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Radiocarbon dates from abandoned penguin colonies in the Antarctic Peninsula region

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Abstract: Sixty-three radiocarbon dates on organic remains from 21 abandoned colonies of chinstrap (*Pygoscelis antarctica*) and Adélie (*P. adeliae*) penguins on 12 islands in the Antarctic Peninsula region are evaluated for determining the occupation history of penguins in this region. This record also provides a means for assessing sea-level change, glacial advances and retreats, and population responses by penguins to these events. All conventional dates were corrected for the marine-carbon reservoir effect by applying a $\Delta R = 700 \pm 50$ BP and marine calibration curves. The 63 calibrated dates give 2σ ranges (95% confidence intervals) from modern to 5990 yr BP. These dates indicate progressively older occupations from north to south along the Antarctic Peninsula. No sites older than approximately 540 BP occur in the northern peninsula, either because they have not yet been found or older sites have been destroyed by solifluction and glacial scouring. Three dates from one locality near Rothera Point, Adelaide Island, also were calibrated with a $\Delta R = 750 \pm 50$ and 800 ± 50 BP. No difference was found between calibrated dates using these two other ΔR values, indicating that local corrections for variation in upwelling intensity may not be necessary.

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Key words: abandoned colonies, Adélie penguin, chinstrap penguin, occupation history, radiocarbon dates

Introduction

Abandoned penguin colonies in Antarctica provide a source of well-preserved organic remains that date from hundreds to thousands of years old. These remains not only include bones, tissue, and eggshell fragments of penguins that once occupied these sites, but also hard parts from their prey that accumulated in the sediments from penguin guano. The high concentration of these organic remains in ornithogenic soils allows study of the occupation history and diet of penguins in the past. A radiocarbon chronology of the abandoned sites also can be compared to the palaeoclimatic record in Antarctica, based on ice cores and marine sediments, to investigate ecological responses by penguins to episodes of climate change (Smith *et al.* 1999).

Early research on abandoned colonies concentrated on nutrient cycling and chemistry of the ornithogenic soils that characterize these deposits (Ugolini 1972, Speir & Heine 1982, Speir & Cowling 1984, Speir & Ross 1984, Myrcha *et al.* 1985, Tatur 1987, 1989, Heine & Speir 1989, Tatur & Myrcha 1989, Tatur *et al.* 1997). These soils were first identified and described in the Antarctic by Syroechkovsky (1959) and Tedrow & Ugolini (1966) (see also discussion by Campbell & Claridge 1987). Other studies on abandoned colonies have concentrated on the occupation history of penguins and palaeoclimatic inferences as obtained from radiocarbon dates of bones from ornithogenic soils (Harrington & McKellar 1958, Spellerberg 1970, Stonehouse 1970, Bochenski 1985, Moors *et al.* 1988, Baroni & Orombelli 1991, 1994, Smith *et al.* 1999), or on biochemical analyses of ancient guano in lake sediments (Zale 1994a, Sun *et al.* 2000). Palaeodietary studies and taphonomy of bone deposits in abandoned colonies of chinstrap (*Pygoscelis antarctica* Forster) and Adélie (*P. adeliae* Hombron & Jacquinot) penguins were initiated by Emslie (1995) and Emslie *et al.* (1998) in the Antarctic Peninsula region.

Accurate interpretation of data from abandoned colonies is dependent on the radiocarbon chronology obtained from organic remains recovered from these sites. Numerous methods have been proposed for correction and calibration of radiocarbon dates of marine organisms in Antarctica, necessary due to the marine-carbon reservoir effect (Harkness 1979, Björck *et al.* 1991, Gordon & Harkness 1992, Emslie 1995, Berkman & Forman 1996, Berkman *et al.* 1998). These methods adjust the conventional radiocarbon age by either subtracting a pre-determined number of years from all dates, or by applying a correction and calibration to each date using a ΔR value that incorporates changing differences in reservoir effects between the atmosphere and ocean through time (Stuiver *et al.* 1986, 1998). The former method provides a corrected date in radiocarbon years, while the latter produces a date calibrated to calendar years BP. Both methods are based on radiocarbon dates obtained on modern (pre-1950) specimens of marine organisms that yield ages from 100 s to > 1000 years due to ingestion of old carbon during life. Here, I examine 60 radiocarbon dates on pygoscelid penguin bone, tissue, and prey remains, and three on ornithogenic sediments, from abandoned colonies in the Antarctic Peninsula region. These dates are assessed for their accuracy in estimating the

Table I. Radiocarbon dates (in years BP) on penguin (*Pygoscelis* sp.) bone collagen, eggshell carbonates, or dried dermal tissue and squid (*Psychroteuthis glacialis* Thiele) beaks from test pits (TP) in abandoned colonies or modern (pre-1950) sites. Conventional dates were corrected and calibrated for the marine-carbon reservoir effect using a $\Delta R = 700 \pm 50$ years (see Emslie 1995) and the MARINE98 database of Stuiver & Reimer (1993). The conventional date, mean corrected date (both in radiocarbon years BP), and calibrated 2σ range(s) (95% confidence interval in calendar years BP) are provided for 60 samples from 21 sites on 11 islands. Three dates on modern specimens also are provided. Multiple 2σ ranges are provided for corrected dates that intersected two or more regions of the calibration curve. All dates are from Emslie (1995) and Emslie *et al.* (1998) except for UA 1033 (C. Hjort, personal communication 1997), Lu-3101 from Björck *et al.* (1991), and SRR-3784, SRR-3785, and SRR-3786 (R.I. Lewis Smith, personal communication 2001). Dates from the Rothera area and Rothera Point are provided here for the first time. Levels are 5–10 cm deep beginning with level 1 at the surface (0–5 cm) of each test pit (TP) excavated at each site.

Site/sample	Species	Material	Laboratory number	Conventional date	Corrected date	Calibrated range (2σ)
King George Island						
Uchatka, TP 1, level 1	*Pygoscelis* cf. *P. antarctica*	bone	CAMS 15626	1300 ± 70	600 ± 85	425–40 or 35–0
	P. antarctica	bone	CAMS 15629	1280 ± 60	580 ± 80	405–40 or 35–0
level 2	*P. antarctica*	bone	CAMS 15625	1380 ± 60	680 ± 80	475–135
	Pygoscelis cf. *P. antarctica*	bone	CAMS 15628	1350 ± 50	650 ± 70	445–130
	cf. *Pygoscelis* sp.	bone	CAMS 15644	1340 ± 60	640 ± 80	450–80
level 3	*Pygoscelis* sp.	bone	CAMS 14609	1330 ± 70	630 ± 85	450–55 or 15–0
Blue Dyke, TP 1, subsurface	*P. antarctica*	bone	CAMS 15624	1330 ± 60	630 ± 80	445–65 or 5–0
	P. antarctica	bone	CAMS 14821	1500 ± 60	800 ± 80	540–280
Low Head, surface	*P. antarctica*	bone	CAMS 15627	1410 ± 60	710 ± 80	495–235
	P. antarctica	bone	CAMS 14817	1440 ± 60	740 ± 80	510–255
Penguin Island						
surface	*Pygoscelis* cf. *P. adeliae*	bone	CAMS 14815	1420 ± 60	720 ± 80	500–240
Seymour Island						
surface	*Pygoscelis* cf. *P. adeliae*	bone	CAMS 14814	1460 ± 60	760 ± 80	520–265
	Pygoscelis cf. *P. adeliae*	bone	CAMS 15623	1490 ± 60	790 ± 80	535–275
Devil Island						
surface	*P. adeliae*	bone	UA 1033	1425 ± 80	725 ± 95	515–145
TP 1, level 3	*P. adeliae*	bone	Beta 143249	1480 ± 40	780 ± 65	515–285
Litchfield Island						
site 1, TP 2, level 1	*P. adeliae*	bone	CAMS 42001	1380 ± 50	680 ± 70	465–225, 220–195, or 165–150
	P. adeliae	bone	CAMS 42380	1300 ± 50	600 ± 70	405–55 or 15–0
site 1, TP 2, level 2	*P. adeliae*	bone	CAMS 42002	1330 ± 50	630 ± 70	425–105
site 2, TP 1, level 1	*P. adeliae*	bone	CAMS 41997	1230 ± 60	530 ± 80	310–40 or 35–0
site 2, TP 1, level 2	*P. adeliae*	bone	CAMS 41998	1540 ± 40	840 ± 65	545–325
site 2, TP 2, level 1	*P. adeliae*	bone	CAMS 41999	1360 ± 50	660 ± 70	450–135
site 2, TP 2, level 2	*P. adeliae*	bone	CAMS 42000	1240 ± 50	540 ± 70	305–40 or 35–0
modern TP 1, level 3	*P. adeliae*	bone	CAMS 42011	1170 ± 60	470 ± 80	275–40 or 35–0
Humble Island						
site 1, level 1	*P. adeliae*	bone	CAMS 42003	1400 ± 50	700 ± 70	475–240
	P. adeliae	bone	CAMS 42004	1360 ± 40	660 ± 65	445–140
	P. adeliae	bone	CAMS 42005	790 ± 50	-	
	P. adeliae	bone	CAMS 42006	1160 ± 50	460 ± 70	265–40 or 35–0
Biscoe Point						
site 1, TP 1, level 1	*P. adeliae*	bone	CAMS 42007	1540 ± 50	840 ± 70	550–315
	P. adeliae	bone	CAMS 42370	1530 ± 50	830 ± 70	545–310
site 1, TP 1,level 2	*P. adeliae*	bone	CAMS 42371	1790 ± 40	1090 ± 65	745–540
site 2, level 1	*P. adeliae*	bone	CAMS 42377	1650 ± 50	950 ± 70	650–460
site 3, level 1	*P. adeliae*	bone	CAMS 42378	1460 ± 50	760 ± 70	510–270
site 4, level 1	*P. adeliae*	bone	CAMS 42379	1460 ± 50	760 ± 70	510–270
site 5, TP 1, level 1	*P. adeliae*	bone	CAMS 42372	1350 ± 50	650 ± 70	445–130
	P. adeliae	bone	CAMS 42373	1180 ± 50	480 ± 70	270–40 or 35–0

occupation history of penguins during the mid to late Holocene in this region. Different methods for correcting and calibrating these dates for the marine reservoir effect also are examined.

Methods

All organic material collected from the abandoned penguin colonies was obtained through surface collection and excavation of sites located at Seymour Island (64°15'S, 57°20'W), Devil Island by north Vega Island (63°48'S, 57°15'W), King George Island (62°10'S, 58°30'W), Penguin Island (62°10'S, 58°30'W), Palmer station (64°46'S, 64°04'W) and vicinity at southern Anvers Island, and Rothera station (67°34'S, 68°07'W) and vicinity at south-east Adelaide Island (Fig. 1). Each site was excavated by placing a 1 x 1 m test pit within the pebble concentrations and ornithogenic soils.

Table I. (continued) Radiocarbon dates (in years BP) on penguin (*Pygoscelis* sp.) bone collagen, eggshell carbonates, or dried dermal tissue and squid (*Psychroteuthis glacialis* Thiele) beaks from test pits (TP) in abandoned colonies or modern (pre-1950) sites. Conventional dates were corrected and calibrated for the marine-carbon reservoir effect using a $\Delta R = 700 \pm 50$ years (see Emslie 1995) and the MARINE98 database of Stuiver & Reimer (1993). The conventional date, mean corrected date (both in radiocarbon years BP), and calibrated 2σ range(s) (95% confidence interval in calendar years BP) are provided for 60 samples from 21 sites on 11 islands. Three dates on modern specimens also are provided. Multiple 2σ ranges are provided for corrected dates that intersected two or more regions of the calibration curve. All dates are from Emslie (1995) and Emslie *et al.* (1998) except for UA 1033 (C. Hjort, personal communication 1997), Lu-3101 from Björck *et al.* (1991), and SRR-3784, SRR-3785, and SRR-3786 (R.I. Lewis Smith, personal communication 2001). Dates from the Rothera area and Rothera Point are provided here for the first time. Levels are 5–10 cm deep beginning with level 1 at the surface (0–5 cm) of each test pit (TP) excavated at each site.

Site/sample	Species	Material	Laboratory number	Conventional date	Corrected date	Calibrated range (2σ)
Biscoe Point						
site 5, TP 1, level 2	*P. adeliae*	bone	CAMS 42374	1600 ± 40	900 ± 65	620–425
	P. adeliae	bone	CAMS 42375	1580 ± 50	880 ± 70	615–405
	Pyschroteuthis	beak	CAMS 38709	1580 ± 50	880 ± 70	615–405
site 5, TP 1, level 3	*P. adeliae*	bone	CAMS 42376	1600 ± 50	900 ± 70	625–420
	Pyschroteuthis	beak	CAMS 38708	1650 ± 50	950 ± 70	650–460
Cormorant Island						
site 1, TP 1, level 2	*Pygoscelis* sp.	bone	CAMS 42008	1700 ± 50	1000 ± 70	675–490
	Pygoscelis sp.	bone	CAMS 42009	1760 ± 60	1060 ± 80	745–510
Torgersen Island						
TP1, level 1	*P. adeliae*	bone	CAMS 42010	1190 ± 40	490 ± 65	270–40 or 35–0
	Pyschroteuthis	beak	CAMS 38710	1280 ± 50	580 ± 70	365–40 or 35–0
Ginger Island						
TP 1, level 3	*P. adeliae*	bone	Beta 141904	1090 ± 40	390 ± 60	-
TP 1, level 4	*P. adeliae*	bone	Beta 141905	1580 ± 50	880 ± 70	615–405
TP 1, level 5	*P. adeliae*	bone	Beta 141906	1770 ± 40	1070 ± 60	720–535
TP 1, level 7	*P. adeliae*	bone	Beta 144171	3130 ± 40	2430 ± 65	2275–1900
Lagoon Island						
site 2, TP 1, level 2	*Pygoscelis* sp.	bone	Beta 141907	1910 ± 40	1210 ± 60	895–650
site 2, TP 1, level 3	*Pygoscelis* sp.	bone	Beta 141908	4440 ± 50	3740 ± 70	3835–3470
site 2, TP 1, level 4	*Pygoscelis* sp.	bone	Beta 141909	4390 ± 50	3690 ± 70	3800–3435
site 2, TP 1, level 5	*Pygoscelis* sp.	bone	Beta 141910	4550 ± 50	3850 ± 70	3975–3625
site 2, TP 1, level 6	*Pygoscelis* sp.	bone	Beta 141911	4240 ± 50	3540 ± 70	3585–3265
site 3, TP 1, level 2	*Pygoscelis* sp.	bone	Beta 141912	2980 ± 50	2280 ● 70	2050–1715
site 3, TP 1, level 3	*Pygoscelis* sp.	bone	Beta 141913	3510 ± 70	2810 ± 90	2750–2315
site 3, TP 1, level 4	*Pygoscelis* sp.	bone	Beta 141914	5610 ± 80	4910 ± 95	5460–4950
site 3, TP 1, level 5	*Pygoscelis* sp.	bone	Beta 141915	5920 ± 50	5220 ± 70	5715–5450
	Pygoscelis sp.	bone	Beta 141916	6080 ± 50	5380 ± 70	5900–5590
site 4, TP 1, level 2	*Pygoscelis* sp.	bone	Beta 141917	2490 ± 50	1790 ± 70	1490–1220
site 4, TP 1, level 4	*Pygoscelis* sp.	eggshell	Beta 144170	5550 ± 40	4850 ± 65	5305–4950
north side		sediments	SRR-3786	2680 ± 45	1980 ± 70	1700–1370
Rothera Point, Adelaide Island						
south-west		sediments	SRR-3784	3870 ± 55	3170 ± 70	3160–2770
centre		sediments	SRR-3785	2780 ± 55	2080 ± 70	1820–1500
Modern Specimens						
South Georgia						
(AMNH 4361)	*P. papua*	tissue	CAMS 15646	1110 ± 60		
Bay of Whales						
(AMNH 5041)	*P. adeliae*	tissue	CAMS 15643	1330 ± 60		
Hope Bay	*P. adeliae*	bone	Lu-3101	1280 ± 50		

Sediments were removed in 5 or 10 cm levels and washed through three nested screens with mesh sizes of 6.4, 3.2, and 0.025 mm. Organic remains were recovered by sifting through the washed sediments, often with a low-power binocular microscope. Further details on excavation methodology at all sites, except those at Rothera Point, can be found in Emslie (1995) and Emslie *et al.* (1998).

Sites near Rothera Point were excavated in 2000 using similar methodology. Abandoned colonies were first recognized in this area by R.I. Lewis Smith (British Antarctic Survey 1989). One active colony at Ginger Island (67°45'S, 68°41'W) and three abandoned sites (Sites 2, 3, and 4) at Lagoon Island (67°36'S, 68°14'W) were sampled by excavating 1 m^2 test pits in 5–10 cm levels numbered sequentially with depth. Radiocarbon dates from these sites are reported by excavation level.

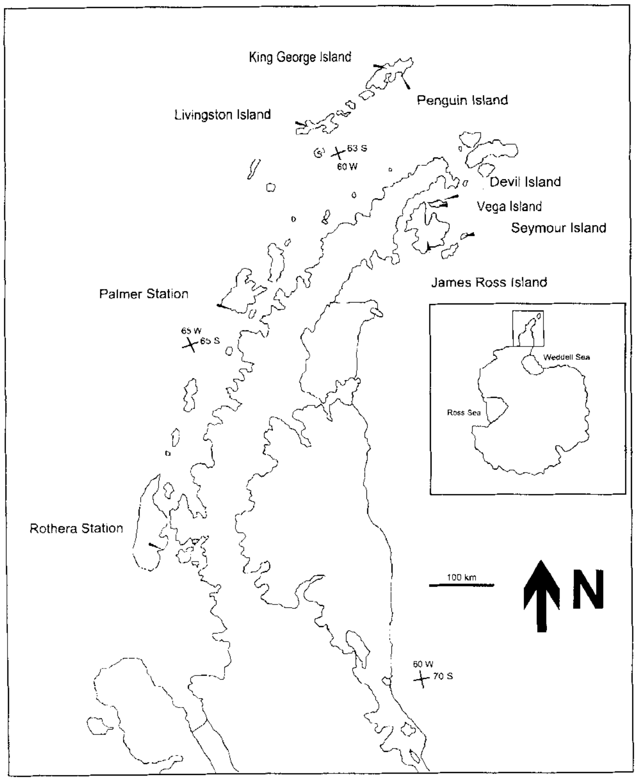

Fig. 1. Map of the Antarctic Peninsula region with locations of study sites where abandoned penguin colonies were sampled. Crosses provide latitude and longitude for specific regions.

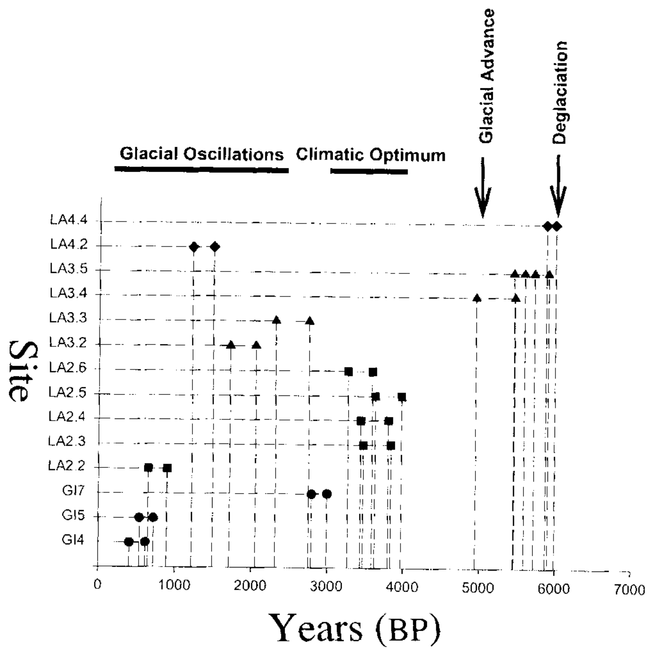

Fig. 2. Distribution of radiocarbon dates from abandoned and active penguin colonies near Rothera Point, Adelaide Island. Each date is plotted by a pair of points representing the 2σ calibrated range (95% confidence interval) after correcting for the marine-carbon reservoir effect. Correlation with glacial history given at the top of the graph is based on data summarized in Ingólfsson *et al.* (1998). Codes and plots refer to: LA4.4 and LA4.2, Lagoon Island Site 4 levels 4 and 2 (plotted with solid diamonds); LA3.5–LA3.2, Lagoon Island Site 3 levels 5–2 (triangles); LA2.6–LA2.2, Lagoon Island Site 2 levels 6–2 (squares); GI7, GI5, and GI4; Ginger Island levels 7, 5, and 4 (circles).

As noted above, radiocarbon dates of organic remains must be corrected for the marine-carbon reservoir effect and upwelling of old water in the southern ocean (Stuiver *et al.* 1986, Björck *et al.* 1991, Gordon & Harkness 1992, Berkman & Forman 1996, Berkman *et al.* 1998). Rather than correcting each date by subtracting a pre-determined value, Stuiver *et al.* (1986, 1998) provide calibration curves based on the reservoir effects between regional and world oceans through time. Thus, they use a regional offset value (ΔR) that is subtracted from the radiocarbon age. The resulting figure is compared to a calibration curve to estimate the true or corrected age (in calendar years) of the dated material using the Pretoria/Beta Analytic calibration program at Beta Analytic, Inc, Coral Gables, Florida.

Calculation of the ΔR depends on radiocarbon dates obtained on modern specimens. These dates will vary by taxa and by geographic location in Antarctica due to differences in species diets, and to variation in the intensity of upwelling and mixing of older waters at continental margins. Moreover, modern samples from which to base a calibration ideally should be from specimens that were collected prior to nuclear testing in the 1950s to avoid additional atmospheric contamination that have influenced carbon ratios in living tissue.

Two specimens of modern, pre-1940 penguins previously were analysed and compared to other published dates by Emslie (1995) to determine a ΔR value for pygoscelid penguins in the Antarctic Peninsula region at 700 ± 50 BP. This value was determined after comparing the ΔRs of 715 ± 50 for the Bay of Whales, which probably overestimates the value due to more intense upwelling there, vs 640 ± 60 for South Georgia, which underestimates the value as waters are less mixed there than around the Antarctic Peninsula (Emslie 1995). A median value of 700 ± 50 thus appears to be a reasonable estimate and this ΔR is applied here to all known dates of penguin bones, tissue, and eggshell from abandoned colonies in the Antarctic Peninsula region.

The method also was applied to squid (*Psychroteuthis glacialis*) beaks identified in the ornithogenic sediments as this species, like pygoscelid penguins, feeds primarily on krill (*Euphausia superba* Dana, Lu & Williams 1994) and therefore may reflect a similar old carbon ratio in its tissues. No modern dates on squid are known from which to assess the accuracy of this calibration. The three dates on sediments from Rothera Point and vicinity were calibrated with this method because the organic material that was dated was largely from penguin guano (R.I. Lewis Smith, personal communication 2001). Zale (1994b) analysed the geochemistry of similar sediments at Lake Boeckella, Hope Bay, and found that the effect of autochthonous carbon (e.g. from plants) on estimating the true radiocarbon age to be negligible (but see also Björck *et al.* 1991).

It is possible that the ΔR applied here for the Antarctic Peninsula region still underestimates the true correction. For example, Emslie (1995) calculates a ΔR of 805 ± 50 based on a modern date on Adélie penguin bone from Hope Bay reported by Björck *et al.* (1991). Thus, two other ΔR values of 750 ± 50 and 800 ± 50 BP were applied to three conventional dates ranging in age from 1910 to 6080 BP to determine how different ΔR values can influence the calibrated results. The two other ΔR values were chosen from other published studies on dating marine-based organisms in Antarctica that require an adjustment for the marine-carbon reservoir effect (see Berkman *et al.* 1998).

Results

Table I provides a summary of 60 radiocarbon dates from 21 abandoned colonies on 11 islands in the Antarctic Peninsula region, plus three dates on sediments from Rothera Point and vicinity, Adelaide Island. Three modern (pre-1950) dates on penguin bone or tissue also are provided. All specimens were well-preserved and contained amounts of nitrogen and amino acids approaching that of fresh tissue. With few exceptions, multiple radiocarbon dates from one site and test pit are older in progressively deeper levels, or reflect the same age as the level above. This trend is shown by dates both on penguin bones and prey remains (squid beaks).

The 2σ calibrated range for each date using a ΔR = 700 ± 50 BP indicates that penguin occupation of the King George, Penguin, Devil and Seymour Island sites in the northern Antarctic Peninsula region extends from modern to 540 BP (Table I). Differences in chinstrap vs Adélie penguin occupation of this region were discussed by Emslie (1995). The 2σ calibrated range for sites in the Palmer station region is slightly longer, from modern to 745 BP, with all sites representing only Adélie penguin occupation until the recent expansion of chinstrap and gentoo (*Pygoscelis papua* Forster) penguins into the region (Emslie *et al.* 1998, Smith *et al.* 1999). At Rothera Station, the 2σ calibrated range is more extensive, from modern to 5900 BP, with all occupations presumably representing Adélie penguins (Table I).

The 21 dated localities form a rough transect from north to south along the Antarctic Peninsula (Fig. 1) and the calibrated dates indicate progressively older occupation southwards along this transect, with the oldest dates from Lagoon Island near Rothera Point. Some of these dates also indicate multiple occupation periods of the same colonies (sites 2–4, Fig. 2). General palaeoclimatic trends for the Antarctic Peninsula (summarized by Ingólfsson *et al.* 1998) correspond with the occupation history of penguins in the Rothera region (Fig. 2).

Three dates (Beta 141907, 141911, and 141916) calibrated with multiple ΔR values (= 700 ± 50, 750 ± 50, and 800 ± 50 BP) indicate broad overlap and no differences in 2σ calibrated ranges (Table II).

Discussion

Berkman *et al.* (1998) summarized all published methods for dating marine organisms in Antarctica except for that of Emslie (1995), who provided two additional dates on pre-1950 penguin tissue or bone from sub-Antarctic South Georgia and the Bay of Whales, Ross Sea. These dates were used to estimate a ΔR = 700 ± 50 for the Antarctic Peninsula region (Emslie 1995). However, Baroni & Orombelli (1991) used a ΔR = 779 ± 60 to correct dates from Victoria Land, Ross Sea, while another modern date from Hope Bay in the Peninsula indicated a ΔR = 805 ± 50 should be used in that region. Thus, a ΔR correction may be subject to local variables including the intensity of upwelling of water containing old carbon (Emslie 1995). Data presented here, however, indicate that application of three ΔRs (700, 750, and 800 ± 50 BP) on radiocarbon dates from the same region provides overlapping results and few differences in interpreting the age of the sites (Table II). These results suggest that local variations in upwelling may make little difference in interpreting the true age of pygoscelid penguin remains in Antarctica.

When comparing the data from Rothera with the glacial history record, the estimated calibrated dates seem to match the palaeoclimatic record (Fig. 2). This record, summarized by Ingólfsson *et al.* (1998), indicates that a warming trend and episode of deglaciation occurred at about 6000 BP, agreeing with the radiocarbon chronology for when penguins began to occupy Lagoon Island. A cooling period and glacial advance began at about 5000 BP and lasted for approximately 1000 years. Although this advance is not recorded in northern Marguerite Bay specifically, where the abandoned colonies are located, no calibrated penguin dates occur within that interval. Dates younger than 4000 BP occur within warming periods (the penguin optimum, 4000–3000 BP) or glacial

Table II. Alternate ΔR values for calibrating three radiocarbon dates (in years BP) on penguin (*Pygoscelis* sp.) bone collagen from abandoned colonies on Lagoon Island, near Rothera Point. The sample lab number, ΔR value, mean corrected date, and calibrated 2σ range (95% confidence interval) are provided for each sample.

Sample/method	Corrected date	Calibrated range (2σ)
Beta 141907		
ΔR = 700 ± 50	1210 ± 60	895–650
ΔR = 750 ± 50	1160 ± 60	820–620
ΔR = 800 ± 50	1110 ± 60	760–560
Beta 141911		
ΔR = 700 ± 50	3540 ± 70	3585–3265
ΔR = 750 ± 50	3490 ± 70	3530–3210
ΔR = 800 ± 50	3440 ± 70	3460–3150
Beta 141916		
ΔR = 700 ± 50	5380 ± 70	5900–5590
ΔR = 750 ± 50	5330 ± 70	5870–5570
ΔR = 800 ± 50	5280 ± 70	5770–5510

oscillations (3000 BP to present) and lack resolution for precise correlation with climatic events.

These data suggest that penguins were unable to occupy islands in the Rothera region until deglaciation exposed ice-free terrain at about 6000 BP. This first occupation lasted for approximately 1000 years, then ceased perhaps due to a glacial advance or increased snow deposition that again covered the islands. A warming trend at 4000 to 3000 BP can be correlated with re-occupation of Lagoon Island, after which glacial oscillations occur with no consistent correlation with the penguin occupation. The correspondence of these two independent records suggests that the ΔR correction of 700 ± 50 years and the calibration method is accurate. Moreover, the close association of three dates on squid (*Pyschroteuthis glacialis*) with those from penguin bones from the same stratigraphical levels at Biscoe Point and Torgersen Island (Table I) indicates that this calibration method is appropriate for other krill-eating species in the Antarctic marine system. Thus, this method to correct for the marine-carbon reservoir effect is recommended for all radiocarbon dates of pygoscelid penguin remains in Antarctica.

The absence of abandoned colonies older than approximately 540 years (based on calibrated ranges, Table I) in the northern end of the Antarctic Peninsula remains an enigma. Tatur *et al.* (1997, p. 414) also noted a striking absence of sites older than 1300 years (based on surface guano) and hypothesized that these sites may have been eroded and destroyed by "solifluction and polygonal ground-forming processes." Only limited evidence indicates that penguins occupied King George Island in the mid Holocene (Bochenski 1985, Barsch & Mäusbacher 1986, Tatur *et al.* 1997, Sun *et al.* 2000). Moreover, a sediment core from Lake Boeckella, Hope Bay, has produced guano remains that suggest a large population of penguins colonized the surrounding terrain around 5550 BP (Zale 1994a, 1994b). It is possible that ornithogenic soils and abandoned sites predating 540 BP simply have not yet been located in the northern Antarctic Peninsula region, or that glaciation during the Little Ice Age (AD 1500–1850; Grove 1988) was sufficient to cover most islands with snow and ice, perhaps scouring and erasing any previous record of penguin occupation. The ice-core and oxygen isotope record from Siple station indicates that the Antarctic Peninsula did experience colder climates than today during the Little Ice Age, more so than east Antarctica (Mosley-Thompson *et al.* 1990).

The preservation of ornithogenic soils rich in bone and eggshell fragments of mid Holocene age at Rothera Point tends to falsify the suggestion that glacial scouring should account for the absence of old sites in the northern peninsula area. In addition, marine terraces and raised beaches on small islands near Rothera Point, including Lagoon and Anchorage Islands, have numerous polygonal features (Smith 1996, Emslie personal observation 2000) indicating that ground-forming processes have been active in this region. Freeze-thaw action in the pebbly ornithogenic soils over thousands of years has reduced most penguin bones preserved in these sediments to small rounded fragments, but these, as well as eggshell fragments and other organic remains, are still abundant and well preserved. Thus, if abandoned colonies can survive glacial processes at Rothera, other explanations are needed for their absence in the northern peninsula. It is likely that a combination of factors that limit penguin distribution were responsible for the occupation and abandonment of specific areas. More detailed ground surveys and test excavations are warranted, especially on the high terraces and large ice-free regions on King George, Livingston, Seymour, James Ross, and Vega islands. These islands are considered to have the greatest potential for locating abandoned colonies and ornithogenic soils of early to middle Holocene age. Location of these sites would provide valuable information not only on the occupation history and diet of penguins, but also on the glacial and sea-level history of the northern Antarctic Peninsula and Weddell Sea region.

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