GLACIAL GEOLOGY OF CAPE BIRD, ROSS ISLAND, ANTARCTICA

BY

TINA M. DOCHAT[1], DAVID R. MARCHANT[2], and GEORGE H. DENTON[1,3]

[1]Institute for Quaternary Studies, University of Maine, Orono, Maine, USA
[2]Department of Earth Sciences, Boston University, Boston, Massachusetts, USA
[3]Department of Geological Sciences, University of Maine, Orono, Maine, USA

Dochat, Tina M., Marchant, D.R. and Denton, G.H., 2000: Glacial geology of Cape Bird, Ross Island, Antarctica. *Geogr. Ann.*, 82 A (2–3): 237–247.

ABSTRACT. Located on the northwest coast of Ross Island in McMurdo Sound, Cape Bird features virtually unweathered surface drift with erratics from the Transantarctic Mountains (TAM) and with enclosed marine shell fragments. This Cape Bird drift is cut by Holocene beaches. The chronology of drift deposition and beach formation comes from AMS radiocarbon dates of associated marine shells, and of penguin bones and skin. The results indicate that a grounded ice sheet with a surface elevation in excess of 590 m deposited Cape Bird drift after 26,860 ^{14}C yr BP. The enclosed erratics, shells, and foraminifers indicate that a component of the ice within this sheet flowed through the TAM, grounded on the Ross Sea floor, and ultimately advanced landward onto the lower slopes of Mount Bird. On the basis of similar physical weathering characteristics, far-traveled erratics, radiocarbon chronology, and geomorphic setting, Cape Bird drift is correlated with Ross Sea drift elsewhere in the McMurdo Sound region.

Reconstructed surface contours for the grounded ice sheet are based on the areal distribution and upper limit of Cape Bird/Ross Sea drift on ice-free areas alongside McMurdo Sound. The ice surface sloped down to the west from the Ross Embayment toward the TAM. A major flowline within this sheet passed westward around northern Ross Island, southward over Capes Bird and Royds, and then again westward across the sound. This ice-flow direction is required because of the paucity of kenyte erratics in Cape Bird drift. Kenyte, a distinctive bedrock lithology, is common on the west coast of Ross Island, south of Cape Bird. Therefore, the lack of widespread kenyte erratics in Cape Bird drift precludes northward flow of grounded glacier ice during the last glacial maximum (LGM).

Wave-washed sediment and beach ridges at Cape Bird extend to 7.6 m above mean high tide (MHT). A set of five low-elevation beaches, all less than 4.0 m above MHT, is parallel with the modern coastline. A higher set features six beach ridges transverse to the modern coastline between 4.9 m and 7.6 m above MHT. Storm waves probably produced both sets of beaches. AMS radiocarbon dates of collagen from buried penguin bones indicate that the lower ridges are modern storm beaches. The upper beaches formed around 3585 ^{14}C yr BP, when relative sea level stood about 3.6 m above MHT.

Given that the mapped upper limit of Cape Bird drift exceeds 590 m elevation and that the marine limit at Cape Bird is only 7.6 m above MHT, the raised beaches at Cape Bird probably reflect only the isostatic uplift since seasonally open water appeared off Cape Bird following recession of an ice-shelf front about 3585 ^{14}C yr BP, rather than the total isostatic uplift after retreat of the ice-sheet grounding line. It is less likely that the lowness of the beaches at Cape Bird reflects tectonic subsidence on this volcanically active island. In either case, the beaches at Cape Bird do not represent the total isostatic uplift since deglaciation. Therefore, the best measure of the thickness of glacier ice at Cape Bird during the LGM comes from the areal distribution, upper limit, and AMS radiocarbon chronology of Cape Bird drift.

Introduction

It has been postulated that the greatest change in the areal extent of the Antarctic Ice Sheet during the last glacial maximum (LGM) occurred in the Ross and Weddell Embayments (Hollin 1962; Denton *et al.* 1989a, 1991). The idea is that grounding lines of outlet glaciers and ice streams advanced seaward across the continental shelf as eustatic sea level fell in response to the growth of Northern Hemisphere ice sheets. This reconstruction of extensive grounded ice at (or near) the continental shelf edge in the Ross Embayment is based on the areal distribution and upper-elevation limit of virtually unweathered drift in the southern and central Transantarctic Mountains (TAM) (Stuiver *et al.* 1981; Denton *et al.* 1989a,b; Bockheim *et al.* 1989), as well as on the recognition of till tongues and submarine deltas on the Ross Sea floor (Shipp *et al.* 1999). But this viewpoint is still controversial, as key questions remain about the extent of grounded ice at the LGM. For example, on the basis of the relatively low elevation (≤32 m) of raised beaches on the Victoria Land coast, Colhoun *et al.* (1992) called for modest LGM ice thickening in selected areas along the TAM front, rather than for widespread expansion of grounded ice across the Ross Embayment. This paper describes glacial drift at Cape Bird, located near the northern tip of Ross Island, that points to ice-surface elevations in excess of 590 m in northeastern McMurdo Sound, consistent with the model of extensive grounded ice at the LGM.

Ross Embayment, McMurdo Sound, and the Ross Ice Shelf

The Ross Embayment encompasses nearly 800,000 km^2. It is floored by thin continental crust. The high TAM form the western and southern rim of the embayment. Today the Ross Sea and the Ross Ice Shelf occupy this marine embayment. Defined by volcanic islands and peninsulas, McMurdo Sound, with water depths of 300–800 m, is on the western side of the embayment at the latitude of the calving margin of the Ross Ice Shelf. West Antarctic ice streams, along with outlet glaciers that pass through the TAM from the East Antarctic Ice Sheet, feed this ice shelf. During winter months, an apron of sea-ice extends north of the calving margin of the ice shelf (on average about 78° S in the western Ross Embayment) to about 66° S latitude. The Ross Ice Shelf generally has a smooth upper accumulation surface free of debris. An exception is the McMurdo Ice Shelf appendage tucked into McMurdo Sound just north of the topographic obstacles of Minna Bluff, Mt Discovery, and Mt Morning (Fig. 1; see also Kellogg *et al.* 1990). Surface debris on the McMurdo Ice Shelf includes remains of fish, sponges, starfish, and shells, as well as poorly sorted sands and gravels. The combination of sea water/sediment freezing onto the base of the McMurdo Ice Shelf and intense surface ablation initiates an internal upward migration of ice with this enclosed debris (Debenham 1919; Kellogg *et al.* 1990). Accentuated surface ablation is here a consequence of prevailing southwesterly winds, which are adiabatically warmed as they descend from Minna Bluff and Mt Discovery and pass across the ice shelf (Fig. 1).

Ross Island and Cape Bird

Ross Island is located near the western margin of the Ross Embayment (Fig. 1). McMurdo Sound adjoins western Ross Island, the Ross Sea fringes northern Ross Island, and the McMurdo and Ross Ice Shelves abut southern Ross Island. Ross Island itself comprises four volcanoes: Mts Terror (3262 m), Terra Nova (2130 m), Erebus (3794 m), and Bird (1800 m). Only Mt Erebus is active today. Although glacier ice mantles most of Ross Island, small ice-free areas occur at Hut Point, Cape Royds, Cape Evans, Turks Head, Cape Crozier, and Cape Bird. There is extensive ice- free terrain 15 km south of Cape Bird at the northwest margin of Ross Island (between 161°21'E and 166°30'E longitude and 77°13'S and 77°20'S latitude) adjacent to McMurdo Sound. For simplicity we here refer to this ice-free area as Cape Bird even though this designation is not strictly correct. The ice-free terrain extends from the coast up to the western margin of an ice cap centered on Mt Bird. This ice cap feeds several outlet glaciers that flow around parasitic cinder cones and terminate on land. Shell Glacier is the largest of these glaciers. It descends from 560 m to about 50 m elevation, effectively dividing the ice-free areas at Cape Bird into northern and southern sectors (Fig. 2). Exposed bedrock at Cape Bird consists of lava flows, breccias, agglomerates, and pillows of trachyte and basalt. Kenyte does not crop out at Cape Bird, although this distinctive alkali-rich volcanic rock is common farther south along the west coast of Ross Island at Capes Royds/Barne, Cape Evans, and Turks Head. Instead, trachyte and basalt bedrock at Cape Bird forms 15° to 20° slopes that extend from the coast up to the margin of the Mt Bird ice cap. Steep cliffs face the coast at two areas in the north-central and southern sectors of this ice-free region.

Glacial geology of Cape Bird

Cape Bird drift

A single, little weathered, and nearly continuous diamicton mantles most of the volcanic bedrock in the ice-free area at Cape Bird. This poorly sorted diamicton extends without variation in weathering indices or lithology from the northern tip of the ice-free area to two unnamed glaciers south of Shell Glacier. The diamicton exposed north of Shell Glacier is thick (>30 m in places) and extends without morphological break from the coast up to (and underneath) the lower margin of Mt Bird ice cap (Fig. 2). The exposed upper limit of this diamicton is at 590 m elevation. To the south of Shell Glacier, the diamicton occurs in isolated patches that thin to feather edges on weathered volcanic bedrock.

This widespread diamicton is matrix-supported, slightly to well-stratified, and light gray in color (2.5Y 5/4). It features erratic clasts of granite, dolerite, sandstone, quartzite, marble, granodiorite, garnet-bearing granite, and orthoquartzite. Kenyte is an extremely rare erratic (only five clasts were found). Granite erratic boulders tend to be subrounded, without cavernous weathering. Dolerite erratic boulders are slightly more angular than granite boulders and also lack both cavernous weathering and ventifaction. Striations are pre-

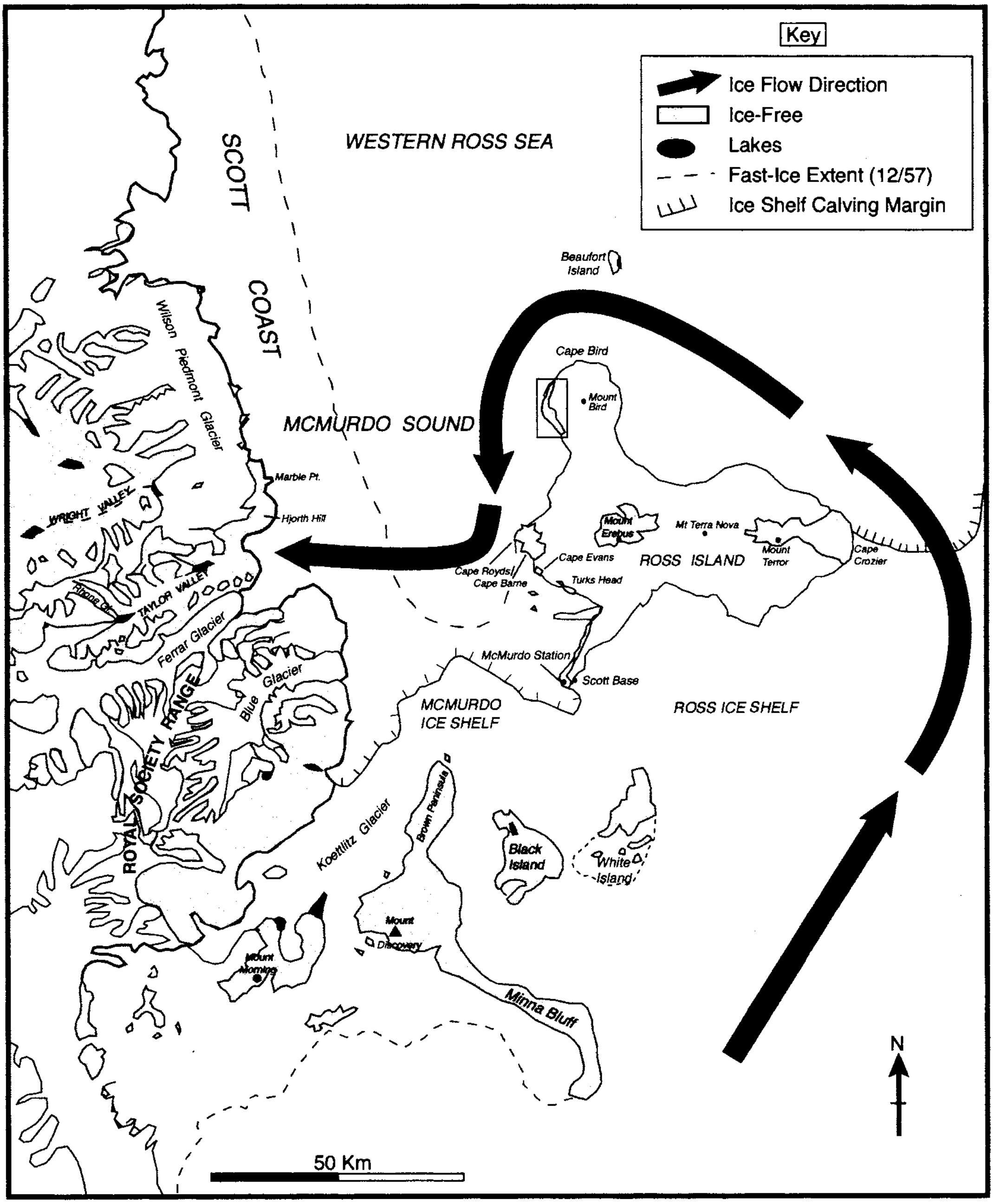

Fig. 1. Location map. Large arrows indicate a principal flowline for LGM ice grounded in McMurdo Sound and the western Ross Embayment. See text for explanation. See Denton and Hughes (2000) for a reconstruction of a grounded ice sheet in McMurdo Sound at the LGM.

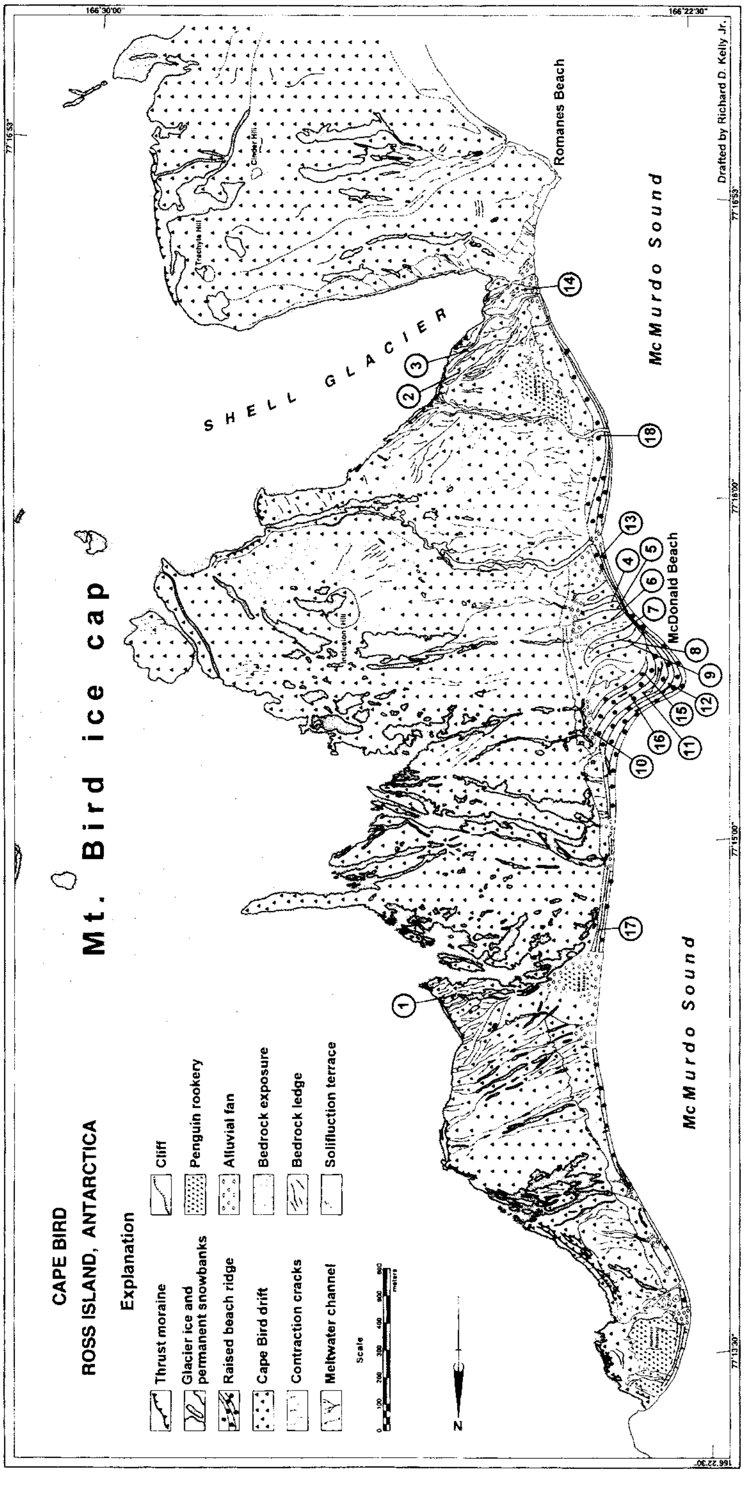

Fig. 2. Surficial geology map of Cape Bird. Circled numbers refer to radiocarbon sample sites in Table 1.

Fig. 3. Thrust moraines alongside Shell Glacier, Cape Bird.

served on some dolerite boulders. Reworked marine shell fragments (mostly barnacles, *Bathylasma corolliforme* (Hoek)), sponge spicules, echinoderm spines, and foraminifers, as well as thin (2–5 cm) lenses of debris-laden ice, occur within the diamicton north, and less commonly south, of Shell Glacier. Foraminifers within the diamicton include *Cibicides refulgens, Ehrenberingina glabra, Trifarina, Cassidulina, and Cassidulinoides porrecta* (T. Kellogg, personal communication, 1994).

In natural sections in meltwater channels north of Shell Glacier, the diamicton features a succession of alternating layers of mud (1–5 cm thick), fine- to coarse-grained sand (10–75 cm thick), and gravel (10–20 cm thick). Within these stratified layers are erratic cobbles of granite, marble, dolerite, and sandstone, as well as local volcanic clasts. Enveloping mud-rich layers terminate abruptly at the margin of these clasts, rather than bending above or below them. The erratic clasts in this diamicton constitute from 1 to 5% of the cobble fraction. About 5% of all cobbles are striated. In general, the diamicton thickens from a maximum of >30 m near the coast to about 2 m at its upper limit near the ice-cap margin.

The widespread diamicton is here termed Cape Bird drift. Marine shell fragments and far-traveled TAM erratics indicate that Cape Bird drift could not have been deposited by local ice flowing off Mt Bird. Rather, granite, dolerite, and sandstone erratics within Cape Bird drift, as well as enclosed marine shells and foraminifers, indicate that a component of the ice flowed through the TAM, grounded on the sea floor, and ultimately advanced landward onto the lower slopes of Mt Bird. Radiocarbon dates of enclosed marine shells indicate that Cape Bird drift was deposited after 26,860 ± 390 ^{14}C yr BP (UGA-6795), the age of the youngest dated marine shell fragment from Cape Bird drift (Table 1). The erratics, striated cobbles, and stratified layers of mud, sand, and gravel together indicate deposition from glacial ice. In fact, regelation ice is inferred from the finely laminated, horizontally stratified sediments that terminate at the margin of included pebbles and cobbles. Such a configuration of mud layers and pebbles is predicted for basal freezing of sediments and can be seen today in dirty ice along the base of Shell Glacier and the Mt Bird ice cap.

Moraine ridges

Up to 40 m long and 10 m high, linear ridges occur parallel to and within 5 to 10 m of the margins of both Shell Glacier and the ice cap centered on Mt Bird (Fig. 3). These ridges show ice-proximal slopes that are steeper (as much as 35°) than distal slopes (as much as 25°), and contain an internal core of ice as much as 8 m thick. Where exposed in section, this core consists of alternating bands of clear and debris-rich ice. The debris-rich bands are 10–15 cm thick and dip 35° to 45° back toward the glacier. Laminated muds within these bands terminate abruptly at clast margins. The loose debris on the ice core is thin, little weathered, and matrix-supported. This debris is thinnest along ridge crests

Table 1. Radiocarbon dates, Cape Bird, Ross Island, Antarctica.

Site no.[1]	Lab. no.[2]	Age[3] (^{14}C yr BP)	δ^{13}C (‰)	Material	Context and significance[4]
1	UGA-6793	40,155 ± 1350 **38,855 ± 1350**	+1.37	Marine shell	Shell fragment reworked into Cape Bird drift. Sample locality at 266 m elevation. Maximum age for Cape Bird drift.
2	UGA-6794	34,460 ± 730 **33,160 ± 730**	+0.79	Marine shell	Shell fragment reworked into Cape Bird drift. Sample locality at 137 m elevation. Maximum age for Cape Bird drift.
3	UGA-6795	28,160 ± 390 **26,860 ± 390**	+0.46	Marine shell	Shell fragment reworked into Cape Bird drift. Sample locality at 122 m elevation. Maximum age for Cape Bird drift.
4	UGA-6826	4415 ± 80 **3115 ± 80**	−19.5	Penguin bone (collagen)	Abraded penguin bone from 7.5 m elevation reworked into beach no. 11. Affords an age for the upper set of beaches.
5	UGA-6805	4295 ± 80 **2995 ± 80**	−17.7	Penguin bone (collagen)	Abraded penguin bone from 7.2 m elevation reworked into beach no. 10. Affords an age for the upper set of beaches.
6	UGA-6808	4820 ± 90 **3520 ± 90**	−19.9	Penguin bone (collagen)	Abraded penguin bone from 6.3 m elevation reworked into beach no. 9. Affords an age for the upper set of beaches.
7	UGA-6809	4885 ± 95 **3585 ± 95**	−22.7	Penguin bone (collagen)	Abraded penguin bone from 5.7 m elevation reworked into beach no. 8. Affords an age for the upper set of beaches.
8	UGA-6796	4420 ± 75 **3120 ± 75**	−19.7	Penguin bone (collagen)	Abraded penguin bone from 5.4 m elevation reworked into beach no. 7. Affords an age for the upper set of beaches.
9	AA-15332	4537 ± 56 **3237 ± 56**	−23.4	Penguin bone (collagen)	Abraded penguin bone from 5.1 m elevation reworked into beach no. 6. Affords an age for the upper set of beaches.
9	AA-15333	4504 ± 56 **3204 ± 56**	−22.8	Penguin bone (collagen)	Ditto, except different sample.
10	UGA-6810	1440 ± 60 **140 ± 60**	−23.3	Penguin bone (collagen)	Abraded penguin bone from 3.4 m elevation reworked into beach ridge no. 3. Young age represents date of modern beach (within modern storm limit).
11	UGA-6799	1915 ± 60 **615 ± 60**	−21.3	Penguin bone (collagen)	Abraded penguin bone from 2.8 m elevation in beach ridge no. 3. Young age represents date of modern beach (within modern storm limit).
12	AA-15328	1187 ± 45 **modern**	−25.2	Penguin bone (collagen)	Abraded penguin bone from 2.0 m elevation reworked into beach ridge no. 2. Young age represents date of modern beach (within modern storm limit).
13	UGA-6802	730 ± 65 **modern**	−29.0	Penguin bone (collagen)	Abraded penguin bone from 1.6 m elevation reworked into beach ridge no. 1. Young age represents date of modern beach (within modern storm limit).
14	UGA-6792 B	1195 ± 55 **modern**	−20.7	Penguin bone (collagen)	Abraded penguin bone from 30 cm depth reworked into stratified gravels. Sample collected from distal portion of modern fan that overlies elevated wave-cut terrace situated about 750 m south of McDonald Beach. Sample elevation is 7.6 m. Provides minimum age for terrace construction and former marine limit at Cape Bird.
14	UGA-6792 H	1035 ± 50 **modern**	−0.14	Penguin skin	Ditto, except sample is of penguin skin from 35 cm depth.
14	UGA-6792 H	1080± 50 **modern**	−0.14	Penguin skin	Ditto, except repeat analysis of penguin skin.
15	AA-15331	11,039 ± 74 **9739 ± 74**	−22.6	Penguin bone (collagen)	Abraded penguin bone from 3.8 m elevation reworked into beach ridge no. 5. Anomalous old date is questionable given the low elevation of the beach within the modern storm limit.
16	AA-15330	5175 ± 58 **3875 ± 58**	−21.5	Penguin bone (collagen)	Abraded penguin bone from 3.6 m elevation in beach ridge no. 4. Anomalous old date is questionable given the low elevation of the beach within the modern storm limit.
17	NZ-5990	8080 ± 160 **6780 ± 160**	–	Penguin remains	Penguin remains from *in-situ* guano horizon buried beneath 30 cm of stratified beach sediments that probably represent a modern storm beach. Date from Speir and Cowling (1984). Anomalous old date is questionable given the low elevation of the beach (3.5 m) within the modern storm limit.
17	NZ-5590	7070 ± 180 **5770 ± 180**	–	Penguin remains	Ditto, except different sample.
18	UGA-6807	3510 ± 60 **2210 ± 60**	−19.7	Penguin bone (collagen)	Penguin bone from abandoned rookery that overlies beach ridge at about 6.0 m elevation. This beach occurs about 325 m north of Mc Donald Beach.

[1] See Figs 2 and 5 for location of radiocarbon sample sites.
[2] UGA prefix indicates AMS samples prepared at the University of Georgia Center for Applied Isotope Studies and analyzed at the NSF-Arizona AMS Facility. AA prefix indicates AMS samples processed and analyzed at the NSF-Arizona AMS Facility.
[3] Top age of each sample is not corrected for marine reservoir effect. Bottom age in bold is corrected for marine reservoir effect of 1300 ^{14}C yr (Berkman and Forman 1996). The word 'modern' is written where a correction of an original date would result in a negative age.
[4] Elevations of radiocarbon samples from beaches are relative to MHT.

Fig. 4. Oblique air photograph of raised beaches at McDonald Beach, Cape Bird.

(10–30 cm) and thickest at the base of distal slopes (>1.0 m). Erratics of granite, dolerite, and sandstone, as well as reworked marine shell fragments, are locally abundant.

The morphology, proximity to glacier margins, and internal core of banded ice together suggest that the ridges are thrust moraines produced alongside the margins of the Mt Bird ice cap and Shell Glacier. The enclosed shell fragments and erratic cobbles indicate that the moraines are made up of reworked Cape Bird drift. An important point is that the Mt Bird ice cap and Shell Glacier both must have been less extensive than now during deposition of Cape Bird drift. Therefore, because these glaciers have advanced seaward since deposition of Cape Bird drift, we conclude that the mapped upper limit of 590 m at the ice cap margin represents a minimum surface elevation for the ice that deposited Cape Bird drift. This conclusion is supported by the fact that Cape Bird drift lacks a clear upper limit defined by a moraine.

Coastal sediments

Sediments below 7.6 m elevation at Cape Bird commonly are sorted, stratified, clast-supported, and free of fine-grained silt and clay. This contrasts sharply with the texture of sediments above 7.6 m, most of which are matrix-supported. Furthermore, sediments below 7.6 m elevation are fashioned into gravel ridges or horizontal terraces. Therefore, we conclude that the upper limit of wave washing (hereafter, marine limit) lies at 7.6 m elevation (obtained using electronic distance-measuring (EDM) equipment with reference to mean high tide (MHT)). What follows is a description of the morphology, sedimentology, and organic content of beaches and stratified sediments below the marine limit at Cape Bird.

Beaches at Cape Bird are among the best developed in the western Ross Embayment (Fig. 4). The beaches are continuous along much of the Cape Bird coast and are constructed of imbricated cobbles and gravels. Beaches below 4.0 m elevation are parallel to the modern coastline. In contrast, beach ridges above 4.0 m elevation, particularly those at McDonald Beach, are perpendicular to the modern coastline. As seen in Figs 4 and 5, these higher beaches, which trend roughly east–west, are truncated by a steep scarp (0.8 to 1.4 m high) located 30–100 m inland of the modern coastline.

The lower set of beaches at Cape Bird is composed of five sharp-crested gravel ridges. These ridges are numbered sequentially in Fig. 5. Ridge 1 is nearest the present-day coastline. It extends laterally for a distance of 4.6 km and reaches a maximum elevation of 1.6 m. Unlike all other beaches at Cape Bird, this ridge is cored by ice. The average $\delta^{18}O$ composition of the ice core is –0.14‰, indicating that it is frozen seawater. Melting of the core has produced numerous pits on the ridge surface. Farther inland, beach ridges 2, 3, 4, and 5 occur at progressively higher elevations (each ridge on average is about 0.5 m higher or

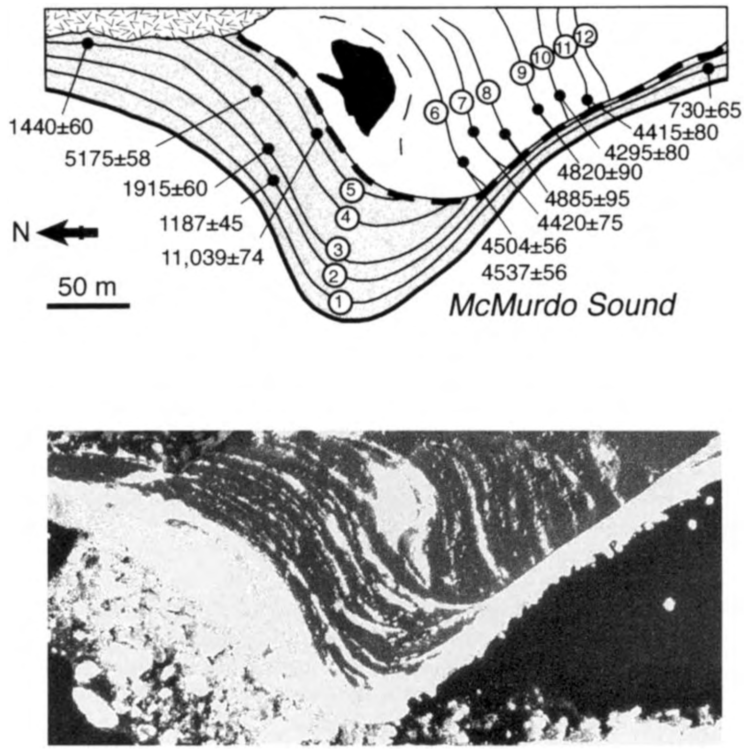

Fig. 5. Geomorphic map of beach ridges at Cape Bird. Top panel shows two sets of raised beaches at McDonald Beach. Shaded region shows five beach ridges that lie below 4.0 m elevation. Circled numbers refer to beach sequence outlined in text. Maximum marine limit as measured from beach ridge number 12 is 7.6 m above MHT. Radiocarbon ages shown on diagram are uncorrected for marine-reservoir effect (see Table 1 for corresponding site numbers, laboratory numbers, and corrected ages). As outlined in the text, the upper set of storm beaches was probably produced about 4885 ^{14}C yr BP (3585 ^{14}C yr BP, corrected) and the lower set of beaches (ridge numbers 1 to 5) is modern. Dashed line marks the scarp that separates the upper and lower sets of beaches. Bottom panel highlights McDonald Beach as depicted on USGS air photograph, TMA 3063, frame 104.

lower than the adjacent ridges), and lack evidence of active thermokarst.

The seven gravel ridges at McDonald Beach that are nearly perpendicular to the present-day coast constitute the upper set of beaches at Cape Bird. These ridges (numbered 6–12 on Fig. 5) exhibit a slightly greater degree of surface weathering (some volcanic clasts are fractured and ridge crests are more subdued) than the beaches below 4.0 m elevation, but otherwise are similar in spacing and internal structure to the low-elevation beaches. Beach elevations are listed in Table 1.

Fig. 5 shows the key geometric relationships among the upper and lower sets of beaches and the intervening scarp at McDonald Beach. The scarp is best explained by shoreline erosion and truncation of the upper beaches during major storms. The modern marine limit (upper elevation of wave washing during storms) in this sector of the Ross Embayment is 3.5 to 4.0 m above MHT (Kirk 1991; Colhoun *et al.* 1992). Because they are less than 4.0 m in elevation and are parallel to the modern coastline, the lower beaches were almost certainly produced during modern storms. Further, because beaches of the upper and lower sets are similar in internal structure and texture, all of the gravel ridges at McDonald Beach are probably storm beaches. If this inference is correct, then the upper beaches were produced by storms at a time when relative sea level was higher than at present. Assuming little change either in the energy of storm waves at McDonald Beach or in the sediment supply over the past several thousand years, the upper set of beaches formed when relative sea level was about 3.6 m higher than today (the maximum marine limit of 7.6 m, less the modern storm limit of about 4.0 m).

Excavations in beaches at Cape Bird (locations in Fig. 5) revealed penguin bones. With the exception of a single site north of McDonald Beach, these bones do not occur within buried *in-situ* nesting horizons. Rather, bones are generally abraded and are dispersed throughout the beach gravels. Therefore, we argue that the penguin bones were reworked into the beaches during storms. Assuming only limited reworking of fragile penguin remains, AMS radiocarbon dates of buried bones should afford a chronology of beach development.

Radiocarbon chronology

A chronology of Cape Bird drift and beaches comes from AMS radiocarbon dates of reworked marine shell fragments and penguin remains. Table 1 lists radiocarbon dates of samples from Cape Bird. Unless otherwise noted, all ages in the text are corrected by 1300 ^{14}C yr for the marine reservoir effect (Berkman and Forman 1996). Dates of reworked marine shell fragments from Cape Bird drift range from 26,860 ± 390 ^{14}C yr BP (UGA-6795) to 38,855 ± 1350 ^{14}C yr BP (UGA-6793). Because the dated marine shells must have been transported by a grounded ice sheet that advanced across the sea floor and onto Cape Bird, we argue that deposition of Cape Bird drift occurred after 26,860 ^{14}C yr BP.

Radiocarbon dates of collagen from penguin bones buried in beaches afford minimum ages for Cape Bird drift and constrain the onset of seasonally open marine waters off Cape Bird. Four uncorrected dates of bones in the low set of beaches range from 730 ± 65 ^{14}C yr BP (UGA-6802) to 1440 ± 60 ^{14}C yr BP (UGA- 6810); one abraded penguin bone gave a slightly older age of 1915 ± 60 ^{14}C BP (UGA-6799). If corrected by 1300 ^{14}C yr for the marine reservoir effect (Berkman and Forman 1996), these dates, and therefore the lower set of beaches, are essentially modern. Seven corrected dates of collagen from abraded penguin bones in the upper beaches range from 2995 ± 80 ^{14}C yr BP (UGA-6805) to 3585 ± 95 ^{14}C yr BP (UGA-6809). If our conclusion that the beach ridges formed during storms is correct, then relative sea level was 3.6 m above MHT at about 3585 ^{14}C yr BP.

Four radiocarbon dates of samples from beaches at Cape Bird are at odds with the above scenario. All four samples were collected below the modern storm limit at McDonald Beach, that is, below 4.0 m above MHT. The first sample is of collagen from an abraded penguin bone in beach ridge 5 (at about 3.8 m above MHT). It yielded an age of 9739 ± 74 ^{14}C yr BP (AA-15331). The second sample, also collagen from an abraded penguin bone, is from within beach ridge 4 and afforded an age of 3875 ± 58 ^{14}C yr BP (AA-15330). Two other anomalous dates both come from earlier work on an *in-situ* organic horizon (largely penguin guano) buried beneath 30 cm of stratified sand and gravel (probable storm beach) at the northern limit of McDonald Beach about 3.5 m above MHT. Described as penguin remains, one sample from this layer gave a date of 8080 ± 160 ^{14}C yr BP (uncorrected, NZ-5990); the other sample was a penguin bone that yielded an age of 7070 ± 180 ^{14}C yr BP (uncorrected, NZ-5590) (Heine and Speir 1989; Speir and Cowling 1984). Taken at face value, these dates suggest that the lower set of storm beaches at Cape Bird is older than the upper set by about 4000 ^{14}C yr. We feel that an age difference in this sense is very unlikely because of the geometric relationship between the two sets of beaches, and because the samples are located within the modern storm beaches. Therefore, we conclude that the dates of abraded old penguin bones (9739 ± 74 ^{14}C yr BP and 3875 ± 58 ^{14}C yr BP) in beach ridges 5 and 4 are incorrect. The two dates from the *in-situ* nesting horizon (Heine and Speir 1989) buried beneath a probable storm beach, likewise, appear to be anomalously old. Similar problems with old and stratigraphically inverted dates of penguin remains have been encountered at Dunlop Island on the Scott Coast (C. Baroni, personal communication to G.H.D. 1999). Hence, there may be problems in using penguin remains to date deglaciation of the Ross Embayment. For now, we accept the dates that are in accord with the general morphology at McDonald Beach and consider 2995 ± 80 ^{14}C yr BP to 3585 ± 95 ^{14}C yr BP to reflect the age of the upper set of beaches at Cape Bird. The lower set of beaches lies within the present storm limit and is almost certainly modern.

Discussion

Several points arise from the data presented above. First, the AMS radiocarbon dates of marine shells, together with the areal extent and upper limit of Cape Bird drift, indicate that glacier ice covered Cape Bird up to at least 590 m elevation at some time after 26,860 ^{14}C yr BP and prior to 3585 ^{14}C yr BP. Second, because McMurdo Sound adjacent to Cape Bird is between 300 and 800 m deep, the ice that deposited Cape Bird drift must have been grounded on the floor of the sound. Third, because the modern ice cap centered on Mt Bird has reworked Cape Bird drift into prominent thrust moraines, we argue that this cap is now at its Holocene maximum.

Flowlines within the grounded ice body that deposited Cape Bird drift can be inferred from the provenance of far-traveled erratics. Because the dolerite, sandstone, and granite erratics were probably derived from the TAM, and because Cape Bird drift contains numerous reworked marine shell fragments, we conclude that a component of the glacier ice flowed through the TAM and into the ice sheet grounded on the Ross Sea floor before it ultimately advanced landward onto the lower slopes of Mt Bird. The absence in Cape Bird drift of numerous erratics of kenyte (the common bedrock lithology on western Ross Island south of Cape Bird) indicates that grounded ice did not flow northward along the west coast of Ross Island, that is, from Cape Royds to Cape Bird. Otherwise kenyte erratics would be common in Cape Bird drift. The rare kenyte erratics present (only five found in the mapped area) likely were reworked.

On the basis of similar surface weathering characteristics, radiocarbon chronologies, and geomorphic setting, we correlate Cape Bird drift with Ross Sea drift along the Scott Coast (Denton and Marchant 2000; Hall *et al.* 2000). If this correlation is correct, then an ice sheet with upper limits of as much as 350 m elevation along western McMurdo Sound at Hjorth Hill (Hall *et al.* 2000) and of more than 590 m at Cape Bird was grounded on the floor of the sound after 26,860 ^{14}C yr BP (UGA-6795) and before 3885 ^{14}C yr BP. The data from Cape Bird alone cannot yield the precise configuration of the ice-sheet in McMurdo Sound at the LGM. However, it is evident that grounded ice could not have flowed eastward across McMurdo Sound because reconstructed ice-surface elevations are at least 200 m higher at Cape Bird than they are at Hjorth Hill. Furthermore, the presence of numerous kenyte erratics within Ross Sea drift in Taylor Valley (Hall *et al.* 2000) implies that grounded glacier ice must have flowed from the kenyte source on Ross Island westward across the sound (Fig. 1; Denton and Marchant 2000; Hall *et al.* 2000). Taken together, our data imply that the grounded ice sheet included a flowline that passed westward around northern Ross Island, then southward across Cape Bird, Capes Royds/Barne, and Cape Evans, and finally westward again across McMurdo Sound (Fig. 1). An additional implication is that a grounded ice sheet with surface elevations in excess of 590 m occupied the Ross Embayment east of Ross Island at the LGM (Fig. 1). This scenario is consistent with the mapped upper limits in excess of 710 m elevation for Ross Sea drift at Cape Crozier, 80 km east of Cape Bird at the eastern tip of Ross Island (Denton and Marchant 2000). The paucity of kenyte erratics in Cape Bird drift indicates that grounded ice did not flow northward along the west coast of Ross Island, even during the waning phases of the last glaciation. This suggests that ice withdrew from McMurdo Sound prior to the retreat of ice grounded east of Ross Island.

Given that the mapped upper limit of Cape Bird drift is at 590 m elevation, and that the marine limit is only 7.6 m above MHT, the beaches at Cape Bird probably reflect isostatic uplift only since the development of seasonally open water off Cape Bird by 3585 ^{14}C yr BP, after retreat of a lingering ice shelf. Alternatively, the lowness of beaches at Cape Bird could indicate tectonic subsidence on volcanically active Ross Island. In either case, the beaches do not reflect either the total thickness of grounded LGM ice or the total isostatic uplift since recession of grounded ice.

Conclusions

- An ice sheet grounded on the floor of McMurdo Sound impinged on Cape Bird on the northwestern tip of Ross Island to an elevation in excess of 590 m. This ice sheet deposited Cape Bird drift after 26,860 ^{14}C yr BP and prior to 3585 ^{14}C yr BP. A component of this grounded ice must have originally flowed through the TAM and into the Ross Embayment in order to transport granite, dolerite, and sandstone erratics to Cape Bird.
- The paucity of kenyte erratics in Cape Bird drift indicates that grounded glacier ice did not flow northward along the west coast of Ross Island from Cape Royds toward Cape Bird during the last glaciation.
- Because the modern ice cap centered on Mt Bird has reworked Cape Bird drift into prominent thrust moraines, we argue that this cap is now at its maximum Holocene extent.
- On the basis of similar surface weathering characteristics, radiocarbon chronology, and geomorphic setting, we correlate Cape Bird drift with Ross Sea drift along the Scott Coast and on volcanic islands and peninsulas in McMurdo Sound (Denton and Marchant 2000; Hall *et al.* 2000). If this correlation is correct, than a grounded ice sheet in McMurdo Sound must have flowed westward from Ross Island to the Scott Coast at the LGM. This conclusion is reached because reconstructed ice-surface elevations are 200 m higher at Cape Bird (at least 590 m) than they are along the Scott Coast (350 m at Hjorth Hill (Hall *et al.* 2000)). If we combine our ice-surface elevation and provenance data, then it becomes apparent that grounded ice at Cape Bird included a flowline that passed westward around the northern tip of Ross Island,

southward from Cape Bird to Cape Evans, and then westward again across McMurdo Sound toward the TAM.
- Significant glacial-isostatic rebound probably occurred at Cape Bird while an adjacent ice shelf lingered after recession of grounded ice. Otherwise, the marine limit at Cape Bird would be much higher than 7.6 m elevation. Alternatively, tectonic subsidence of Ross Island could have depressed beach elevations. In either case, the beaches do not reflect the total thickness of grounded glacier ice that lapped onto Cape Bird at the LGM. Rather, the best evidence at Cape Bird for thick glacier ice in McMurdo Sound and east of Ross Island during the LGM comes from the areal distribution, upper limit, and AMS radiocarbon chronology of Cape Bird drift.

Acknowledgements

We thank Charles Lagerbom, Robin Verow, and Jonathan Whittier for assistance in the field. The Office of Polar Programs of the United States National Science Foundation supported this work. We are grateful to the NSF-Arizona Accelerator Mass Spectrometry (AMS) Facility for dating the radiocarbon samples.

Tina M. Dochat, Institute for Quaternary Studies, University of Maine, Orono ME 04469, USA.

David R. Marchant, Department of Earth Sciences, 675 Commonwealth Avenue, Boston University, Boston, MA 02215, USA.

George H. Denton, Department of Geological Sciences and Institute for Quaternary Studies, University of Maine, Orono, Maine 04469-5790, USA.

References

Berkman, P.A. and Forman, S.L., 1996: Pre-bomb radiocarbon and the reservoir correction for calcareous marine specimens in the Southern Ocean. *Geophysical Research Letters,* 23: 363–366.

Bockheim, J.G., Wilson, S.C., Denton, G.H., Andersen, B.G. and Stuiver, M., 1989: Late Quaternary ice surface fluctuations of Hatherton Glacier, Transantarctic Mountains. *Quaternary Research,* 31: 229–254.

Colhoun, E.A., Mabin, M.C.G., Adamson, D.A. and Kirk, R.M., 1992: Antarctic ice volume and contribution to sea-level fall at 20,000 yr BP from raised beaches. *Nature,* 358: 316–319.

Debenham, F., 1919: A new mode of transportation by ice. *Quarterly Journal of the Geological Society of London,* 75: 51–76.

Denton, G.H. and Hughes, T.J., 2000: Reconstruction of the Ross ice drainage system, Antarctica, at the last glacial maximum. *Geografiska Annaler,* 82 A: 143–166.

Denton, G.H. and Marchant, D.R., 2000: The geologic basis for a reconstruction of a grounded ice sheet in McMurdo Sound, Antarctica, at the last glacial maximum. *Geografiska Annaler,* 82 A: 167–211.

Denton, G.H., Prentice, M.L. and Burckle, L.H., 1991: Cainozoic history of the Antarctic Ice Sheet. *In*: Tingey, R.J. (ed.): The Geology of Antarctica. Clarendon Press. Oxford. 365–433.

Denton, G.H., Bockheim, J.G., Wilson, S.C. and Stuiver, M., 1989a: Late Wisconsin and early Holocene glacial history, inner Ross Embayment. *Quaternary Research,* 31: 151–182.

Denton, G.H., Bockheim, J.C., Wilson, S.C., Leide, J.E. and Andersen, B.G., 1989b: Late Quaternary ice-surface fluctuations of Beardmore Glacier, Transantarctic Mountains. *Quaternary Research,* 31: 183–209.

Hall, B.L., Denton, G.H. and Hendy, C.H., 2000: Evidence from Taylor Valley for a grounded ice sheet in the Ross Sea, Antarctica. *Geografiska Annaler,* 82 A: 275–303.

Heine, J.C. and Speir, T.W., 1989: Ornithogenic soils of the Cape Bird Adelie penguin rookeries, Antarctica. *Polar Biology,* 10: 89–99.

Hollin, J.T., 1962: On the glacial history of Antarctica. *Journal of Glaciology,* 4: 173–195.

Kellogg, T.B., Kellogg, D.E. and Stuiver, M., 1990: Late Quaternary history of the southwestern Ross Sea: Evidence from debris bands on the McMurdo Ice Shelf, Antarctica. *In:* Elliot, D.H. (ed.): *Contributions to Antarctic Research I. American Geophysical Union Antarctic Research Series,* 50. 25–56.

Kirk, R.M., 1991: Raised beaches, late Quaternary sea level and deglacial sequences on the Victoria Land coast, Antarctica. *In*: Gillieson, D. and Fitzsimons, S. (eds): Quaternary Research in Australian Antarctica 3. University of New South Wales, Canberra. 85–106.

Shipp, S.S., Anderson, J. and Domack, E., 1999: Late Pleistocene-Holocene retreat of the West Antarctic Ice-Sheet system in the Ross Sea: Part 1-Geophysical results. *GSA Bulletin,* 111: 1486–1516.

Speir, T.W. and Cowling, J.C., 1984: Ornithogenic soils of the Cape Bird Adelié penguin rookeries, Antarctica-Chemical Properties. *Polar Biology,* 2: 199–205.

Stuiver, M., Denton, G.H., Hughes, T.J. and Fastook, J.L., 1981: History of the marine ice sheet in West Antarctica during the last glaciation: A working hypothesis. *In*: Denton, G.H. and Hughes, T.J. (eds): The Last Great Ice Sheets. John Wiley and Sons. New York. 319–436.

Manuscript received May 1999, revised and accepted Jan. 2000.