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The last deglaciation of Cape Adare, northern Victoria Land, Antarctica

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Abstract: We present two ^{10}Be exposure ages from erratic boulders at Cape Adare, northern Victoria Land. The exposure ages obtained suggest that Cape Adare was covered by ice during the last glacial period, and the younger age points to deglaciation around 16.2 ka. Comparison of our younger ^{10}Be exposure age with published radiocarbon dates for Adélie penguin occupation at Cape Adare suggests that the onset of penguin colonization (at 2–3 kyr before present) lagged behind the deglaciation by at least 11.5 kyr. These observations indicate that penguin colonization did not occur until several thousand years after ice free ground became available.

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Introduction

Understanding the size and configuration of the Antarctic Ice Sheets during and since the last glacial period is important for the reconstruction of past sea level fluctuations. This knowledge also helps to predict future sea level change more accurately because the data can be used to constrain ice sheet models. The timing of deglaciation for both the East and West Antarctic Ice Sheets in the Ross Sea region has been the subject of numerous studies. Much of this work has focused on radiocarbon dating of marine sediments (e.g. Conway *et al.* 1999, Domack *et al.* 1999, Licht *et al.* 1999, Anderson *et al.* 2002, Licht & Andrews 2002, Mosola & Anderson 2006), but there has also been considerable interest in the use of radiocarbon dates from ornithogenic soils (i.e. soils mainly formed by bird and guano remains) for constraining deglacial chronologies (e.g. Baroni & Orombelli 1994, Emslie *et al.* 2003, 2007). In this paper, we discuss how deglaciation ages obtained from cosmogenic isotope dating of erratic boulders deposited during glacial retreat can be combined with dating of these other materials to further constrain the timing of onshore deglaciation and landward retreat of the grounding-line. We focused our study on Cape Adare, on the coast of northern Victoria Land (Fig. 1). Ornithogenic soil from there has recently been dated to determine the onset of post-glacial Adélie penguin colonization (Emslie *et al.* 2007), and we collected erratic boulders from nearby for surface exposure dating to determine the timing of deglaciation. To our knowledge, Cape Adare is the first location in Antarctica where both types of dating have been undertaken.

Methods

Site description and sampling

Cape Adare is the northernmost promontory of Adare Peninsula, a prominent NNW–SSE orientated landform 77 km in length, which lies at the north-west corner of the Ross Sea, in northern Victoria Land (Figs 1 & 2a). It comprises a 340 m-thick sequence of alternating basaltic lavas and volcaniclastic deposits, for which a K–Ar age of 3.79 ± 0.03 Ma has been obtained (Muller *et al.* 1991). Overlying the lavas is a gently undulating surface covered by regolith, strewn with numerous scattered erratic boulders and cobbles up to 4 m in diameter. These are derived from both the non-volcanic hinterland 40 km to the south (metasedimentary rocks of the Robertson Bay Group, which are intruded by granitoids of the Admiralty Intrusives; Borg *et al.* 1987, Rossetti *et al.* 2006) and local trachytic lavas of the McMurdo Volcanic Group (Kyle 1990). The site is exposed and windy, and is ice free at the present day, as is all of Adare Peninsula north of Hanson Peak (Fig. 1b). The closest glacier to Cape Adare is Warning Glacier, which is located 25 km to the south, on the western side of Adare Peninsula, and drains into Robertson Bay. Near the modern sea level, on the western side of Cape Adare (Ridley Beach), is an Adélie penguin colony with an estimated size of 85 000–135 000 nests (the largest in Antarctica; Ainley 2002). In addition, abandoned nesting sites are present on a cliff face overlying the beach and extending onto the western margin of a snow free terrace at *c.* 300 m a.s.l. (Emslie *et al.* 2007).

During January 2006, two of us (JLS and SR) visited Cape Adare to study the volcanic sequences there. JLS and SR also

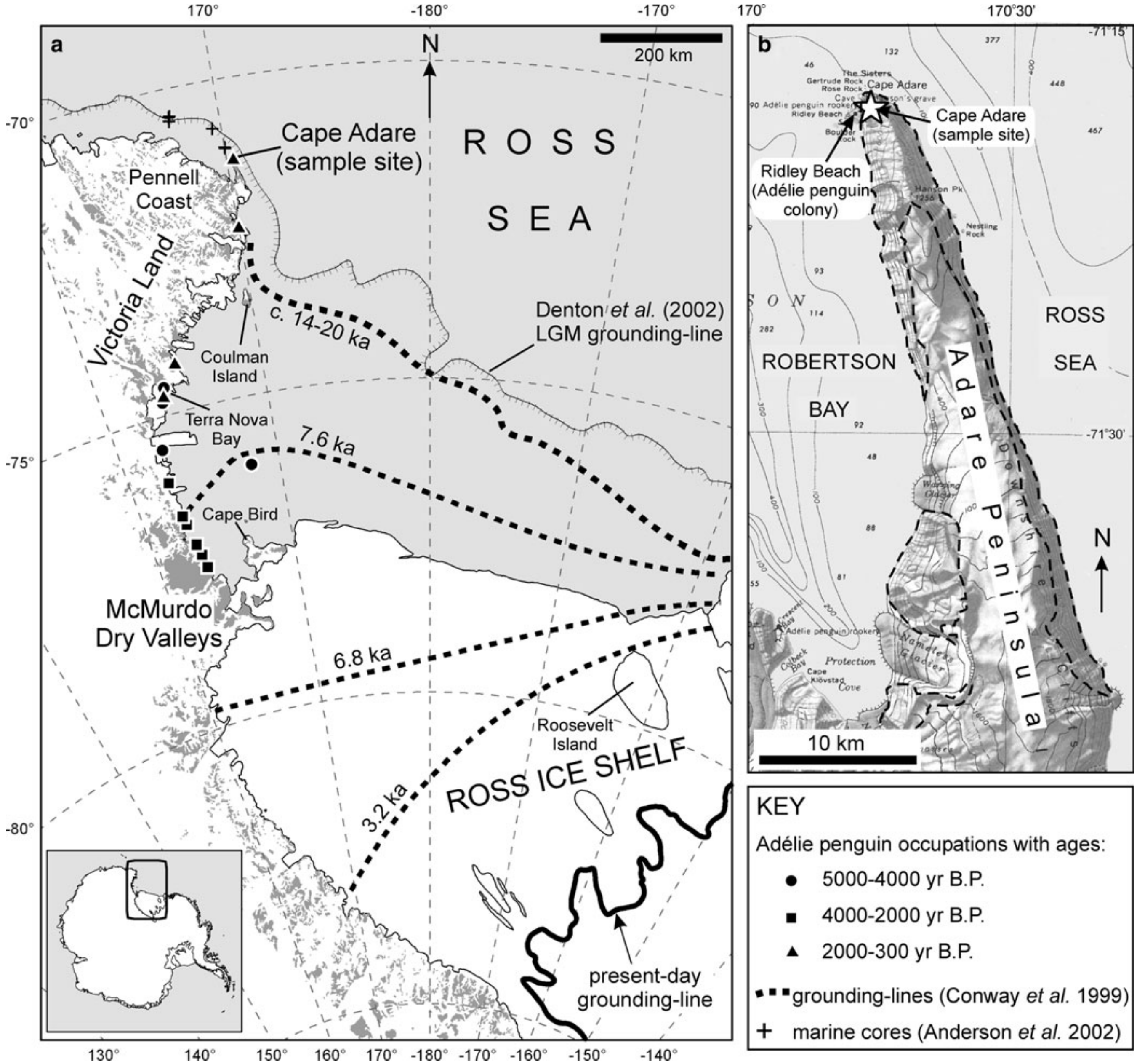

Fig. 1. a. Map of Ross Sea region, showing the sampling site at Cape Adare, location of the Pennell Coast marine sediment cores, location of Adélie penguin nesting sites with ^{14}C ages (from Emslie *et al.* 2007 and Baroni *et al.* 2007), and approximate locations of the grounding-line (after Conway *et al.* 1999 and Denton *et al.* 2002). **b.** Map of Adare Peninsula, showing Cape Adare in more detail. Contour heights/depths are in metres; present-day ice free areas are outlined with a black dashed line. We thank USGS for permission to use part of the Cape Adare 1:250 000 reconnaissance series map.

observed an abundance of erratic boulders, but due to time constraints were able to obtain just two samples (T5.31.2 and T5.31.3) from those lying on the regolith surface (Fig. 2b) at 340 m a.s.l. These boulders are composed of pale grey-green, indurated, fine-grained quartzose metasandstone derived from the Robertson Bay Group and were collected from the uppermost surfaces of boulders measuring approximately 4 m wide by 4 m long by 1.5 m high. One sample (T5.31.3) shows a conspicuously abraded surface (Fig. 2c), reflecting erosion during glacier transport. The other sample (T5.31.2) is strongly foliated (Fig. 2b). Although our dataset from Cape Adare is very limited, the exposure ages from the two samples provide important first-order constraints on ice sheet retreat in this area, about which virtually nothing is currently known.

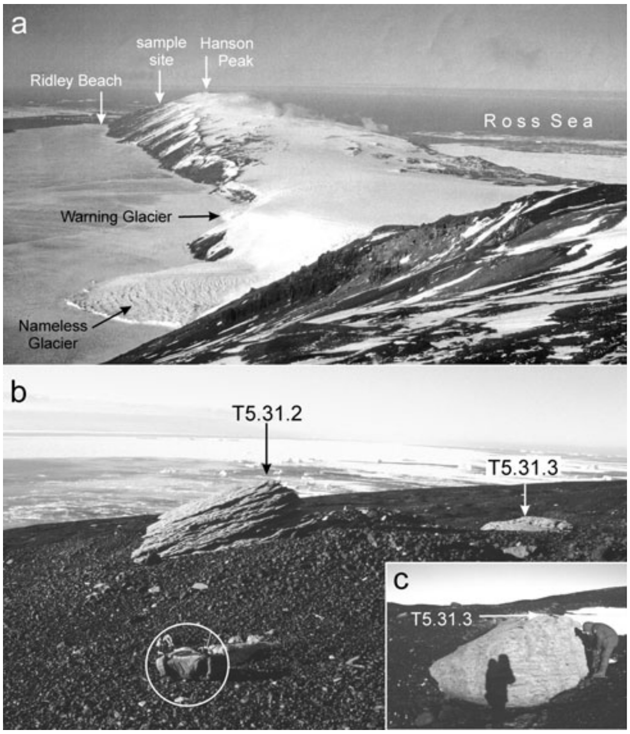

Fig. 2. Photographs of sample site at Cape Adare. **a.** View of Adare Peninsula from the south. Hanson Peak is 1256 m a.s.l. **b.** Erratic boulders (T5.31.2 and T5.31.3) lying on regolith surface. Rucksack (circled) for scale; view is looking east towards the Ross Sea. **c.** Erratic boulder T5.31.3, with abraded surface. Person for scale.

Surface exposure dating using cosmogenic nuclides

We applied the technique of surface exposure dating (using the abundance of the cosmogenic nuclide ^{10}Be in pure quartz grains separated from rock; Gosse & Phillips 2001) to our samples to determine when ice last covered Cape Adare. During glacial periods, several metres of ice may overlie bedrock and stop penetration of cosmic rays, thereby halting the production of cosmogenic nuclides within the rock. With the subsequent onset of deglaciation, debris transported within the ice and now deposited becomes exposed to cosmic radiation, and accumulation of ^{10}Be begins. Therefore, cosmogenic isotopes are a useful tool for dating deglaciation in Antarctica (e.g. Stone *et al.* 2003, Bentley *et al.* 2006, Mackintosh *et al.* 2007). We chose erratic boulders rather than bedrock for surface exposure dating because nuclide inheritance is more likely in bedrock if there has been insufficient erosion to destroy any evidence of past periods of exposure (Bierman *et al.* 1999). This is likely in the Arctic and Antarctica where high areas may have been covered by non-erosive cold-based ice (e.g. Davis *et al.* 1999). We are confident that the height of the boulders above the surrounding ground and their situation on a windy exposed surface precludes the possibility that

Table I. Exposure Ages from Cape Adare

Sample	Latitude (S)	Longitude (E)	Altitude (m a.s.l.)	Sample thickness (cm)	Topographic shielding correction	Mass quartz (g)	^{10}Be prod. rate (at g^{-1} yr^{-1})	1σ error (at g^{-1} yr^{-1})	^{10}Be conc. (at g^{-1})	1σ error (at g^{-1})	^{10}Be age* (yr)	1σ error (yr)	^{10}Be age$^{\$}$ (yr)	1σ error (yr)
T5.31.2	71º18.029'	170º14.023'	341	6	0.98188	9.7092	8.3852	0.5277	199259	9655	23895	1898	24150	1918
T5.31.3	71º18.014'	170º14.000'	343	5	0.99997	5.4823	8.6266	0.5288	139219	11392	16199	1656	16315	1668

^{10}Be age*: assuming an erosion rate of zero.
^{10}Be age$^{\$}$: assuming an erosion rate of 20 cm yr^{-1}.
Pure quartz was extracted from crushed rock samples at Edinburgh University, UK, following the procedures of Kohl & Nishiizumi (1992) and Bierman *et al.* (2002). Quartz separates were dissolved in concentrated hydrofluoric acid and spiked with 250 µg of commercially prepared Scharlab ^{9}Be carrier from a 1000 ± 5 ppm Be standard. The carrier was also added to a procedural blank. We performed perchloric acid fumes and anion exchange chromatography to remove Fe, and then extracted Be using anion exchange chromatography. Hydroxides of Be were precipitated from solution by adjusting the pH. These were then fired and mixed with Nb before packing into targets for analysis using accelerator mass spectrometry (AMS). AMS measurements were made at the Scottish Universities Environmental Research Centre, East Kilbride, UK, using the analytical standard NIST SRM 4325, which has ^{10}Be/^{9}Be = 3.06 × 10^{-11}. Measured ^{10}Be/^{9}Be ratios were corrected using the laboratory blank, which gave ^{10}Be/^{9}Be = 9.430 × 10^{-15} ± 1.135 × 10^{-15}. For calculating the exposure ages, we used ^{10}Be production rates calculated using a value of 5.1 ± 0.3 at g^{-1} yr^{-1} scaled to altitude and latitude for each site (Stone 2000). The topographic shielding correction was calculated using the online Geometric Shielding Calculator written by G. Balco (http://hess.ess.washington.edu/math/general/skyline_input.php). We used a sample density of 2.65 g cm^{-3} and an attenuation length of 160 g cm^{-3}.

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snow accumulation has shielded the samples from incoming cosmic rays since their deposition. Moreover, due to the large boulder size and gentle ground slopes, the erratic boulders are unlikely to have tumbled into position since they were first exposed by retreating ice cover. We measured the abundance of ^{10}Be in our samples to give an exposure age (see footnote to Table I for details of procedures and nuclide data).

Results and discussion

^{10}Be exposure ages

We obtained ^{10}Be exposure ages of 23.9 ± 1.9 ka and 16.2 ± 1.7 ka for samples T5.31.2 and T5.31.3, respectively (Table I). These ages were calculated assuming post-depositional erosion rates of zero. Erosion rates in Antarctica are typically very low (Nishiizumi *et al.* 1991), and in northern Victoria Land rates of 20 cm myr^{-1} have been reported (Oberholzer *et al.* 2003). Applying an erosion rate of 20 cm myr^{-1} to our samples increases the exposure ages by only 100 years (Table I); rates of this magnitude only become significant for periods of exposure in the order of several hundreds of thousands to millions of years (Ackert & Kurz 2004).

Our samples were collected from the same regolith surface, but have differing apparent exposure ages. We follow the reasoning of Bentley *et al.* (2006) and Briner *et al.* (2007) and use the youngest age (16.2 ± 1.7 ka; sample T5.31.3) as that most likely to represent the onset of the last deglaciation of Cape Adare. We suggest that the older age of sample T5.31.2 (23.9 ± 1.9 ka) represents accumulation of cosmogenic nuclides during one or more periods of exposure prior to the last deglaciation, i.e. it has a 'complex history'. In addition, the sample is foliated and may therefore have been susceptible to losing material by spalling or shedding along the foliation plane. However, this would result in a falsely young apparent exposure age, which would contradict the younger age of the non-foliated sample. Either way, the apparent age of sample T5.31.2 cannot be used to constrain the last deglaciation. We think that a complex history for the younger sample (T5.31.3) is unlikely because it shows strong abrasion that gives evidence for transport within an ice sheet. Such erosion would have removed any cosmogenic nuclides accumulated during previous periods of exposure.

Previous exposure age dating in Victoria Land

To date, numerous surface exposure ages have been published for the McMurdo Dry Valleys (Fig. 1a) of southern Victoria Land (e.g. Margerison *et al.* 2005, Staiger *et al.* 2006), but there have been relatively few for northern and central Victoria Land. However, Van der Wateren *et al.* (1999) recorded some of the oldest known glacial erosion surfaces, with ^{21}Ne exposure ages of 3.84 and 11.2 Ma for summit plateaus at 1420 m a.s.l. and 2726 m a.s.l. in central and northern Victoria Land, respectively. In addition, these authors studied the Everett Range, Admiralty Mountains (~200 km west of Cape Adare), which is, to date, the closest area to Cape Adare for which exposure ages exist. Two bedrock samples from there yielded ^{10}Be–^{26}Al dates of ~100 ka and ~400 ka, with no evidence for pre-exposure. In the Terra Nova Bay region of central Victoria Land (Fig. 1a), Oberholzer *et al.* (2003) used surface exposure dating to show that the summits of the Deep Freeze Range have not been glacially-modified since 5.3 Ma, and that erosion rates since then have been very low (~17 to 23 cm myr^{-1}). There were, however, limited glacier advances at lower elevations in the region around 309 ka and 34 ka. The reported deglaciation ages are all much older than our deglaciation age of 16.2 ka, but the samples were taken from much higher elevations and several hundred kilometres away from Cape Adare, so are not directly comparable.

Ice sheet configuration in northern Victoria Land during the last glacial period

In order to evaluate how our exposure age for Cape Adare fits into the broader picture of ice sheet expansion and retreat in the Ross Sea and Victoria Land regions during and after the last glacial period (Fig. 1a), we need to take into account the configuration of the East Antarctic Ice Sheet (EAIS) at that time. Today the Ross Sea embayment is fed by ice draining from both the EAIS and the West Antarctic Ice Sheet. During the last glacial period, the EAIS flowed through the Transantarctic Mountains to provide a significant amount of ice to the central and western Ross Sea (Farmer *et al.* 2006, Licht *et al.* 2005). Although these reconstructions do not explicitly show it, we envisage that any ice that overrode Cape Adare would have come from the EAIS.

To the south-west of Cape Adare, a study of ice sheet dynamics close to the Rennick Glacier suggested minimal variation in the surface elevation of the EAIS since 3.5 Ma (Oberholzer *et al.* 2008). However, there is no information about the onshore EAIS configuration during the last glacial period. Anderson *et al.* (2002) studied subglacial and glaciomarine sediments deposited since the last glacial period at the Pennell Coast, offshore from northern Victoria Land (Fig. 1a). The authors concluded that grounded ice had extended at least to the middle shelf during the last glacial period, and began its retreat prior to 12.0 ^{14}C ka BP (marine reservoir corrected) and probably by 14.3 ^{14}C ka BP (marine reservoir corrected). [Reservoir corrected radiocarbon dates are not equivalent to calendar ages (as surface exposure dates are) because the rate of radiocarbon production in the atmosphere has not been constant through time. This means that, for direct comparison, radiocarbon dates are usually calibrated. This may be done using one of a variety of calibration programs; to avoid variation in the methods of calibration, we have reported only uncalibrated dates here.] This grounding-line position agrees with that reconstructed for northern Victoria Land in the models of Denton *et al.* (1991) and Denton & Hughes (2002; Fig. 1a). We consider that the radiocarbon dates of the marine sediments only provide a minimum age for the grounding-line retreat, so it may have reached its maximum position at the Pennell Coast either several thousand years, or only a few years, earlier than 14.3 ka. South of Cape Adare, the grounding line of the Ross Ice Sheet was located approximately 60 km north of Coulman Island during the last glacial period, and began its retreat southwards at about 14 ka (Bindschadler 1998, Conway *et al.* 1999, Domack *et al.* 1999, Shipp *et al.* 1999, Licht & Andrews 2002, Licht 2004), reaching Roosevelt Island around 3.2 ka (Conway *et al.* 1999; Fig. 1a). The location of the grounding-line around Cape Adare itself has been extrapolated between Coulman Island and the Pennell Coast, without sediment core data being available to accurately constrain its position (e.g. Anderson *et al.* 2002, fig. 3b and 13).

Deglaciation of Cape Adare

We obtained an exposure age (16.2 ± 1.7 ka) from an erratic boulder lying on a surface 340 m a.s.l. at Cape Adare, which we interpret as probably representing deglaciation of this surface. It therefore follows that the surface was ice free (i.e. not overridden by an ice sheet) from 16.2 ± 1.7 ka onwards. At 16.2 ka, the ice sheet had either thinned locally to expose the surface at 340 m a.s.l., or had retreated landward from Cape Adare. Local ice sheet thinning would not preclude the possibility that grounding-line retreat in the western Ross Sea and along the Pennell Coast started up to a few thousand years later (as inferred from the marine data). Deglaciation ages from coastal regions of East Antarctica range from 10 to 45 ka BP and therefore suggest that the Last Glacial Maximum (LGM) occurred at different times at different locations in Antarctica (Wagner *et al.* 2004). More widespread thinning around Cape Adare, however, would not have been possible without grounding-line retreat from the nearby shelf (the ice sheet would need to be sufficiently thick to maintain its grounding-line position on the shelf). If the EAIS retreated from Cape Adare at 16.2 ka, this would imply that the grounding-line also started to retreat from the shelf off the Pennell Coast and the western Ross Sea at this time, which is slightly earlier than the deglaciation ages inferred from the marine sediments.

Adélie penguin colonization in the western Ross Sea

In the Ross Sea region, radiocarbon dates from Adélie penguin remains (such as bones, tissue and eggshell) have been used to constrain the chronology of deglaciation (e.g. Baroni & Orombelli 1994, Emslie *et al.* 2003, 2007). Adélie penguins are thought to colonize soon after ice free terrain becomes available following ice sheet retreat (Ainley 2002), and some authors have implied that ages from abandoned penguin colonies may thus be considered deglaciation ages (e.g. Emslie 2001).

Contrary to what has been reported in some papers (Ingólfsson *et al.* 1998, Cunningham *et al.* 1999, Licht *et al.* 1999), ^{14}C ages from penguin colonies at Cape Adare were first published by Emslie *et al.* (2007). Ornithogenic soils from five sites at Cape Adare were sampled and dated: two mounds on the beach and three abandoned sites on a terrace 285–319 m above the beach. Dates from bone and eggshell at these sites vary from 1980 ± 60 to 3090 ± 40 ^{14}C yr BP (uncorrected). At the terrace site, the dates are 2140 ± 40 to 2890 ± 50 ^{14}C yr BP (uncorrected). The dates from the mounds near sea level are hard to interpret because there is no information about the relative sea level history of the area. A comparison of the colonization ages of the terrace with our exposure age for Cape Adare reveals a time period of at least 11.5 kyr between deglaciation (16.2 ± 1.7 ka) and the onset of penguin colonization (2–3 ka). The large age difference suggests that penguins did not colonize until a few thousand years after Cape Adare became ice free.

Adélie penguins have nested in the Ross Sea continuously since *c.* 7200 ^{14}C yr BP (uncorrected), and prior to that between *c.* 27 000 and 45 000 ^{14}C yr BP (uncorrected), but it is not known where they nested during the last major ice advance (Ainley 2002, Emslie *et al.* 2007). A glacial refuge for Adélie penguins must have been a place that was exposed when much of the coast of Antarctica was covered with ice (Ainley 2002, Emslie *et al.* 2007), and that permitted at least seasonal access to open water (e.g. via polynyas, Thatje *et al.* 2008). Ainley (2002, chapter 9) speculated that Cape Adare could have been such a refuge. However, our exposure age demonstrates that Cape Adare was overridden by ice before 16.2 ka, making this highly unlikely. Extensive sampling and dating of ornithogenic soils from elsewhere in the Ross Sea embayment shows that there are probably no sites in this region that were ice free between *c.* 27 and 14 ka. Therefore, Adélie penguins probably nested elsewhere at that time. Ice free sub-Antarctic islands (e.g. the Balleny Islands or South Georgia; Ainley 2002, Emslie *et al.* 2007) may have been potential sites. In the future, samples for surface exposure dating should be collected from sub-Antarctic islands in order to determine if they could have been refuges for penguins during the last glacial period.

Conclusions

We have reported the first cosmogenic surface exposure ages from Cape Adare. This is the first time that surface exposure ages have been compared with radiocarbon dates of ornithogenic soils from the same locality to give first-order constraints on ice sheet retreat history. Our results suggest that Cape Adare was covered by ice during the last glacial period, but became ice free around 16.2 ka. The deglaciation occurred by either local thinning of the ice sheet or landward retreat of its grounding-line.

We compared our surface exposure age with dates for Adélie penguin occupation at Cape Adare, and found that there was a period of at least 11.5 kyr between deglaciation (at 16.2 ± 1.7 ka) and the onset of penguin colonization (2–3 ka). This suggests that penguins probably did not colonize Cape Adare until several thousand years after ice free ground became available there. Our results confirm that penguin colonization dates provide only minimum ages for deglaciation and should not be used in isolation to indicate the onset of ice free conditions.

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