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Recent occupation by Adélie Penguins (*Pygoscelis adeliae*) at Hope Bay and Seymour Island and the 'northern enigma' in the Antarctic Peninsula

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Abstract We excavated active and abandoned Adélie Penguin (*Pygoscelis adeliae*) colonies at Seymour Island and Hope Bay, Antarctic Peninsula, to determine an occupation history for this species at these sites. Previous research at Hope Bay has indicated an occupation there since the middle Holocene, based on a sediment record from Lake Boeckella. Excavations revealed only shallow and relatively fresh ornithogenic soils in the active colonies at the two localities. At least 53 abandoned pebble mounds were located at Hope Bay of which nine were excavated and four were sampled by probing to recover organic remains to determine their age. Radiocarbon dating of egg membrane, feather, and bone from both sites revealed a young occupation dating to less than ~600 years after correcting for the marine carbon reservoir effect. The mismatch in the geologic record of Adélie Penguin occupation in the northern Antarctic Peninsula, including Lake Boeckella sediments and geologic deposits and lake sediments on King George Island, with more direct evidence of breeding colonies from ornithogenic soils from active and abandoned colonies is hereby referred to as the 'northern enigma' as it does not occur in other regions of Antarctica including the southern Antarctic Peninsula, East Antarctica, or the Ross Sea, where the penguin record extends to the early to middle Holocene and matches well with the geologic record of deglaciation and penguin occupation. As yet, there is no convincing explanation for the 'northern enigma'.

Keywords Adélie Penguin · Occupation history · Ornithogenic soils · Hope Bay · Seymour Island

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Introduction

Millions of breeding pairs of Adélie (*Pygoscelis adeliae*), Chinstrap (*P. antarctica*), and Gentoo (*P. papua*) Penguins occur throughout the Antarctic Peninsula region. These three species overlap in distribution, and often intermingle on the same beaches, especially in the northern Antarctic Peninsula where numerous active and abandoned colonies exist. These colonies are characterized by ornithogenic soils that accumulate over time, contain well preserved tissues of penguins and their prey, and provide direct evidence for past occupations by breeding penguins (Tatur 1989; Emslie et al. 2014). Investigations of ornithogenic soils at abandoned penguin colonies in the northern peninsula have indicated that Gentoo Penguins have occupied parts of this region for at least the past 1100 years (Emslie et al. 2011), while Chinstrap and Adélie Penguins have records that so far extend back by only 500–600 years, even though the northern peninsula underwent deglaciation by 6000 BP (Ingólfsson 2003). However, pygoscelid bones have been recovered from beach and lake deposits in the northern peninsula that date to the early to middle Holocene (see reviews in Emslie

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2001; Emslie et al. 2011, 2014). Moreover, while the Adélie Penguin record extends to 6000 BP in the southern Antarctic Peninsula (Emslie and McDaniel 2002), and much longer in East Antarctica and the Ross Sea (Emslie and Woehler 2005; Emslie et al. 2007), it is only in the northern Antarctic Peninsula where there is a mismatch between the geologic record (lake sediments, raised beach, and moraine deposits) with that from ornithogenic soils. We term this mismatch, first noted by Tatur (1989), the 'northern enigma' because it does not occur in other regions of Antarctica.

Current Adélie Penguin breeding colonies follow a distributional pattern in being associated with open water surrounded by pack ice or polynyas at the onset of the breeding season (Ainley 2002). The six largest colonies (>100,000 breeding pairs) in Antarctica occur mostly in the Ross Sea and East Antarctica, though one (Hope Bay, Trinity Peninsula) is in the northern Antarctic Peninsula. Adélie Penguins in the peninsula can also be divided into two major populations with one in the southern peninsula, from Gerlache Island at 64°36′S and southward, and the other in the northern peninsula and maritime islands from Livingston Island at 62°39′S and northward, and wrapping around eastward into the Weddell Sea south to Seymour Island at 64°18′S (Woehler 1993; Ainley 2002). The 400-km wide unoccupied region between Livingston and Gerlache Islands is known as the Adélie 'gap' (Fig. 1), with the two populations on either side having distinct wintering as well as breeding grounds as shown by stable isotope evidence (Polito et al. 2011).

To further document the occupation history of Adélie Penguins in the northern Antarctic Peninsula, we investigated active and abandoned penguin colonies on Seymour Island and at Hope Bay in summer 2013–2014 in collaboration with the Argentine Antarctic Program (Instituto Antártico Argentino). Seymour Island has one active Adélie Penguin colony at Penguin Point on the southeastern side of the island facing the Weddell Sea, while Hope Bay opens to the Antarctic Sound on the tip of the peninsula proper (Fig. 2). While the colony at Seymour Island currently stands at ~22,000 breeding pairs, Hope Bay supports a large colony of Adélie Penguins estimated at ~120,000 breeding pairs and is the sixth largest colony for this species in the Antarctic (Woehler 1993; Ainley 2002; Harris 2006). Moreover, previous research on a sediment core from Lake Boeckella, Hope Bay, has indicated that penguins have inhabited this colony, based on guano bioelements that have accumulated in the lake sediments, since the middle Holocene (5550 BP, Zale 1994). Thus, this site has high potential in providing ancient ornithogenic soil corresponding to a middle Holocene occupation that would help resolve the 'northern enigma'. We also sampled

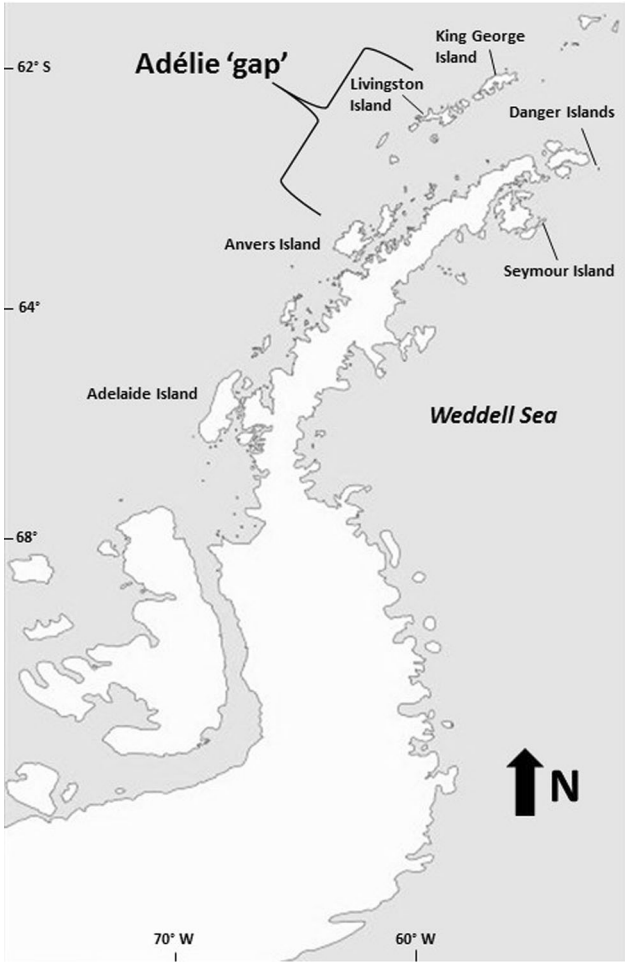

Fig. 1 Map of the Antarctic Peninsula with major locations discussed in the text as well as the area of the Adélie 'gap', or the 400 km section where no Adélie Penguin colonies currently occur

the active Adélie Penguin colony at Penguin Point, Seymour Island, to determine the age of this colony as well.

Materials and methods

Abandoned penguin colonies are recognized by concentrations of similar-sized pebbles on the surface, often forming low mounds that stand out from surrounding natural landscapes. Probing into the mounds reveals ornithogenic soil with the presence of pebbles, bone, eggshell, and soil with a pink to reddish color from krill pigments in penguin guano (Emslie et al. 2014). At Hope Bay, each abandoned pebble mound was mapped using a handheld GPS device (Garmin GPSmap 62st). Selected sites were excavated using the methods of Emslie et al. (2011). A 50 × 50 cm pit was established in the middle of each pebble mound, surface pebbles and plants (usually lichen covered pebbles) were removed and placed on a tarp, and

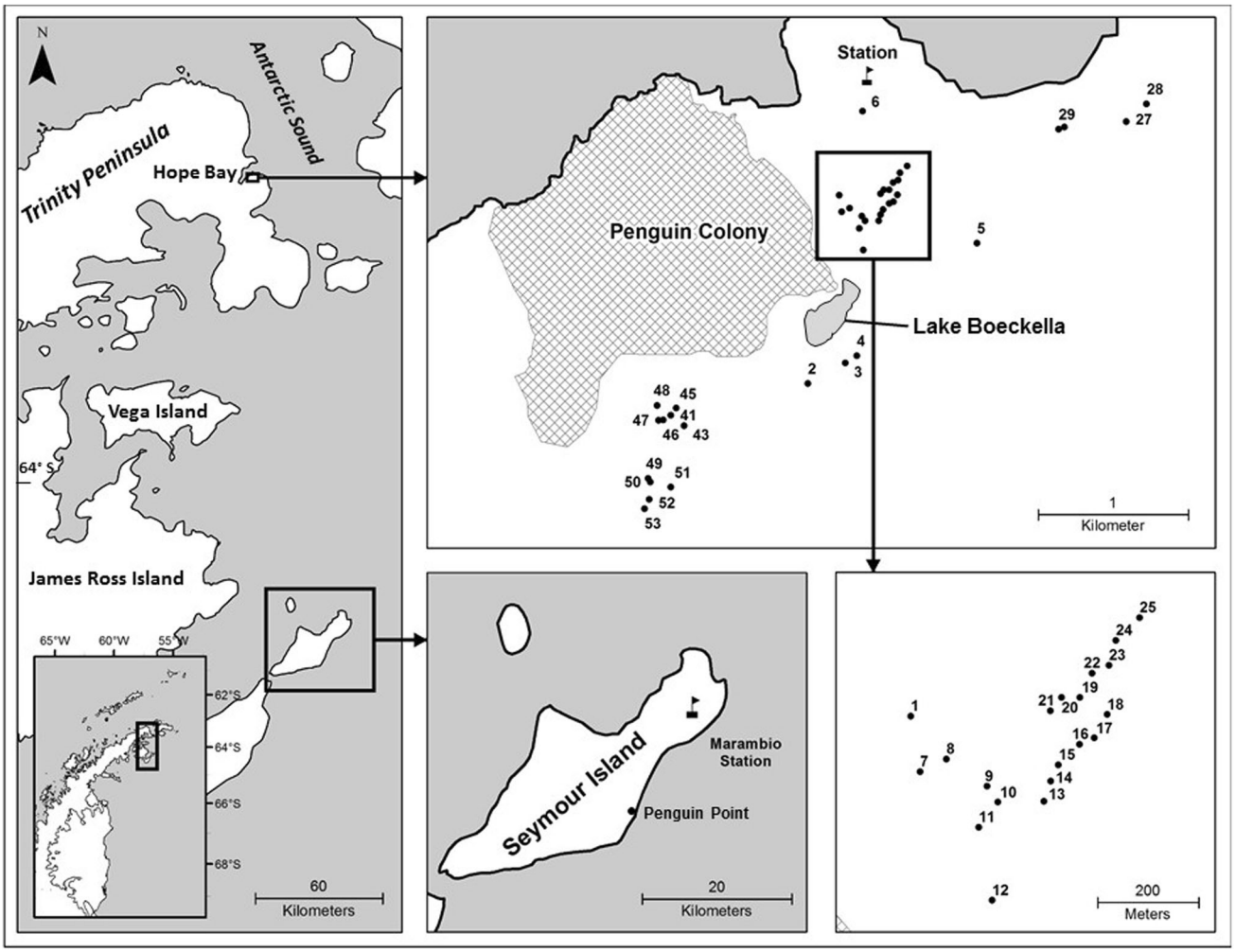

Fig. 2 Location of Adélie Penguin colonies and abandoned sites at Penguin Point, Seymour Island, and Hope Bay, Trinity Peninsula. The 53 abandoned sites (pebble mounds) at Hope Bay are shown in relation to the active penguin colony and Lake Boeckella

the pit was excavated in 5-cm levels until reaching the bottom of the ornithogenic soil, recognized by a change in soil color and texture.

All soil from each level was screened in the field through two stacked screens with mesh sizes of 0.64 and 0.32 cm^2. The top screen was sorted in the field to recover larger bones, feathers, and other organic remains and to remove large rocks and pebbles; remaining sediments were washed, dried, and sorted in the lab to recover penguin eggshell, bone, and prey remains (otoliths, squid beaks) using a low-power stereomicroscope. All excavated sites were backfilled and the surface stones replaced. Photographs were taken before, during, and after the excavations to document all procedures at each site.

Twenty samples of feather, bone, and egg membrane recovered from the sites were submitted to Woods Hole National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility for radiocarbon dating. Uncorrected radiocarbon dates (in ^{14}C years BP) were corrected for the marine carbon reservoir effect using a delta R of 700 ± 50 years (see Emslie 2001), then calibrated using Calib 7.0 (Stuiver and Reimer 1993) and the Marine13 calibration curve to provide a 2-sigma range in calendar years BP.

Results

Surveys were conducted at Penguin Point, Seymour Island (Fig. 2), on 6 and 27 February 2014 but no abandoned mounds were located. Several pebble mounds within the active colony were probed, but ornithogenic soils in all cases were shallow (<5 cm deep) and fresh, indicating a young age for the occupation. One mound exposed in cross section near the front of the beach had ornithogenic soils extending to a depth of ~20 cm and were the deepest of these soils found in the entire colony. Samples of penguin bone, eggshell, and feather were collected in situ from the

bottom of the ornithogenic soil within this exposure (Fig. 3).

Surveys and excavations of abandoned mounds at Hope Bay were conducted from 11–23 February 2014. Most of these mounds ranged from approximately 3–5 m in diameter and were located on the east and north sides of Lake Boeckella (Fig. 4), as well as immediately south and east of Esperanza Station. Pebble mounds with lichens covering the surface were also located on terraces above and east of Lake Boeckella and near the edge of Buenos Aires Glacier. A total of 53 abandoned mounds were numbered and mapped (Fig. 2); excavations were conducted at nine sites (3, 4, 9, 15, 22, 26, 27, 39, and 42) and additional samples were collected by probing with a trowel at four others (43, 44, 49, and 51). All sites had ornithogenic soils that were no more than three levels (10–15 cm) deep. Active penguin mounds within the colony also were probed, but all had shallow ($\sim$5 cm depth) and obviously young ornithogenic soils.

A total of 20 radiocarbon dates were completed on penguin bone, feather, or egg membrane (Table 1). Dates on two samples of penguin feather and egg membrane from Penguin Point were too young in age for calibration, verifying a relatively recent occupation at this site. The remaining 18 radiocarbon dates from Hope Bay ranged in age from 0–680 cal. year BP, again indicating a relatively young age for the current occupation of Adélie Penguins.

Discussion

Our investigations here continue to yield information on the occupation history of pygoscelid penguins, especially Adélie Penguins, in the northern Antarctic Peninsula region. As in previous studies of active and abandoned colonies, only young ornithogenic soils from recent occupations of the three pygoscelid species have been located in the northern peninsula at Livingston, King George, Ardley, Penguin, Devil, Litchfield, Humble, Cormorant, and Torgersen Islands (Emslie 2001; Emslie et al. 2003, 2011, 2013), though new unpublished radiocarbon dates suggest an occupation of the Danger Islands (63°25′S, 54°40′W; Fig. 1) by Adélie Penguins as early as 2800 BP (M. Polito, pers. comm.). It is only in the southern Antarctic Peninsula at Adelaide and Lagoon Islands where the record is older for Adélie Penguins with an occupation history in accordance with the geologic record for deglaciation beginning at $\sim$6000 BP (Emslie and McDaniel 2002). In the north, geologic deposits (raised beaches and moraines) and lake sediment cores have provided evidence, including bones, of pygoscelid penguins that date from the early Holocene and younger on King George and Ardley Islands (Tatur 1989; del Valle et al. 2002; Roberts et al. 2017). The apparent recent occupation and mismatch between ornithogenic soils that provide direct evidence of penguin occupation with these geologic and lake-core records is an enigma that does not occur in other regions of Antarctica and seems restricted to the northern Antarctic Peninsula.

Explanations for this ‘northern enigma’ range from older ornithogenic soils having been scoured away or buried by glacial movements, erosion from solifluction and freeze–thaw processes (Tatur et al. 1997), or submerged underwater from sea level rise. However, glacial movements, solifluction, and sea level rise have not removed or submerged older ornithogenic soils in the southern Antarctic Peninsula, East Antarctica or the Ross Sea, where intact pebble mounds and soils have been dated as old as

Fig. 3 View of an exposed profile of ornithogenic soils at Penguin Point, Seymour Island, near the front of the beach. *Arrow points* to the base of the ornithogenic soils where penguin bones and feathers were recovered at $\sim$20 cm depth

Fig. 4 View of Lake Boeckella looking southeast from the active penguin colony on the west side of the lake. The locations of three abandoned pebble mounds, *Sites 2*, *3*, and *4*, are labeled in the figure with the edge of Buenos Aires Glacier in the background. Site 4 provided the oldest radiocarbon date on ornithogenic soil from Hope Bay at 680–515 cal. year BP

Table 1 Radiocarbon dates from Adélie Penguin tissues from ornithogenic soils at Seymour Island and Hope Bay, Antarctic Peninsula

Lab no.	Location	Material	Uncorrected ^{14}C age	Calibrated 2-sigma range
OS-110023	Seymour Beach Site, bottom	Tail feather	765 ± 20	–
OS-110212	Seymour Beach Site, bottom	Egg membrane	925 ± 20	–
OS-110720	Site 4 Lev 1	Bone	1730 ± 20	680–515
OS-110213	Site 9 Lev 1	Egg membrane	1340 ± 20	420–135
OS-110721	Site 15 Lev 1	Bone	1460 ± 20	490–290
OS-110214	Site 15 Lev 2	Egg membrane	1280 ± 25	325–45
OS-110215	Site 15 Lev 3	Egg membrane	1370 ± 25	455–220
OS-110216	Site 22 Lev 1	Egg membrane	1320 ± 20	415–115
OS-110217	Site 26 Lev 1	Egg membrane	1480 ± 25	500–300
OS-110218	Site 26 Lev 2	Egg membrane	1590 ± 20	615–425
OS-110219	Site 27 Lev 1	Egg membrane	1460 ± 20	490–290
OS-110221	Site 39 Lev 1	Egg membrane	1180 ± 20	235–0
OS-110024	Site 39 Lev 2	Egg membrane	1270 ± 20	305–50
OS-110222	Site 42 Lev 1	Egg membrane	1160 ± 20	230–0
OS-110223	Site 42 Lev 2	Egg membrane	1240 ± 20	275–45
OS-110224	Site 43 0–10 cm probe	Egg membrane	1170 ± 25	230–0
OS-110225	Site 44 0–10 cm probe	Egg membrane	1120 ± 20	–
OS-110025	Site 49 0–10 cm probe	Egg membrane	1070 ± 25	–
OS-110026	Site 51 0–10 cm probe	Egg membrane	1100 ± 20	–
OS-110722	Site 51 0–10 cm probe	Bone	1430 ± 20	475–275

Uncorrected dates are in radiocarbon years before present (BP); dates were corrected for the marine carbon reservoir effect (delta $R = 700 \pm 50$ years) and calibrated with Calib 7.0 (Stuiver and Reimer 1993) to provide 2-sigma ranges in calendar years BP. Absence of 2-sigma values are dates that were too young for calibration and essentially modern in age. All dates were completed at the Woods Hole National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility and are designated with OS numbers

~27,000 BP (Baroni and Orombelli 1994; Emslie et al. 2007), so why would the northern peninsula be an exception? In addition, it is possible that older ornithogenic soils are more limited in distribution in the northern peninsula and have yet to be located. However, numerous areas have been investigated throughout the South Shetland Islands and western Antarctic Peninsula and it seems unlikely that older soils would have been missed. A final hypothesis is that pygoscelid penguins simply did not occupy most of the northern peninsula as breeding birds until the last ~1100 years and thus ornithogenic soils did not begin forming until then, but this idea is based solely on negative data. If true, though, the presence of guano bio-elements in lake sediments dating from the early to middle Holocene needs further explanation with future investigations.

Two lake-core records that relate to this 'northern enigma' are of particular interest here. Zale (1994) reported high levels of penguin guano bio-elements (Ca, Cd, Cu, P, Sr, and Zn) in sediments from Lake Boeckella, Hope Bay, though no penguin bones or feathers were reported in the core samples. These sediments began forming at 6300 BP; the bio-elements first appear at 5550 BP, increase substantially from 3500 to 850 BP, and remain present at lower levels thereafter. In addition, the first historic observations of the Hope Bay colony were reported by the Nordenskjöld expedition in 1904 when up to 100,000 breeding pairs were estimated at this colony, or near the same size as it is today (Zale 1994). These data suggest that the colony was perhaps larger, and occupied a greater area, at 3500 to 850 BP than today to account for the higher levels of bio-elements recorded in lake sediments dating to that period.

We conducted extensive surveys of ice-free terrain during our investigations at Hope Bay, especially on ridges and terraces surrounding Lake Boeckella, to locate any ancient deposits of ornithogenic soils that would correlate with the lake sediment record reported by Zale (1994). We located four abandoned pebble mounds (Sites 2, 3, 4, and 12) near the eastern shore of the lake, on the opposite shore from where the active colony currently extends (Figs. 2, 4). Excavations of Site 4 provided an earliest age of occupation between 680 and 515 cal. year BP (Table 1), with no other evidence of an earlier occupation near the lake. Of the 13 sites that were dated at Hope Bay, Site 4 was the oldest (Table 1). Thus, any ornithogenic soils dating to the middle Holocene are no longer present or evident in the

terrain surrounding Lake Boeckella or the current Adélie Penguin colony.

Also in the northern peninsula, a sediment core from Ardley Lake, Ardley Island (King George Island; Fig. 1), again indicated a mismatch in the age of guano bio-elements in the lake core with dates obtained from active and abandoned Gentoo Penguin colonies nearby. High levels of bio-elements as well as juvenile penguin bones were recovered from this core and dated the first occupation by Gentoo Penguins to the early Holocene (~7400–7200 cal. year BP; Roberts et al. 2017), while the earliest dates on the active Gentoo Penguin colony, located on the opposite side of the island from the lake, indicated an occupation commencing no earlier than 1025 BP (Emslie et al. 2013). The landscape around the lake consists of rocky terrain and exposed bedrock and no pebble mounds or other indications of penguin breeding are nearby. The high levels of guano bio-elements, as well as the juvenile penguin bones, imply an earlier occupation of the island by breeding penguins but again no direct evidence for this occupation has been located. Another lake to the west of Ardley Lake, Y2, was cored by Chinese scientists who reported bio-elements indicating penguin occupation beginning by 3000 BP (Sun et al. 2000, 2004; Liu et al. 2005; Wang et al. 2007), also not in accordance with the record of ornithogenic soils on this island.

Besides bio-elements in cores, lake sediment records can provide information on the timing of deglaciation of specific regions, which would open beaches and terrain for breeding penguins. The records from ten lakes at Byers Peninsula, Livingston Island, overall indicate deglaciation of this region by ~3000 BP (Björck et al. 1991, 1996). However, the penguin occupation there (Gentoo and Chinstrap) is currently restricted to the west and north sides of the peninsula. Radiocarbon dates on abandoned pebble mounds from Gentoo Penguins indicate the earliest occupation was at ~1100 BP, or almost 2000 years after deglaciation had occurred (Emslie et al. 2011). This record lends support to the hypothesis that pygoscelid penguins only recently began breeding in the northern Antarctic Peninsula, but given the deglaciation record of the northern peninsula by the middle Holocene, there remains no explanation as to why penguins would not be breeding in this region until the late Holocene.

Despite the 'northern enigma', numerous areas and penguin colonies remain to be investigated in the northern peninsula including the large Chinstrap colony at Bailey Head, Deception Island, and the large Adélie colony at Paulet Island. It is likely that direct evidence for early to middle Holocene occupations by pygoscelid penguins does exist in this region, but in localized areas as penguins began to expand into the peninsula following Holocene deglaciation. The general trend, however, is that most active colonies are relatively young in age and sites with ancient ornithogenic soils remain elusive. Thus, there is as yet no convincing explanation for the 'northern enigma'.

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