. Here we present a new lake sediment record, and cosmogenic exposure results from bedrock, which confirm that Rauer Group (eastern Prydz Bay) was ice-free for much of MIS 3. We also refine the likely duration of the Last Glacial Maximum (LGM) glaciation in the region. Lacustrine and marine sediments from Rauer Group indicate the penultimate period of ice retreat predates 50 ka. The lacustrine record indicates a change from warmer/wetter conditions to cooler/drier conditions after ca. 35 ka. Substantive ice sheet re-advance, however, may not have occurred until much closer to 20 ka. Contemporary coastal areas were still connected to the sea during MIS 3, restricting the possible extent of grounded ice in Prydz Bay on the continental shelf. In contrast, relative sea levels (RSL) deduced from field evidence indicate an extra ice load averaging several hundred metres thicker ice across the Bay between 45 and 32 ka. Thus, ice must either have been thicker immediately inland (with a steeper ice profile), or there were additional ice domes on the shallow banks of the outer continental shelf. Further work is required to reconcile the differences between empirical evidence of past ice sheet histories, and the history predicted by ice sheet models from far-field temperature and sea level records.

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Unglaciaded areas in East Antarctica during the last glacial (Marine isotope stage 3) - new evidence from Rauer Group

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Highlights

- East Antarctic Ice Sheet margin during MIS 3 was similar to that observed today
- New relative sea level constraint provides indication on ice sheet profile during MIS 3
- Onset of the penultimate period of ice sheet and glacier retreat predates 50 ka
- Short (< 10 ka) duration of LGM ice sheet advance in coastal areas

Keywords

lake sediments,
exposure dating,
ice sheet reconstructions,
Antarctica

Abstract

Limited information on the East Antarctic Ice Sheet (EAIS) geometry during Marine Isotope Stage 3 (MIS 3; 60-25 ka) restricts our understanding of its behaviour during periods of climate and sea level change. Ice sheet models forced by global parameters suggest an expanded EAIS compared to the Holocene during MIS 3, but field evidence from East Antarctic coastal areas contradicts such modelling, and suggests that the ice sheet margins were no more advanced than at present. Here we present a new lake sediment record, and cosmogenic exposure results from bedrock, which confirm that Rauer Group (eastern Prydz Bay) was ice-free for much of MIS 3. We also refine the likely duration of the Last Glacial Maximum (LGM) glaciation in the region.

Lacustrine and marine sediments from Rauer Group indicate the penultimate period of ice retreat predates 50 ka. The lacustrine record indicates a change from warmer/wetter conditions to cooler/drier conditions after ca. 35 ka. Substantive ice sheet re-advance, however, may not have occurred until much closer to 20 ka.

Contemporary coastal areas were still connected to the sea during MIS 3, restricting the possible extent of grounded ice in Prydz Bay on the continental shelf. In contrast, relative sea levels (RSL) deduced from field evidence indicate an extra ice load averaging several hundred metres thicker ice across the Bay between 45 and 32 ka. Thus, ice must either have been thicker immediately inland (with a steeper ice profile), or there were additional ice domes on the shallow banks of the outer continental shelf. Further work is required to reconcile the differences between empirical evidence of past ice sheet histories, and the history predicted by ice sheet models from far-field temperature and sea level records.

1. Introduction

Empirically derived Antarctic ice sheet histories are important for understanding the response of the ice sheet to changes in climate and sea level, and for testing ice sheet models. To date, most effort has been made in reconstructing the geometry of the ice sheet during the global Last Glacial Maximum (ca. 25-18 ka, thousand years before present), and in the timing and rate of retreat after this period (Anderson et al. 2002, Hillenbrand et al. 2014, Mackintosh et al. 2014). Relatively little is known about the size of the ice sheet prior to this ice advance, and the duration of the ice advance maximum.

The lack of information for the geometry of the ice sheet during Marine Isotope Stage 3 (MIS 3; 60-25 ka) in East Antarctica limits our understanding of its behaviour during periods of climate and sea level change. Globally, MIS 3 is characterized by fluctuating climate conditions on millennial time scales, which affected ice volumes representing about 20 to 40 m of sea-level change (e.g. Sidall et al. 2008). Ice-rafted debris (IRD) in sediments from the North Atlantic provides evidence on millennial-scale instabilities of the Laurentide Ice Sheet (Bond et al. 1992). The Antarctic Ice Sheet behaviour during MIS 3 is less clear, despite fluctuations in the IRD record which have also been found in the Southern Ocean (Kanfoush et al. 2000).

Ice sheet models forced by global parameters suggest an expanded East Antarctic Ice Sheet (EAIS) compared to the Holocene during MIS 3, largely driven by lower sea levels and reduced rates of sub-glacial melting of ice shelves (e.g. Pollard and Deconto 2009). However, field evidence from the few East Antarctic coastal areas where data are available contradicts such modelling, and suggests that the ice sheet margins were no more advanced than at present in many places (Fig. 1): At Lützow Holm Bay (Miura et al. 1998), at the coastline of eastern Prydz Bay (Hodgson et al. 2006, 2009; Berg et al. 2010a) likely at Burger Hills (Gore et al. 2001) and potentially the Windmill Islands (Kirkup et al. 2002, Cremer et al. 2003) and at the western Ross Sea coastline (Emslie et al. 2007). Resolution of this contradiction is important from an ice sheet behaviour perspective, and also to better understand the role of ice sheet changes in the evolutionary and biogeographic history of the terrestrial and marine biotas of the Antarctic continent (Convey et al. 2009).

Age constraints of sediment records for many of these sites are derived from radiocarbon dating of organic matter and carbonates, which raises some problems as the early part of MIS 3 is at the limit of radiocarbon dating (Taylor and Southon, 2007). Mixing of carbon from different sources during sedimentation can lead to erroneous ages. Also, for many records,

the latter part of MIS 3 record may be missing due to erosion by the ice sheet during the LGM. Thus, further evidence, and a more diverse set of dating techniques is needed to resolve the apparent contradiction between modelling and field observations.

In this study we present new evidence for an un-glaciated coastal area in East Antarctica during MIS 3, at Rauer Group. Two pieces of evidence previously suggested that Rauer Group may have been partly ice free during MIS 3. First, sediments from a coastal inlet have been radiocarbon dated to 43.6 to 32.2 ka (Berg et al. 2010a) indicating marine deposition during the middle part of MIS 3. Second, substantial differential weathering (up to 2 m) along banded gneiss bedrock (White et al. 2009) suggests a period of subaerial exposure. Here we present a new lake sediment record, and cosmogenic exposure results from bedrock which confirm that Rauer Group was ice free for much of MIS 3 and refine the likely duration of the LGM.

Figure 1. Map of Antarctica with place names of the major ice-free coastal areas and place names mentioned in the text.

2. Regional setting

Rauer Group is an ice-free archipelago on the eastern margin of Prydz Bay (Fig. 1 and 2). The islands of Rauer Group support a range of shallow and mostly saline lakes (Hodgson et al. 2001, Wagner et al. 2008). The timing of ice sheet retreat on Rauer Group in the late Pleistocene/early Holocene is well constrained from marine sediment cores (Berg et al. 2010 a, b) as well as from cosmogenic dating of glacial erratics (White et al. 2009, 2014), and indicates that the outer islands had deglaciated by 16 ka, with retreat reaching the present margin by 11 ka.

Skua Lake (9.4 m above sea level (a.s.l.); unofficial name) is one of the deepest water bodies on Filla Island, with a maximum water depth of 120 cm (Fig. 2). Skua Lake was one of the few depressions to have retained water during the March 2007 survey, but shorelines indicate that the lake level had recently been 20-30 cm above the 2007 level. By the time of sediment sampling in March 2007 the lake was covered with 8.5 cm thick ice. Conductivity of the water indicated brackish to saline conditions (Wagner et al. 2008). Topography around the lake basin is of higher elevations with an outlet at 11.5 m a.s.l. on the southern side (Wagner et al. 2008).

Figure 2. Map of Rauer Group with coring locations indicated (C), with minimum bedrock exposure durations (red) and periods of pre-LGM sedimentation from organic radiocarbon ages (green) in marine and lake basins. Exposure durations include the post-LGM duration of c. 10 ka at Mather Peninsula, increasing to >16 ka at Hop Island. Ages at Filla inlet have been obtained from a marine sediment core (Berg et al. 2010a) (B) Detailed map of the surroundings of Skua Lake and the un-named lake. Black ellipsoids represent sills, levelled during the field campaign (Wagner et al. 2008). Altitude of sills and lake level are given in m a.s.l. Photograph of Skua Lake (by S. Ortlepp). Note the deep centre of the lake, where core Co1008 was recovered (A).

3. Material and methods

3.1 Lake sediments

Sediment cores were recovered from the deep central part of Skua Lake with an Eijkelpamp piston corer from the ice cover of the lake. Sediments were stored at 4°C prior to core opening.

For elemental analysis semi-quantitative XRF scans were obtained on core halves using an ITRAX XRF core scanner (Cox Ltd.; Croudace et al. 2006). Settings for the analysis with a

molybdenum X-ray tube were 30 mA and 30 kV. The measurement was conducted with an exposure time of 20 sec, and a step-size of 2 mm. Results of the XRF measurement are given as counts per second (cps), which is a semi-quantitative measure of element concentration. In our discussion we use element counts (cps) normalized to cps of Titanium (Ti), which represents the siliciclastic sediment component, in order to eliminate dilution effects.

For further analysis the sediments were sub-sampled in 2 cm slices, and freeze-dried. Elemental analysis for total sulphur (S) was conducted on ground aliquots (< 63 μ m) with a Vario Micro Cube combustion elemental analyser (VARIO Corp.) and total organic carbon (TOC) and total inorganic carbon (TIC) was quantified with a DIMATOC 200 (DIMATEC Corp.). Two samples of sediments from a very shallow un-named lake basin close to Skua Lake (68°48.758' S; 77°51.114'E; Fig. 2) and from recent marine mud were sampled and analysed for their fossil content. The samples were wet sieved on a 0.1 mm sieve and the residue left on the sieve analysed using a dissecting microscope.

AMS radiocarbon measurements were carried out on bulk organic carbon of sediment samples, following the pre-treatment protocol for alkali-acid-alkali (AAA) extraction (Rethemeyer et al. 2013) and graphitisation with an AGE graphitisation system (Wacker et al. 2010). For one sample radiocarbon measurements have been made both on the humic acid fraction (extracted with AAA) and on the humin acid fraction. Three sediment samples have been processed in duplicate, including all pre-treatment steps. The carbonate sample was hydrolysed with phosphoric acid prior to graphitisation as outlined in Wacker et al. (2013).

For conversion of radiocarbon ages (^{14}C yr BP or ^{14}C ka for kilo years) into calendar ages (cal yr BP or ka for kilo years) calibration was made with calib rev7.1 (Stuiver and Reimer 1993), using the SHcal13 calibration dataset (Hogg et al. 2013) for lacustrine samples and Marine13 (Reimer et al. 2013) for marine samples. Since marine reservoir ages for MIS 3 are not quantified we use the Marine Antarctic Reservoir Effect of 1200 years for reservoir correction.

3.2 Cosmogenic exposure dating

Cosmogenic exposure samples were collected from bedrock in a transect perpendicular to the ice sheet. Samples were collected from on or near local summits, targeting bedrock with minimum post-glacial erosion at each site (Fig. 3), although the absolute amount of post-glacial subaerial erosion differs between the three sites. Sites at Hop and Filla Islands preserved meso-scale bedrock forms consistent with glacial erosion, but micro-scale bedforms such as glacial polish and striae had been removed via subaerial weathering. In contrast, remnant striations and glacial polish was commonly preserved on the inland portions of Mather Peninsula, indicating post-glacial erosion has been limited. Sample locations were paired with erratics (White et al. 2014) and were located with a Garmin e-trex

1 GPS. Elevations were cross-checked with the Australian Antarctic Division topographic map,
2 accurate to 10 m. Topographic shielding correction was used, but is negligible ($< 5^\circ$) at all
3 sites and shielding uncertainties produce age uncertainties of $<1\%$.

4 Rock disaggregation and quartz purification was performed at Macquarie University using
5 standard procedures (Kohl and Nishiizumi 1992). Be and Al were extracted from the quartz
6 using ion chromatography at the Australian Nuclear Science and Technology Organisation
7 (ANSTO) following procedures described in Child et al. (2000). $^{10}\text{Be}/^9\text{Be}$ and $^{26}\text{Al}/^{27}\text{Al}$ ratios
8 were measured at ANSTO's ANTARES AMS Facility using methods described previously
9 (Fink et al. 2004, Fink and Smith 2007) and referenced to ^{10}Be standard NIST-4325 using a
10 nominal isotope ratio of $27,900 \times 10^{-15}$ (Nishiizumi et al. 2007) and to ^{26}Al standard KN-4-2
11 with a nominal value of $30,960 \times 10^{-15}$. Measured $^{10}\text{Be}/^9\text{Be}$ ratios were corrected by full
12 chemistry procedural blanks which gave a mean $^{10}\text{Be}/^9\text{Be}$ value of $10.8 \pm 1.4 \times 10^{-15}$ using ~
13 $350 \text{ ug } ^9\text{Be}$ sourced from a 1080 ug/g solution of beryl.. and represents no more than a 4%
14 correction to final ratios. Independent repeat sample measurements ($n=2$ for ^{10}Be , $n=2-5$ for
15 ^{26}Al) were combined as weighted means with the larger of the total statistical error or mean
16 standard error. Final analytical error in ^{10}Be concentrations (atoms/g) are derived from a
17 quadrature sum of the standard mean error in the AMS ratio, 2% for AMS standard
18 reproducibility, and 1% in Be spike assay. In the case of ^{26}Al , we apply a 3% for AMS
19 standard reproducibility and 4% for Al-ICP measurement.

20 *In-situ* ^{14}C measurements were done at the University of Cologne following the procedures
21 described in Fülöp et al. (2015). The ultra-pure quartz aliquot (0.5 g) was leached using
22 HNO_3 , and heated in-vacuo at 500°C for 2 hours in a fused silica tube with added solid
23 carbonate carrier. The sealed tube was then heated at 1650°C for 2 hours under a modified
24 atmosphere and cracked in-vacuo. The sample was cleaned from other gas species and the
25 amount of CO_2 quantified, then reduced in the presence of Fe_2O_3 to graphite using a micro
26 furnace at ANSTO (Smith et al. 2010). $^{14}\text{C}/^{13}\text{C}$ isotope ratio measurements were done at the
27 ANTARES AMS Facility. We calculate the final in-situ ^{14}C concentration from the measured
28 data as outlined in Hippe and Lifton (2014), using the measured fraction of modern carbon (F
29 ^{14}C value = 0.1094 ± 0.002). The sample was measured in 2014, and we use a mean lifetime
30 of 8223 years in calculations. Full procedural blanks from saturated natural quartz samples
31 (more detail in Fülöp et al., 2015), yielding $10^{+16}/_{-10} \times 10^3$ (± 1 S) atoms in-situ ^{14}C , were
32 subtracted from the final concentration. No correction was made for graphitization blank, as
33 this was not quantified. Exposure ages are calculated using CRONUS-Earth online calculator
34 (Balco et al. 2008). We quote ages based on the time variant Stone (2000)/Lal (1991) scaling
35 model, the Heyman (2014) production rate of 3.99 ± 0.22 atoms ^{10}Be /g/yr and use a
36 $^{26}\text{Al}/^{10}\text{Be}$ production ratio of 6.75 to calculate the ^{26}Al ages.

Figure 3. Cosmogenic bedrock sample sites from Hop Island (KK-HI-01-97, -02-97), Filla Island (007C) and Mather Peninsula (113C). Squares represent precise sample locations for 007C and 113C. White arrow in 113D photo indicates presence of remnant striated and polished bedrock, similar to that sampled at the precise location of 113C. Hop Island site photo is from the general area of orthogneiss bedrock where samples were collected, and is illustrative of character of sampling location only.

4. Results and discussion

4.1 Skua Lake

The sediment core Co1008 retrieved from Skua Lake is 236 cm long. The sediments are mainly silty to sandy and of dark colour, due to mafic mineral grains and from reducing conditions in the sediments. The sediment grains are angular and poorly sorted, which is in accordance with the relatively small catchment of the lake and correspondingly short transport distances of detrital lithic material. In most parts of the sediment sequence gypsum crystals are interspersed in the minerogenic matrix, which is also reflected by high sulphur concentrations of up to 9% and maxima in S/Ti ratios parallel to high Ca/Ti ratios in the horizons with gypsum (Fig. 4). A total of ten ^{14}C -ages have been obtained for core Co1008 (Table 1). Duplicate pre-treatment and AMS measurement of three samples have been performed. While one sample (COL1398) did not yield sufficient carbon for a valid AMS result, the other two samples (COL1399 and COL2093 at 102 cm; COL1397 and, COL2094 at 202 cm) show that duplicates are very similar in age, but they do not reproduce within the analytical error of AMS measurement (Table 1). This can be explained by the low TOC contents and inhomogeneity of the samples due to grain size effects.

We define four units based on lithological and geochemical characteristics in core Co1008.

Unit I (236-192 cm): The sediments are finely laminated, *in situ* layers of decayed microbial mats alternating with lighter, likely carbonaceous layers. The minerogenic sediment fraction is rich in coarse-grained components (>1mm), which are likely ice rafted across the frozen lake surface or blown out on the lake ice (Doran et al. 1994). In the lower part of unit I (**Unit**

1 **Ia**, 236-209 cm) TOC contents are between 1.6 and 4.3% (Fig. 4). The presence of
2 carbonate is supported by TIC contents up to 1.3% and high Ca/Ti ratios concurrent with
3 high Ca/S ratios (Fig. 3). We interpret this subunit as deposited in an aquatic, likely lacustrine
4 environment, on the basis of deposition of TOC and simultaneous precipitation of
5 carbonates.

6 Above 209 cm (**Unit Ib**, 209-192 cm) TOC values are lower (<1%) and very low carbonate
7 contents are seen (low TIC and low Ca/Ti ratios). In freeze-dried samples from unit Ib a white
8 powder was observed. This points to the presence of the mineral Mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10 \text{H}_2\text{O}$)
9 in the fresh sediments. Mirabilite decays into Thenardite (Na_2SO_4) by dehydration (Gore et
10 al. 1996). Formation of Mirabilite has been ascribed to cryo-concentration of brines from
11 freezing seawater (Marion et al. 1999) and saline Antarctic ponds (Schmidt et al. 1991).
12 Mirabilite precipitation in Skua Lake likely resulted from the formation of brines during
13 freezing of the water column. Above 196 cm S contents, S/Ti and Ca/S ratios increase and
14 macroscopic gypsum crystals occur. The occurrence and increase of gypsum in the
15 sediments of unit Ib point to a successive desiccation of the lake. We suggest that the
16 sediments were deposited in a more saline and less productive environment.

17 Radiocarbon ages from unit I clearly indicate a pre-Holocene age: ^{14}C value of samples from
18 the lower unit Ia are not distinguishable from the procedural blank, which means that the age
19 of the organic carbon in the sediments is >50 ka. ^{14}C ages of humins and humic acids from
20 the same sample provided consistent ages (COL2216, 232 cm depth, table 1), the younger,
21 evaporitic sediments from unit Ib dated to 34.0 - 42.1 ka cal BP.

22 **Unit II (192-154 cm)**: The lower half of this unit consists of gypsum, while the top half is
23 formed by cryoturbated sands. The TOC content is low, and the siliciclastic component is
24 poorly sorted. Gypsum is abundant throughout the unit in variable proportions and mirabilite
25 was found in some horizons (Fig. 4). Gypsum crystals mainly have a lensoidal shape and are
26 >2mm in length. The geochemical parameters in unit II forms a continuation of the top cm of
27 unit I. However, sediments in unit II have a massive structure and show indications of
28 reworking or mixing: carbonaceous material occurs in incorporated lenses seen as peaks in
29 Ca/Ti and Ca/S ratios and deep cracks in the sediments are filled with gypsum crystals, likely
30 due to cryoturbation. The sediments of unit II are interpreted as the product of a period of
31 sub-aerial exposure of the lake bottom.

32 **Unit III (154-122 cm)**: The sediments of unit III are layered, with differences in grain size,
33 sorting, carbonate content and colour. Low TOC, water and sulphur contents together with
34 the variability of the siliciclastic components points to a depositional environment which was
35 dynamic and did not provide good conditions for the production or preservation of organic
36 matter. Deposition of unit III probably took place in a very shallow, occasionally desiccated

lake where littoral influences were strong and flowing water deposited clastic sediments in the lake centre.

Unit IV (122-0 cm): The base of unit IV is defined by a sharp increase in water content (from ~7 to 16%). In the first ~10 cm of unit IV a clay layer, followed by a carbonate-rich layer and first gypsum crystals occur. From 114 to 94 cm layers of lensoidal gypsum crystals regularly alternate with sand layers. Between 94 and 64 cm sediments mainly consist of idiomorphic gypsum crystals with very low siliciclastic proportions. Between 44 and 28 cm mirabilite was found in most horizons, which points to cryo-concentration of the lake water likely due to freezing in winter. The sediment reflects low energetic, high salinity lacustrine environment consistent with the modern day lake.

The precipitation of gypsum in the lake also reflects a high ion concentrations and points to recurring oversaturation of the water with respect to gypsum, either due to freezing or due to evaporation.

Figure 4. Stratigraphy of core Co1008. Results of geochemical analysis are shown versus depth: Water content, total organic carbon (TOC), total inorganic carbon (TIC), total sulphur (S) and element ratios determined by XRF-analysis. Radiocarbon ages are given as calibrated ages (Table 1). The column to the right shows the interpretation of the depositional environment and the expected timing of deposition.

Since ions are removed from the system by precipitation and preservation of salts in the sediment the on-going formation of gypsum crystals can only be sustained by a resupply of ions into the lake. A direct inflow of marine water into the lake at present and during the Holocene can be excluded due to the topography surrounding Skua Lake. Holocene relative sea level (RSL) reached a maximum height of 8.5 m a.s.l. (White et al. 2009), which is lower than the highest sill between Skua Lake and the sea (11.5 m a.s.l.). Salts in Skua Lake

probably originate directly from aerosols (e.g., from sea spray) or from washed out surficial salt from the catchment (Gore et al. 1996).

Radiocarbon ages from Unit IV indicate a Holocene deposition. Assuming a constant sedimentation rate, the extrapolated age of the sediment surface is close to modern, which points to a low reservoir age of Skua Lake related to $\text{CO}_{2(\text{aq})}$ in lake water being in equilibrium with the atmosphere.

Table 1. Radiocarbon ages obtained from Co1008 and a marine fossil from an un-named lake. Calibration of ^{14}C ages was done using calib7.1 (Stuiver and Reimer 1993) and the SHcal13 calibration dataset (Hogg et al. 2013) for freshwater samples and Marine13 (Reimer et al. 2013) for marine carbonate respectively. A marine reservoir age of 1200 years was used for correction.

Site	Depth [cm]	Unit	Sample ID	^{14}C age [yr BP]	Age [cal yr BP] 2σ	dated material
Skua Lake	18	IV	COL1398	(1560±40) ^a		humins
Skua Lake	18	IV	COL2092	1320±35	1320-1510	humins
Skua Lake	102	IV	COL1399	7720±110	8200-8720	humins
Skua Lake	102	IV	COL2093	6770±40	7500-7670	humins
Skua Lake	202	Ib	COL1397	36400±780	39200-42100	humins
Skua Lake	202	Ib	COL2094	30500±250	34000-34800	humins
Skua Lake	214	Ia	COL2456	>52800	inf. age	humins
Skua Lake	220	Ia	COL2457	>52800	inf. age	humins
Skua Lake	226	Ia	COL2458	>56600	inf. age	humins
Skua Lake	232	Ia	COL2216	>49400	inf. age	humins
Skua Lake	232	Ia	COL2216HA	>49400	inf. age	humic acid
Unnamed lake	-	-	KIA33455	35700±650	38300-39200 ^b	Carbonate (<i>Laternula</i>)

^a carbon content too low for reliable ^{14}C -AMS measurement

^b marine sample calibrated with Marine13 dataset (Reimer et al. 2013)

4.2 Fossils from an un-named lake

Sediments from an un-named lake basin on Filla Island contain fossils of marine organisms *Laternula elliptica*, echinoidea indet. and *spirorbis* sp., of which some are also abundant in recent marine mud from Filla Island (Table 2). The fossils point to a marine origin of the sediment. The carbonate of the *Laternula elliptica* fossil yielded a radiocarbon age of 35.7 ^{14}C ka (Table 1), which indicates that the *laternula* was growing in a non-glaciated marine environment during MIS 3. The fossils are not *in-situ*, but their well-preserved nature argues against abrasive reworking. Thus, given their position above the Holocene RSL (and the MIS3 sea level, based on the Skua Lake core) maximum, we interpret that the marine sediments were glacially transported as a frozen block during the LGM glacial overriding of Filla Island, similar to what occurred nearby at the Sørsdal Glacier moraines (Fitzsimons 1997).

Table 2 Macro-fossils identified in sediment samples from an un-named lake at 68°48.758'S; 77°51.114'E on Filla Island, 26 m a.s.l. and from recent marine mud.

	un-named lake	recent marine mud
Benthic calc. foraminifera indet.	r	a

Agglutinating foraminifera indet.	-	r
Hydroidea indet.	-	r
<i>Spirorbis</i> sp.	r	r
Serpulidae indet.	-	-
Turbellaria indet.	-	r
Gastropoda indet.	-	c
<i>Laternula elliptica</i>	a	-
Ostracoda indet.	-	r
Bryozoa indet.	-	r
Echinoidea indet.	c	a
Pisces indet.	c	r
Marine algae indet.	r	-
Calcareous algae indet.	r	-
Diatoms	-	a

1 r = rare, a = abundant, c = common.

2 **4.3 Bedrock exposure dating**

3 Four bedrock samples were dated, and provide zero-erosion minimum ^{10}Be and ^{26}Al ages
4 ranging from 37 ka to 128 ka. These minimum ages are far older than the paired erratic
5 cobbles (White et al. 2014) deposited on the bedrock, indicating limited erosion of bedrock,
6 and significant prior exposure to cosmogenic radiation during the LGM expansion and retreat
7 (Fig. 2, Tables 3 and 4). The limited erosion indicates the ice covering Rauer Group during
8 the LGM was thin and/or slow flowing, consistent with the style of ice flow immediately inland
9 of the present day archipelago.

10 The preservation of ^{10}Be and ^{26}Al from prior to the LGM means that these sites must have a
11 preserved cosmogenic nuclide inventory from one, or several periods of prior exposure.
12 While the timing and number of exposure periods cannot be deduced from these
13 measurements alone, they do provide some measure of the minimum length of time the sites
14 have remained ice free since the current bedrock surfaces were exposed to within ~ 2 m of
15 the land surface by sub-aerial or subglacial erosion. Measured subaerial erosion rates in
16 salty coastal regions of Prydz Bay (c. 5-25 mm/ka, Spate et al. 1995), and the concordant
17 ^{10}Be and ^{26}Al ages suggest that the cumulative exposure periods most likely occurred over
18 the last few hundred thousand years.

19 Bedrock exposure ages increase from the ice sheet margin to the outer coast, consistent
20 with increasing duration of exposure, and/or reduced glacial and subaerial erosion rates
21 toward the outer islands. Bedrock exposure ages close to the modern ice margin at Mather
22 Peninsula (113C), indicate a minimum pre-LGM total exposure duration of >20ka and of
23 >100 ka at Hop Island (KK-HI 1 & 2, previously reported in White et al. 2009).

24 Maximum durations of exposure are more difficult to constrain from the isotope
25 measurements, as both subaerial and subglacial erosion will limit the true bedrock exposure

age, so true exposure ages are potentially much higher. Indeed, at the seaward sites on Hop Island, the bedrock surface ^{10}Be concentrations are consistent with being in erosional equilibrium with the modern-day subaerial erosion rates. The erosion rates measured on similar metamorphic lithologies at nearby Vestfold (24 mm/kyr) and Larsemann (15 mm/kyr) Hills (Spate et al., 1995) would limit the maximum concentrations obtainable in the rock surface to the values measured in KK-HI01-97 and KK-HI-02-97 indicating these samples have a *minimum* exposure age of at least ~200 ka (Fig. 5). Thus, the outer islands have likely been exposed for much of the last hundred thousand or perhaps several hundred thousand years depending on prevailing erosion rates. In addition the bedrock ^{10}Be concentrations do not preclude periods of burial by an overriding, but minimally erosive, ice sheet.

In contrast, ^{10}Be and ^{26}Al concentrations at Mather Peninsula (113C) suggest the inner peninsulas were covered by the ice sheet for a substantial greater fraction of the past hundred thousand years compared to that at Hop Island but at least were exposed for 30-40 ka. Site 113C lies inland of the area affected by rapid salt weathering, and lower subaerial erosion rates <1 mm/ka are more appropriate, based on the preservation of >10 ka old striae and glacial polish on these bedrock surfaces. Thus at Mather Peninsula, the isotope concentrations must have been limited by subglacial erosion or burial by ice or the ice front had pulled back before ~40-50 ka resulting in a continuous pre-LGM exposure duration for 113C of ~30-35 ka (for erosion rates of 1-5 mm/ka). The maximum duration of exposure at Filla Island (007) is less clear. The weathered nature of the bedrock suggests a few tens of cm of postglacial erosion at the site (Fig. 3) but our *in-situ* ^{14}C measurement at site 007C limits choices of subaerial erosion rates to <~5 mm/kyr, so total exposure recorded by the bedrock at this site during the last few hundred thousand years is likely <100 kyr.

The *in-situ* ^{14}C measurement at site 007C on Filla Island provides further information on the timing of exposure and in particular the duration of the LGM. The ~11 ka ^{10}Be age for erratics across Filla Island (White et al. 2014) indicate coverage by the ice sheet during the LGM. However, the *in-situ* ^{14}C concentration in bedrock at 007C is concordant with effective isotopic saturation, indicating the bedrock has been exposed for most of the last ~40,000 years. Thus, the duration of coverage by ice or ocean during the LGM was short, with the *in-situ* ^{14}C concentrations constraining the duration of LGM ice occupation time to <~10,000, and potentially only a few thousand years (Fig. 6).

Figure 5. ^{10}Be bedrock concentration curves for a range of erosion rates, including the modern day-erosion rate of ~ 20 mm/ka measured by Spate et al. (1995). Coloured lines indicate nuclide concentrations for the four bedrock samples. The length of the colored rectangles indicate the most likely subaerial exposure durations based on the degree of weathering and erosion at each sample site. For example at 007C, given field observations we estimate erosion rates could range between about 2 mm/ka to ~ 6 mm/ka giving a total cumulative exposure of 70 to 100 ka

1
2

Figure 6. Two-nuclide (banana) plot for bedrock exposure sample 007C at Filla Island. Solid line indicates position of expected concentration if bedrock surfaces have remained continually exposed following the initial retreat of the ice sheet. Dotted and dashed lines indicate expected concentrations during an exposure-burial-exposure history where the final exposure is 11 ka, consistent with the age of post-LGM deglaciation at this site. Error bars indicate two-sigma uncertainty range for *in-situ* ^{14}C - and ^{10}Be concentrations on sample 007C.

Table 3. Characteristics of bedrock collected for cosmogenic nuclide samples from Rauer Group

Sample ID	latitude ^a	longitude	alt. (m)	km from ice sheet	sample lithology	weathering	glacial morphology
113C-BR	68.85080	77.91555	90	1.0	Felsic Gneiss	stained and crumbled	occasional polish. Meso-scale glacial morphology preserved
007C-BR	68.81518	77.83350	65	5.6	Quartz vein	highly crumbled	no polish or striae. Macro-scale glacial morphology preserved
KK-HI-01-97	68.8	77.7	30	10.8	Orthogneiss	Highly crumbled	no polish or striae. Macro-scale glacial morphology preserved
KK-HI-02-97	68.8	77.7	45	10.8	Orthogneiss	Highly crumbled	no polish or striae. Macro-scale glacial morphology preserved

^aposition relative to WGS 84 datum, elevation relative to local sea level.

Table 4. Accelerator Mass Spectrometry (AMS) data for cosmogenic nuclide measurements on bedrock at Rauer Group

Sample ID	¹⁰ Be	¹⁰ Be 1σ error	²⁶ Al	²⁶ Al 1σ error	¹⁴ C	¹⁴ C 1σ error	¹⁰ Be production rate muons	¹⁰ Be min exposure duration	external uncertainty	²⁶ Al min exposure duration	external uncertainty	
	at/g	at/g	at/g	at/g	at/g	at/g	atoms/g/ yr	atoms/g/yr	yr	yr		
113C-BR	202760	6570	1220200	82000	-	-	0.200	5.24	36600	2360	33500	3000
007C-BR	275200	8530	1661100	127500	251000	87000	0.198	5.11	51000	3300	59400	7500
*KK-HI-01-97	534000	3600	-	-	-	-	0.195	4.91	107400	6100	-	-
*KK-HI-02-97	644000	9700	-	-	-	-	0.196	4.99	128100	7600	-	-

Exposure durations are derived from CRONUS web calculator (V2.2.1) as described by Balco et al. [2008]. All exposure durations are minimums, and assume a zero erosion rate. Exposure durations calculated using the Lal [1991]/Stone [2000] time invariant production rate scaling scheme, and the Heyman 2014 production rate calibration dataset. *¹⁰Be results as previously published by White et al., 2009

5. Interpretation

5.1 Ice-free conditions at Rauer Group during the late Quaternary

The cumulative evidence from across Rauer Group, from cosmogenic exposure bedrock dating and from radiocarbon dating of marine and lake sediment cores, points to the majority of the archipelago being ice-free (hence not covered by the East Antarctic Ice Sheet) during much of MIS 3.

Marine sediments were accumulating ~18 m below present sea level at Filla Island inlet from before 44 to after ca. 30 ka (Fig. 2). Environmental conditions were similar or even more productive than today (Berg et al. 2010a). Littoral marine environments existed as the snapshot at ca. 40 ka from a *laternula elliptica* fossil shows. At the same time conditions were similar to today at Skua Lake around 40-35 ka. The absence of ice coverage is also supported by the accumulation of cosmogenic isotopes in the bedrock summits from at least Filla Island to seaward (ie Hop island site) for most of the past 50 ka under zero erosion and perhaps even up to 100 ka when considering reasonable sub-aerial erosion rates for this coastal marine location (see fig 5).

A subsequent glacial overriding of Rauer Group well after 32 ka is documented in unit II of core Co1008 from Skua Lake (this study) and in the marine record of Filla Island inlet (Co1010, Berg et al. 2010a, Fig. 2), as well as by the deposition of erratics across the archipelago. The preservation of MIS 3 fossils, weathered bedrock surfaces and lake and marine sediments indicate that glacial ice covering Rauer Group clearly wasn't strongly erosive during the LGM expansion. The cosmogenic nuclide concentrations in 007C from Filla Island indicate that this event was limited in duration, and perhaps lasted for only a few thousand years, likely much less than 10 kyr.

Conditions prior to 45 ka at Rauer Group are less clear. Older sediment from Filla Island inlet likely exists, but was not recovered (Berg et al. 2010a). At Skua Lake, the basal unit (Ia) provides 'infinite' radiocarbon ages (≥ 50 ka), indicating > 20 kyr in only 20 cm of sediment. While no clear break in sedimentation exists, this extremely low sedimentation rate is inconsistent with deposition rates an order of magnitude higher during similar environmental conditions during the Holocene (Fig. 4). Thus, alternatively, it could result from discontinuous sedimentation in the lake and the existence of a hiatus, namely between unit Ia and Ib. While there is no evidence from the lake sediments of true glacial overriding between units Ia and Ib, it could be the result of the lake basin filling with firnified snow (e.g. Gore, 1997), as has been proposed for lakes in the nearby Larsemann Hills (Hodgson et al. 2005, 2006).

Cosmogenic nuclide data provide little constraint prior to 40 ka – bedrock ages require some exposure prior to this period, but the nuclide concentrations are insensitive to the timing of

1 this exposure. Also, even if the lakes were covered in firnified snow, it is feasible that the
2 summits were exposed and thus accumulating nuclides in the period prior to 40 ka.
3 The environmental conditions in Skua Lake during the deposition of unit 1a have likely been
4 different from those during the Holocene and unit 1b. The absence of gypsum and the higher
5 TOC and TIC contents point to a less saline and more productive lake, probably related to
6 warmer and wetter climate conditions. A period similar to this is recorded in a similar
7 stratigraphic position from nearby Larsemann Hills (Hodgson et al. 2006). Hodgson et al.
8 (2006) suggested it deposited during a previous interglacial, likely MIS 5e (ca. 125-117 ka),
9 but the dating of this event at Larsemann Hills is also poorly constrained.

10 **5.2 Regional ice sheet configurations during MIS 3, and response to external forcing**

11 Previous work at Larsemann Hills indicates it was ice free during MIS 3 (Hodgson et al.
12 2005) and perhaps even as far back as the last interglacial (Hodgson et al. 2005, 2006).
13 However, as the Larsemann Hills site was not heavily glaciated during the LGM, the regional
14 ice sheet geometry cannot easily be deduced from this site alone. Rauer Group, however,
15 was overrun by the ice sheet during the LGM, so its glacial evolution is a more sensitive
16 'marker' of regional ice changes. Sediment sequences from Rauer Group confirm that the ice
17 sheet margin along the eastern Prydz Bay coastline was close to its present position since
18 45.2 ka (Berg et al. 2010a), and potentially much earlier (Fig. 5). Also, exposure ages of
19 erratics indicate that the ice sheet was not thicker than present (much) further inland during
20 the last 50 kyr at the Grove Mountains (Lilly et al. 2010, Fig. 6). This suggests that the ice
21 sheet was not more advanced, and the interior ice divides were not thicker than present
22 along the coast in eastern Prydz Bay during MIS 3.

23 The marine and lacustrine records from the coastal oases also provide key constraints on
24 relative sea level (RSL), which can be used to model regional crustal ice loads, and thus
25 provide an indirect measure of regional ice volumes during MIS 3 (Berkman et al. 1998). In
26 Prydz Bay RSL constraints can be derived for Rauer Group and Larsemann Hills (Fig. 7). In
27 a record from Kirisjes Pond (Larsemann Hills) a brief marine transgression around 33.3 to
28 32.4 ka was identified from diatom assemblages and stable isotope composition of organic
29 matter. The position of the lake implies a RSL of ≥ 8 m above present (Hodgson et al. 2009).
30 Our data from Rauer Group extends the MIS 3 record from the Larsemann Hills. The parallel
31 existence of lacustrine and coastal marine environments give a tie-point for RSL: The
32 lacustrine sediments in Skua Lake imply a maximum RSL below 11.5 m a.s.l. Marine
33 conditions and a sill depth of -18 m at the inlet at Filla Island on the other hand, indicate a
34 minimum RSL above -18 m around 45.1 to 32.2 ka. RSL in Rauer Group can therefore be
35 estimated to have been within ± 15 m of present during much of MIS 3, which is consistent
36 with shoreline records from Lützow-Holm Bay (Miura et al. 1998).

1
2 Eustatic sea level fluctuated between ~60-90 m below present during the period between 45
3 and 32 ka (Lambeck et al. 2002, 2014). An extra ice load averaging several hundred metres
4 across the region is needed to produce the RSL deduced from field evidence. As the ice
5 sheet margin along Ingrid Christensen Coast was no more advanced than today, ice must
6 either have been thicker immediately inland (with a steeper ice profile), or there were
7 additional ice domes on the shallow banks of the outer continental shelf, as occurred during
8 the LGM in Prydz Bay (White et al., 2014).

9 The similarity between records of ice sheet extent and relative sea level history at Prydz and
10 Lutzow-Holm Bays suggests that the pattern of a small, relatively thick ice sheet may have
11 been more broadly applicable across the East Antarctic Ice Sheet during MIS 3. If this was
12 the case, it poses questions with regard to the nature of the forcing required to produce such
13 an ice sheet profile. Sea level was lower (Lambeck et al., 2002), and marine and ice core
14 archives from this period indicate lower temperatures and snow accumulation (Van Ommen,
15 2004, Veres et al., 2013). This pattern of climate forcing could be expected to produce an ice
16 sheet that advanced onto the continental shelves, with an ice profile that was similar to, or
17 less steep than the present day, as seen in ice sheet models from this period (e.g. Pollard
18 and Deconto, 2009). In contrast, the steeper ice profile, consistent with observations,
19 requires alternative forcing conditions or ice flow parameters. Such conditions may include,
20 but not be limited to, relatively high marginal ablation by iceberg calving or ocean-based
21 melt, perhaps due to relatively warm ocean conditions around the ice margin (e.g. Van
22 Meerbeek et al., 2009), or colder, stiffer ice or reduced basal sliding. Further geologic
23 observations and ice sheet modelling are required to determine whether the far-field climate
24 records are appropriate for the Antarctic margin during MIS 3, or whether ice sheet models
25 need refinement to produce the ice configuration indicated by existing ice sheet
26 reconstructions.

Figure 7. Relative sea level history at Rauer Group (locations annotated) and Vestfold Hills (no descriptors) since MIS 3, after Zwartz et al. 1998, Hodgson et al., 2009, 2016 and Berg et al., 2010a. Grey area represents zone of potential relative sea levels (RSL) during periods where constraints are limited. Notwithstanding the RSL uncertainties, during MIS 3 eustatic sea levels were ~60-90 m lower than today, so ~ 250 m of extra regional ice load must have been present in the region between 40 and 30 ka to maintain relative sea levels at or close to the present day.

1

2 6. Conclusions

- 3 - Lacustrine and marine sediments from Rauer Group indicate an ice sheet margin position
- 4 similar to the present position in MIS 3. Although the basal age of core Co1008 from Skua
- 5 Lake appears to be at the 50 ka limit of radiocarbon dating (either early MIS 3 or older), a
- 6 change from warmer/wetter conditions to cooler/drier conditions after 42.1 - 34.0 ka can be
- 7 derived from the onset of gypsum precipitation in the lake.
- 8 - Although the ice sheet may have been more advanced on the shelf areas during MIS 3 than
- 9 during the Holocene, (e.g. in Prydz Bay) grounding of the ice was restricted in such a way
- 10 that the contemporary coastal areas were still connected to the sea in MIS 3.
- 11 - Many of the coastal margins of the East Antarctic continent which are ice-free today were
- 12 also de-glaciated during MIS 3. Although the onset of the penultimate period of ice sheet and
- 13 glacier retreat is not well constrained due to limitations in age determination of sediment
- 14 sequences, it predates 50 ka. A return to colder climate conditions, which did not favour the
- 15 production and accumulation of biogenic materials started after 35 ka but the precise timing
- 16 is uncertain and substantive ice sheet re-advance may not have occurred until much closer
- 17 to 20 ka.

1 - Further work is required to reconcile the differences between empirical evidence of past ice
2 sheet histories, and the history predicted by ice sheet models from far-field temperature and
3 sea level records.

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