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Late-Holocene initiation of ice-free ecosystems in the southern Ross Sea, Antarctica

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ABSTRACT: New data on marine sediments, seawater paleotemperatures, and the occupation history of Adélie penguins indicate that modern ice-free conditions in the southern Ross Sea developed only within the last 1000 yr. Here we show that penguins permanently abandoned the southern Victoria Land Coast 2000 yr ago when extensive sea-ice cover blocked access to ice-free terrain for breeding. The first colonization of Ross Island in East McMurdo Sound, where over 300 000 penguins breed today, did not commence until after 1170 yr BP when coastal areas became exposed from under the Ross Ice Shelf. Our results demonstrate that investigations of abandoned penguin colonies can provide increased resolution to Holocene paleoclimatic records and paleoceanographic conditions in Antarctica.

KEY WORDS: Antarctica · Adélie penguins · Late Holocene · Paleoclimate · Ross Sea · Sea ice

INTRODUCTION

The Adélie penguin *Pygoscelis adeliae* is well known as an ice-obligate indicator species that is sensitive to environmental change (Trivelpiece et al. 1990, Smith et al. 1999, Wilson et al. 2001, Ainley 2002). Over 744 000 breeding pairs, or 30% of the world population, occur on the Victoria Land Coast bordering the Ross Sea (Ainley 2002), one of the southernmost marine ecosystems on Earth. Adélie penguins require open water near their breeding colonies, with no more than 2 to 3 km of persistent fast ice that must be crossed on foot to reach ice-free terrain; any additional fast ice, especially lacking tide cracks associated with grounded icebergs, and colonies are very small or absent (Watanuki et al. 1997, Ainley 2002). All extant colonies on Ross Island (see Fig. 1), the largest occupied area in the southern Ross Sea (defined as the area south of the Drygalski Ice Tongue, 75° 24′ S), are near open water, and penguins appear to respond quickly when new areas become accessible with a shift in sea-ice conditions (Wilson et al. 2001, Ainley 2002).

Current penguin distribution patterns in the southern Ross Sea result from meterologic and oceanographic conditions that produce persistent open water in East McMurdo Sound, in contrast to the multi-year fast ice that persists in West McMurdo Sound (Dayton & Oliver 1977, Barry & Dayton 1988). In East McMurdo Sound, wind conditions (Stonehouse 1967, Ainley 2002) and warm, southward-moving currents and ocean swells from the Ross Sea influence the annual break-up of sea ice, which in turn leads to eutrophic marine communities adjacent to penguin colonies on Ross and Beaufort Islands. In West McMurdo Sound, supercooled currents moving northward from under the McMurdo Ice Shelf promote multi-year fast ice, which leads to oligotrophic marine communities and a lack of penguin colonies along the adjacent mainland (Dayton & Oliver 1977, Barry & Dayton 1988).

Preserved organic remains from ornithogenic soils at abandoned penguin colonies, recognized by accumulations of juvenile penguin bones, eggshell fragments, nest pebbles, and guano on the Victoria Land Coast, provide evidence for past occupations by Adélie pen-

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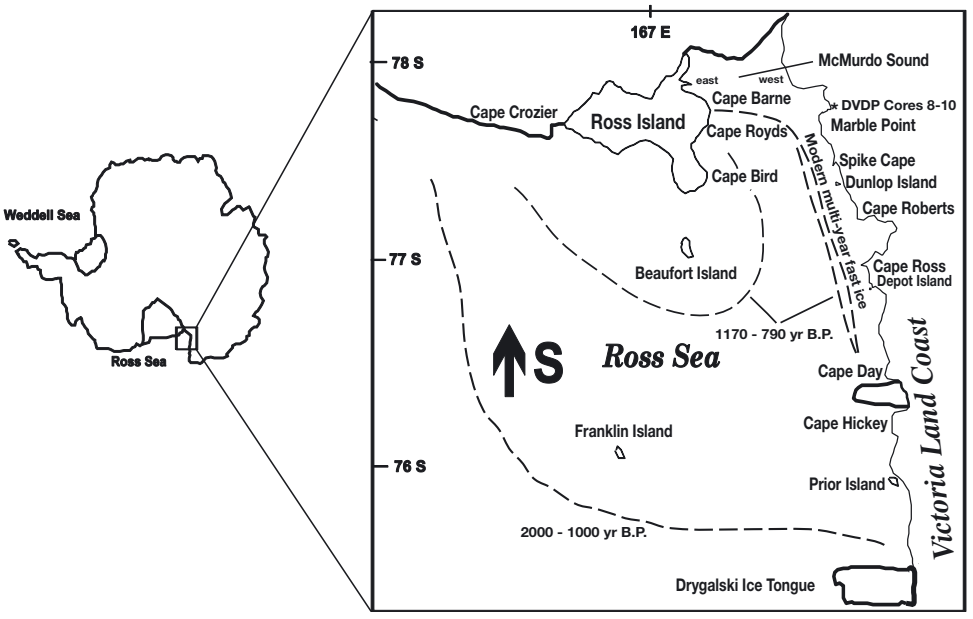

Fig. 1. Map of Antarctica showing the location of the Victoria Land Coast and Ross Island (in box) with detail of the southern Ross Sea and sampling locations (named capes and islands) discussed in the text. The location of the Dry Valley Drilling Project (DVDP) Cores 8 to 10 in a prograding delta at the mouth of Taylor Valley, west McMurdo Sound, is also provided. Bold lines indicate ice tongues and the edge of the Ross Ice Shelf; bold dashed lines represent proposed extent of permanent or multi-year fast ice at 3 time periods including modern, 1170 to 790 yr BP, and 2000 to 1000 yr BP. This last period is when permanent abandonment of the southern Victoria Land Coast occurred, and predates the first occupation of Ross Island by breeding penguins

guins (Baroni & Orombelli 1994, Lambert et al. 2002). These data also indicate that populations north of the Drygalski Ice Tongue have remained relatively stable since the mid-Holocene (Berkman et al. 1998). This stability is due in part to the presence of the Terra Nova Bay, Passage, and Ross Sea polynyas, which developed after retreat of the West Antarctic Ice Sheet (WAIS) 7600 yr ago, based on dates from Cape Bird, Ross Island, and Franklin Island (Conway et al. 1999, but see also Andrews et al. 2002). The grounding line of WAIS had retreated to the south of Cape Ross and Ross Island, and southward along the continental coast to Hatherton Glacier (80° S), by 6800 yr ago (Licht et al. 1996, Conway et al. 1999, Hall & Denton 1999). In contrast to the northern penguin colonies, those south of the Drygalski Ice Tongue apparently have been alternately occupied and abandoned in conjunction with shifts in ocean circulation and persistence of fast ice that influenced penguin access to ice-free terrain.

MATERIALS AND METHODS

To further investigate the occupation history of Adélie penguins in the southern Ross Sea, we sampled 13 abandoned and 3 active colonies at Marble Point and named capes and islands along the Victoria Land Coast, and at 4 capes on Ross Island, in 2001 (Fig. 1, Table 1, Appendix 1). At each site we excavated 1 × 1 m test pits in 5 cm levels. Excavations ceased when bedrock or the bottom of the ornithogenic soils (recognized by a change in sediment texture and color) was reached. The pit was then backfilled. All sediments were screened through 3 fine-mesh sieves (mesh sizes, from top to bottom, of 0.64, 0.32, and 0.025 cm^2) to recover most organic remains preserved in these sites. Thirty-six samples of penguin bone, eggshell and feather fragments recovered from these excavations were submitted for radiocarbon analysis. In addition, 83 previously published radiocarbon dates on Adélie penguin remains from this region were recalibrated for comparison to our data (Table 1, Appendix 1; see below).

Due to upwelling of old carbon in Antarctica, all radiocarbon dates must be adjusted for the marine-carbon reservoir effect. There so far exists no simple or reliable method for correcting these dates, especially given the diversity of materials that often are dated (e.g. marine plants, vertebrates, and calcareous fossils). This problem has received much attention (e.g. Björck et al. 1991, Gordon & Harkness 1992, Berkman & Foreman 1996, Andrews et al. 1999, Domack et al. 1999a), and will not be easily resolved. Here, methods to adjust a conventional radiocarbon-derived age of penguin remains include either (1) subtracting a predetermined number of years from all dates, or (2) cor-

recting and calibrating each date using a ΔR (reservoir) value that incorporates changing differences in reservoir effects between the atmosphere and ocean through time (Stuiver et al. 1986, 1998). Method 1 provides a corrected date in radiocarbon years, while Method 2 produces a date calibrated to 'calendar years before present' (yr BP). Both methods are based on radiocarbon dates obtained on modern (before nuclear testing, pre-1950) specimens of marine organisms that yield ages from 100s to >1000 yr due to ingestion of old carbon during life.

Sediments and calcareous marine fossils that were deposited along the coast in West McMurdo Sound were interpreted from the Dry Valley Drilling Project (DVDP) Cores 8 to 10, which were extracted from the same hole at the base of Taylor Valley (Fig. 1). Radiocarbon dates on calcareous marine fossils recovered from DVDP Cores 8 to 10 were corrected by subtracting 1300 yr from the conventional date, following the method of Berkman & Forman (1996). Calcitic Antarctic scallop *Adamussium colbecki* fossils were further selected for stable oxygen-isotope analyses (Klein et al. 1996) because they represent a comparable paleoecological and geochemical framework to interpret ambient oceanographic conditions through time. Estimated seawater paleotemperatures, based on the $\delta^{18}O$ values (±0.1‰), were derived according to the equations of Craig (1965).

Unless otherwise stated, all radiocarbon dates listed herein from ice cores, debris bands, marine sediments, and calcareous fossils from the published literature (as referenced) are corrected to radiocarbon yr BP (for details on how these dates were corrected, see referenced literature). We assume these corrected dates roughly correspond to our calibrated ages for the penguin remains presented below. We do not consider our correlations between corrected dates versus calibrated dates to be a problem, as discrepancies between them are minimal for material dating to the mid- to late Holocene (Stuiver et al. 1998).

Table 1. *Pygoscelis adeliae.* Calibrated 2σ ranges (in calibrated yr BP) of radiocarbon dates on Adélie penguin remains from 16 sites in the southern Ross Sea, Antarctica. These ranges give maximum and minimum ages for occupation of these sites by breeding penguins based on 119 dates (see online Table 1 for data and references on each date). Multiple ranges are provided for those sites where gaps existed in the radiocarbon record, indicating a site was occupied and abandoned repeatedly in the past. Dates considered to be anomalous are not included in this table. Complete dataset published as Appendix 1, MEPS Electronic Supplement www.int-res.com/journals/suppl/emslie_appendix.pdf

Site	2σ calibrated range (yr BP)	
	Max.	Min.
Beaufort Island	328	0
Cape Barne	1170	0
Cape Royds	947	0
Clear Lake	878	492
Cape Bird	889	0
	4487	2299
Cape Crozier	617	0
Peninsula by Depot Island	4080	2059
Cape Roberts	3441	2694
Spike Cape	5615	5071
Cape Ross	4502	2870
Dunlop Island	6187	2310
Franklin Island	705	468
	2293	1813
	4960	4601
Marble Point	3861	1865
Prior Island	1351	515
	4618	3607
	5585	5276
Cape Day	3676	3026
Cape Hickey	3816	2291
	7434	7171
	15305	9544

RESULTS

The 119 radiocarbon dates on penguin remains indicate that Adélie penguins first occupied the southern Ross Sea beginning at 6000 to 5000 yr BP, though dates from Cape Hickey suggest that an early occupation may have occurred during the late Pleistocene from approximately 10 000 to 15 000 yr BP (Table 1). Occupations during the mid-Holocene occurred only along the continental margin, following the retreat of the WAIS (Licht et al. 1996, Conway et al. 1999, Domack et al. 1999b, Hall & Denton 1999). This initial influx of penguins occurred gradually along the Victoria Land Coast with Dunlop Island occupied first (Fig. 1). By 4000 to 3000 yr BP, during a warming period known as the 'penguin optimum' (Baroni & Orombelli 1994), the occupation extended southward to Marble Point and lasted until 2288 to 1865 yr BP (2σ calibrated range), when all sites were permanently abandoned on this southern coast. One date from Franklin Island (2293 to 1813 yr BP) also extends to this latest age of abandonment (Table 1).

The permanent abandonment of the southern Victoria Land Coast was followed by the first known colonization of Ross Island at 1170 to 790 yr BP, when Cape Barne was occupied by an estimated 3000 to 4000 breeding pairs. This estimate is based on the size of the abandoned area compared to modern Adélie penguin colonies (Fig. 1). Subsequently, Cape Royds, 3 km north of Cape Barne, was occupied at 947 to 653 yr BP. A slightly younger buried soil at Cape Bird (797 to 530 yr BP), containing hundreds of feather but no

eggshell fragments, may have formed while this area was used as a molting site rather than a breeding colony. However, by approximately 600 to 500 yr BP, the colonies at Cape Bird and Cape Crozier had formed and are composed today of over 300 000 breeding birds (8% of world population), with the latter colony being the fifth largest Adélie penguin colony in Antarctica (Woehler 1993, Ainley 2002). Two dates from Prior Island, ranging from 1351 to 815 yr BP, indicate that more northern colonies were also ice-free in the early stages of this most recent colonization event (Table 1).

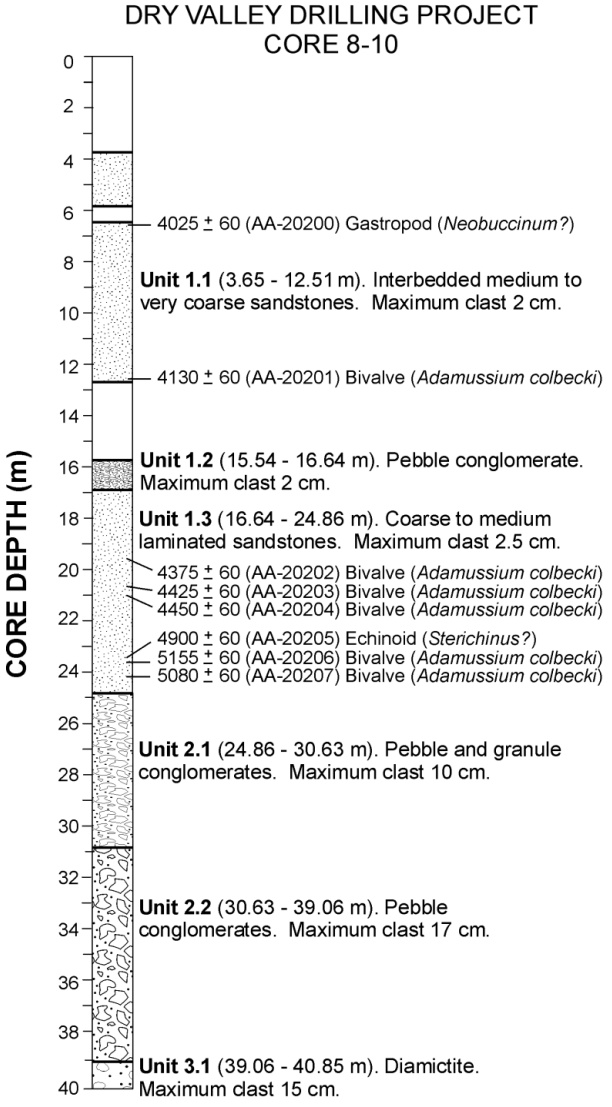

Fig. 2. Sediment profile (depths in m) from the Dry Valley Drilling Project (DVDP) Cores 8 to 10 (see Fig. 1), with uncorrected radiocarbon ages for calcareous marine fossils. Laboratory numbers (AA) for each date from the University of Arizona Radiocarbon Lab. Sedimentary deposits were characterized by McKelvey (1981). Modified from Berkman & Tipton-Everett (2001)

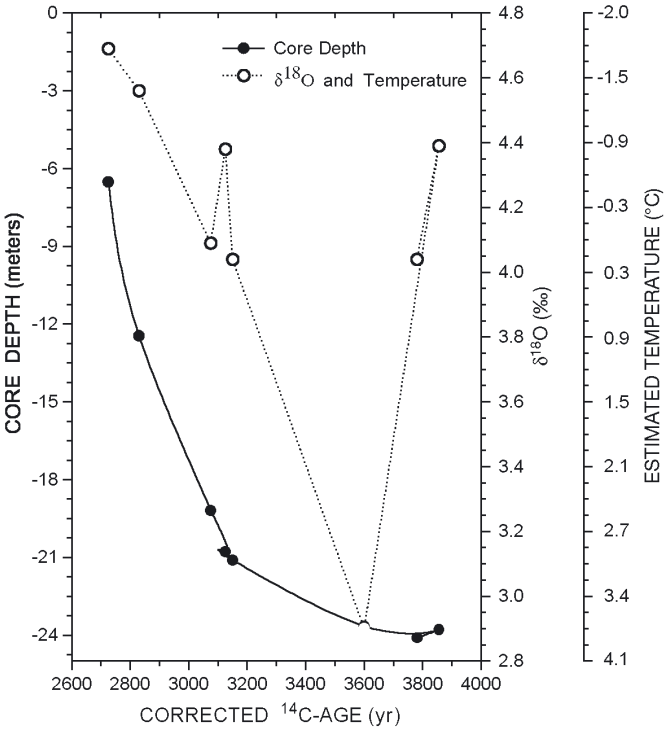

Fig. 3. Radiocarbon ages of Antarctic scallop *Adamussium colbecki* shell fragments, at various depths from DVDP Cores 8 to 10 (Figs. 1 & 2), which were corrected in relation to the 1300 yr radiocarbon reservoir age of the Southern Ocean (Berkman & Forman 1996). Corresponding oxygen-isotope $\delta^{18}O$) values and estimated seawater paleotemperatures from the Antarctic scallop fragments at the various core depths are plotted against these corrected radiocarbon ages

Holocene sediments in DVDP Cores 8 to 10 were fine-grained sands as opposed to the underlying larger clasts that were associated with the high-energy coastal environment that existed prior to the mid-Holocene (McKelvey 1981). Uncorrected radiocarbon dates ranged from 5155 ± 60 to 4025 ± 60 yr BP at approximately 24.1 to 6.5 m depth, respectively (Fig. 2). Corrected radiocarbon ages of the fossil fragments indicate that sediment accumulation rates were relatively low, from 3900 to 3100 yr BP, and that they increased markedly afterwards. Oxygen isotope ratios from the fossil carbonates further indicate that there was a relatively warm interval between 3900 and 3100 yr BP (Fig. 3), with a subsequent shift toward cooler temperatures, reaching modern seawater values for West McMurdo Sound at ~2700 yr BP.

DISCUSSION

Supportive data for the recent development of ice-free ecosystems in the southern Ross Sea exists in the

hydrological (ice-core), geological and glaciological records of East Antarctica (Ingólfsson et al. 1998). The Dome C ice core, for example, indicates a warming period from 4000 to 2500 yr BP, followed by a cooling period that may have caused extensive sea-ice cover to return until ~1000 yr BP (Lorius et al. 1979). The Taylor Dome ice core records a climatic shift beginning ~6000 yr BP reflected in the increased and highly variable methanesulfonic acid concentrations associated with marine primary production and sea-ice coverage (Steig et al. 1998, 2000). These continental ice-cores may not reflect the same climate trends as in the Ross Sea, but debris bands on the McMurdo Ice Shelf also have indicated that southern McMurdo Sound was filled with grounded ice until 7750 yr BP. This ice retreated and left an ice shelf at Black Island by 6600 yr BP (uncorrected radiocarbon yr; Kellogg et al. 1990). Marine sedimentary deposits of diatoms further indicate that there was regional warming from 6000 to 3000 yr BP (Cunningham et al. 1999), with high concentrations of organic carbon in the SE Ross Sea from 5000 to 3000 yr BP (Licht et al. 1998). This warming period was followed by a distinct decrease in carbon deposition, from 3 to 4 g cm^{-2} yr^{-1} in the mid-Holocene, down to 1 to 2 g cm^{-2} yr^{-1} from ~2000 to 1000 yr BP, in the SE to central Ross Sea (Jacobson 1997), a result consistent with the presence of more concentrated sea-ice and lower marine primary productivity. The carbon flux increased again to 2 to 3 g cm^{-2} yr^{-1} at ~1300 to 1000 yr BP when, apparently, ice-free marine conditions returned in the southern Ross Sea. Dry Valley lake records also support a warming period, with an increase in lake levels beginning ~1200 to 1000 yr BP (Lyons et al. 1998, 1999).

New radiocarbon analyses, along with stable isotope measurements from calcareous marine fossil fragments in the uppermost section of the DVDP Cores 8 to 10, further constrain the oceanographic conditions in the southern Ross Sea during the late Holocene (Figs. 2 & 3). The warming interval at 3900 and 3100 yr BP, which is reflected by the $\delta^{18}O$ values of *Adamussium* fragments, coincides with the 'penguin optimum' previously discussed (Baroni & Orombelli 1994). However, the subsequent cooling occurred during a period when sand accumulation was increasing in the prograding delta adjacent to the meltwater streams at the mouth of Taylor Valley (Fig. 1). The simplest explanation for increased accumulation of sands during the cooling period after 3100 yr BP is that increased sea-ice concentrations insulated the beaches from high-energy wave erosion.

On a broader scale, marine sedimentary data from the Antarctic Peninsula also indicate a cooling period, with a re-advance of the Larsen Ice Shelf, beginning at ~2500 yr BP (Leventer et al. 1996, Domack et al. 2001). This cooling corresponds with the Neoglacial in the northern hemisphere, a period that ended with the onset of the Medieval Warm Period at 1000 yr BP (McDermott et al. 2001) when Ross Island was first occupied by breeding penguins.

Abandonment of the entire southern Ross Sea by penguins from ~2000 to 1000 yr BP, from what we now know about present population dynamics, may not be unusual. For penguins in the southern Ross Sea, the most parsimonious explanation for large-scale abandonment or absence is that persistent sea ice inhibited access to colonies. The importance of this factor has been demonstrated recently (since the 2001–2002 austral summer) when Icebergs B-15A and C-16 grounded off the north side of Ross Island, thereby blocking southward moving currents which, combined with light winds, has led to increased persistence of fast ice and concentrated pack-ice through the summer in most of East McMurdo Sound (Arrigo et al. 2002, D.G.A. & G. Ballard unpubl. data). This sea ice has hindered access of penguins to Cape Royds and Cape Bird, and severely decreased the breeding population size and reproductive success at these colonies. It appears that, if this condition persists, these large colonies may soon be abandoned.

Ongoing occupation of Adélie penguins on Ross Island after 1170 yr BP, while their colonies have remained abandoned along the Victoria Land Coast, further indicates that the modern sea-ice and oceanographic conditions that contrast across McMurdo Sound (Stonehouse 1967, Barry & Dayton 1988) have existed, at least in the late Holocene, only during the last millennium. Adélie penguin numbers have shifted considerably over millennia in response to changing climate and sea-ice conditions, and long-term climate change, as it affects sea-ice extent, probably has been the most important factor in controlling distributions of Antarctic penguins (Ainley 2002, see also Emslie 2001). Our results demonstrate that data from abandoned and extant penguin colonies can provide increased resolution to the Holocene paleoclimatic record as revealed in sediment and ice cores, and that integration of biological, geological, and hydrological data are in accord with the occupation record of penguins in the southern Ross Sea.

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versity of Arizona. Oxygen isotope analyses were conducted in the Department of Geological Sciences, University of Michigan. The paper was improved with comments from 4 anonymous reviewers.

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