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E.A. Colhoun
and
D.A. Adamson

Raised Beaches of the Bunger Hills, Antarctica

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Contents

Abstract 1

1. INTRODUCTION 3
1.1 Methods used and marine features observed 5
1.2 Dating 5

2. EXPLANATORY DESCRIPTION OF THE MARINE FEATURES 8
2.1 Geographers Island 8
2.2 Thomas Island 13
2.3 Charnockite Peninsula 18
2.4 The mainland coast east of Cape Surovyi and Kashalot Island 20
2.5 The mainland coast west of Cape Surovyi 23
2.6 The Krylatyy and Vertolyetnyy Peninsulas 32
2.7 The Transkriptsii Inlet 36

3. DISCUSSION AND CONCLUSIONS 38

Acknowledgments 44

References 45

Figures
1. Location map of Bunger Hills 4
2. Location of Figures 3, 8, 15, 16, 19 6
3. Map of raised beach sites on Geographers Island 9
4. Raised beach gravels extending to 9 m on Geographers Island 10
5. Sea ice pushed boulder ridge forming part of kalottenberg at 6.5 m on Geographers Island 10
6. Younger Edisto Moraine formed between shelf ice edge and south-western shore of Geographers Island 11
7. Shelf ice pushed moraine ridges, Geographers Island 11
8. Map of raised beach sites, Thomas Island 12
9. Older and Younger Edisto Moraines, Thomas Island 14
10. The 5.2 m shoreline cut in the Older Edisto Moraine, north-west Thomas Island 14
11. Middle north coast Thomas Island beach profile. 15
12. Wavewashed rock and aligned boulders at lower limit of moraine, north-east Thomas Island 16
13. Fossil geo 4 m deep excavated along a dolerite dyke, eastern Thomas Island 17
14. Sea ice pushed block shoreline and wave formed beach terrace, central Geo Bay, Thomas Island 18
15. Map of raised beach sites Charnockite Island 19

16. Map of mainland coast beach sites east of Cape Surovyi 21
17. Ostrovnaya Bay showing ML at 8.4 m. Snowpatch hollow on right is site of *Laternula* fragments 22
18. Raised beach terrace with ML at 8.5 m on north-west Kashalot Island 24
19. Map of raised beach sites around Fish Tail Bay, Krylatyy and Vertolyetnyy Peninsulas, and Transkriptsii Inlet 25
20. Raised beaches at Ice Axe Bay 26
21. Profile of raised beach forms at Ice Axe Bay 27
22. *Laternula elliptica* in growth position, Ice Axe Bay 28
23. Profile of raised beach forms on the eastern side of Fish Tail Bay West 29
24. Marine limit at 9.4 m in Fish Tail Bay West, showing depressions near the shoreline due to ice floe stranding 30
25. Sea ice pushed block shoreline towards eastern end of Fish Tail Bay West 30
26. Irregular inner part of marine rock platform cut in mafic granulite with low cliff behind, Krylatyy Peninsula 31
27. Profile of beach forms north of Krylatyy Peninsula 34
28. Sloping gravel beach with multiple ridges north of Krylatyy Peninsula 35
29. Raised beach terrace cut in moraine to 9 m height north of Davis station, Vestfold Hills 40

Table

1. Radiocarbon dates 7

Raised Beaches of the Bunger Hills, Antarctica

Eric A. Colhoun
Department of Geography, University of Newcastle,
New South Wales 2308, Australia

and

Donald A. Adamson
School of Biological Sciences, Macquarie University, North Ryde,
New South Wales 2113, Australia

ABSTRACT

The raised marine terraces of the icebound Bunger Oasis are described. The Holocene marine transgression entered the oasis before 7.7 ka BP and raised beaches with marine limits 7.5 ± 1 m above the modern limit were formed throughout most of the oasis by 5.6–5 ka BP. All raised beaches recorded are of middle to late Holocene age and indicate an average isostatic uplift rate of 1.4 m/ka during this time. The raised beaches occur at similar altitudes to those at Vestfold Hills (up to 10 m) but are lower than the beaches on the Windmill Islands (23–30 m). Morphological evidence suggests that at Bunger Hills open water wave action may have been more important during middle than late Holocene times when strong sea ice pushing occurred on most beaches.

The last glaciation ice cover over the inner continental shelf at Bunger Hills appears to have been relatively thin, probably between about 154 and 400 m in thickness. The similarity in maximum altitudes of raised beaches at Vestfold Hills suggests similar ice thicknesses while the higher beaches at Windmill Islands suggests the ice may have been about 450 m thick. The evidence from the raised beaches in East Antarctica suggests that the expansion of continental ice was about 50% that envisaged by the Hughes et al. (1981) model derived from the Ross Sea. The ice sheet may not have extended to the edge of the continental shelf though more evidence is required from the shelf to determine its extent at maximum glaciation.

1. Introduction

Opportunity to study raised beaches on the east Antarctic coast is limited to a few deglaciated oasis areas and adjacent islands. In the central sector (70–120°E) of the Australian Antarctic Territory raised beaches have been reported from Vestfold Hills (Adamson and Pickard 1983 and 1986, Zhang and Peterson 1984), Bunger Hills (Rozycki 1961) and Windmill Islands (Løken 1959, Cameron and Goldthwait 1961). These reconnaissance studies indicate that more detail is required for each area. In January and February 1986, the authors examined the raised beaches of Bunger Hills during the Australian Antarctic Research Expedition that established the Edgeworth David station. They measured the height of marine limits, observed the morphology and sedimentary features of the beaches and obtained marine shells for radiocarbon dating. The results are discussed in this paper.

Bunger Hills Oasis (66° 10'S and 101°E) has an area of 952 km² of which 482 km² is land (Wisniewski 1983). In the south steeply-sloping hills of 100–150 m altitude, composed mainly of Precambrian gneisses, migmatities and charnockites, occur between the Antarctic ice sheet and the deeply indented coast that includes Transkriptsii Inlet, Fish Tail Bay (Rybiy Khvost Gulf), Ostrovnaya Bay and Kinzhal Gulf. From the Antarctic ice sheet the Remenchus Glacier discharges to the east and the Apfels and Scott Glaciers to the west. Kashalot Island lies adjacent to this southern region (Figure 1).

Kapakon Inlet separates Thomas Island and Charnockite Peninsula from the southern region. Thomas Island is tied to the floating Edisto Ice Tongue in the west (Adamson and Colhoun 1992) while Charnockite Peninsula is tied to the Antarctic ice sheet in the east. Many small islands of the Mariner group occur in the north-eastern part of the oasis.

Geographers Island consists of rocky hills and inlets lying between the Edisto Channel and the Highjump Archipelago which underpins the Shackelton Ice Shelf. The 350 m high Mill Island ice dome protrudes from the northern ice shelf beyond which the isostatically depressed outer continental shelf varies between 140 and over 500 m depth. East of Mill Island a deep trough extends north-south across the continental shelf and over 1000 m of water is recorded adjacent to the ice shelf. (Soundings by Royal Australian Navy, Hydrographic Office, Sydney.)

Bunger Hills Oasis is primarily due to Holocene flooding of the inlets and bays of the complex coastal zone. Marine incursion extends beneath the largely floating Shackleton Ice Shelf (Lazarev et al. 1965) and in the west the sea penetrates between the Scott, Obruchev and Denman Glaciers almost to the southern end of the Obruchev Hills some 35 km south-west of Bunger Hills (see Figure 47 in Swithinbank 1988).

Aerial observation suggests that inlets connect the oasis with the open sea on both sides of Mill Island. The Shackleton Ice Shelf has survived because it is heavily underpinned by rock and moraine islands of the Highjump Archipelago. Although the sea penetrates along the margins of the Scott and Denman Glaciers to Obruchev Hills, the Scott Glacier follows a trough and is grounded to approximately the Taylor Islands, 10–15 km west and north-west of Bunger Hills. The modern oasis was formed during early to middle Holocene times with break-up of the Antarctic ice sheet margin (Adamson and Colhoun 1992).

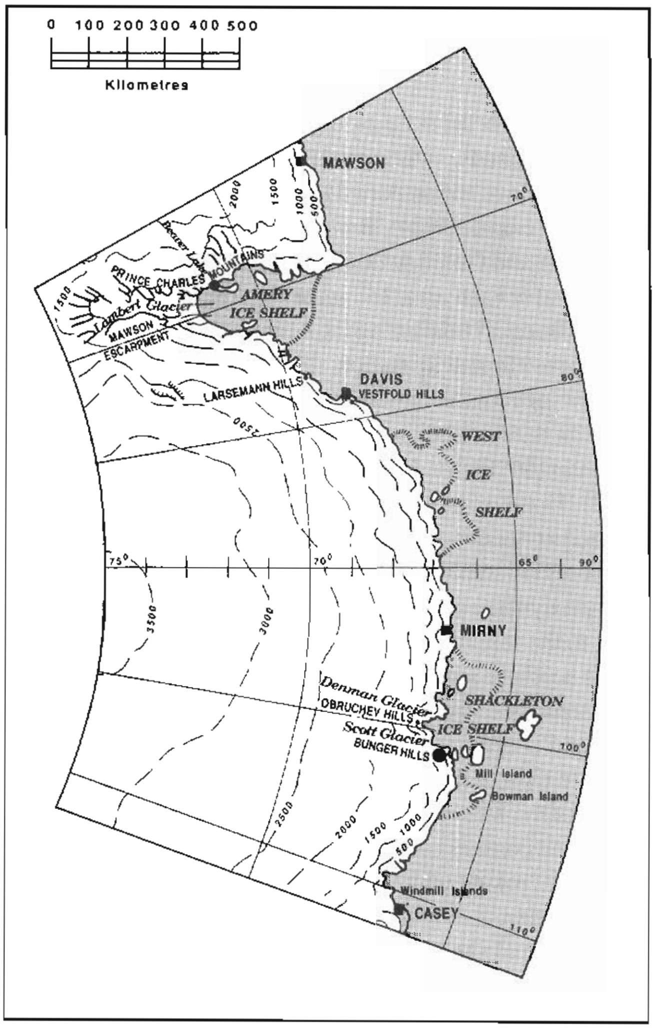

Figure 1. Location map of Bunger Hills.

Today Bunger Oasis forms a heat island and rain rarely falls. Most storms come from the south-east. These polar easterly lows bring warm maritime air (about 0° to +9°C)[1] into the region in summer and light snowfalls. The warm temperature and strong winds cause the sea ice to break-up in the larger inlets, and beaches and headlands in exposed situations experience a short period (maximum 2 months) of open water wave action. The large number of small islands produce limited wave fetches generally of <2–3 km. The longest fetch is 12–20 km in Edisto Channel which would favour strong wave action under north-easterly winds. In Kapakon Inlet which is largely free of islands the longest fetch is 15 km and is east–west. In 1986 the Edisto Channel, Rogatka Strait and southern Fish Tail Bay were open during late

[1] Up to +7°C recorded in 1986; mean annual temperature is approximately -9°C.

January and early February. Elsewhere the coast was icebound, and the ice on most of Transkriptsii Inlet has not melted since before discovery of the oasis in 1947 during Operation Highjump (Byrd 1947).[2]

1.1 Methods used and marine features observed

Dubrovin and Zalewski (1968) reported a tidal range of 1.55 m (max. 2.5 m, min. 0.4–0.5 m) for Fish Tail Bay. Measurement at Edgeworth David station within Transkriptsii Inlet gave the same maximum value which was assumed to be the extreme semi-diurnal tidal range for the region. Former marine limits (ML), which indicated the maximum heights of marine transgression, were identified in each bay by study of the morphological forms particularly the boundary between sorted beach materials and the lower limit of glacial deposits (Figure 2). Where open water occurred the present HWM and ML were identified. The height differences between HWM, the present ML and the raised ML were measured using a hand level along the shortest transect orthogonal to the shoreline across the middle of the bay. The measurements have errors of about ± 0.3 m per 15 m altitude. Where sea ice was present measurement was more difficult because of onshore ice-thrusting sometimes up to 2–3 m above the high-tide sea ice crack. Measurement was made between the high-tide sea ice crack and the raised ML with an error of about ± 0.5 m for 15 m altitude. Measurements are given between HWM and the raised ML throughout the paper except where the difference between the present and former ML is specified. The measurements are accurate to within 1 m (usually 0.5 m) between HWM and the former ML except where indicated (Figures 2, 3, 8, 15, 16, 19).

At each site the forms of marine deposition and erosion, and effects of sea ice were noted. Depositional features included beach deposits, beach ridges, number of terraces present, small marine deltas, nature of sediment, fossil shells, lower limits of adjacent glacial and solifluxion deposits. Erosional features included marine rock platforms, sea cliffs and geos. Sea ice effects included ice pushed boulder lines some of which formed kalottenberg (necklace hills) around former low rocky islands, ice pushed beach ridges which occasionally resembled small moraines, and depressions and sole marks within beach deposits that resulted from melting of grounded ice floes/bergs or sea ice thrust above HWM. In addition, it was noted that on exposed low headlands the combination of wave-washing and sea ice thrusting caused a strong boulder alignment at the lower limit of glacial drift. At other sites the highest ML was masked by either the presence of thick perennial snowbanks or by solifluxion deposits. No highest ML was recorded at such sites though minimum height values were obtained.

1.2 Dating

Fossil shells of *Laternula elliptica* King and Broderip were obtained from natural sections, where they frequently occurred in growth position, and from shallow pits dug in the beach

[2] During the IGY in 1967 the Poles and Soviets had an airstrip on the sea ice which was still visible in 1986 by oil barrels used for markers.

deposits. In addition, reworked shell material was found in both the Older Edisto and Younger Edisto moraines at the western end of Thomas Island where the Edisto Ice Tongue has been grounded for a long time (Adamson and Colhoun 1992). The dates were obtained from Beta Analytic, USA through the Macintosh Centre for Quaternary Dating, Sydney University (Table 1). The values should be reduced by about 1300 yr to correct for old carbon circulating in Antarctic sea water (Adamson and Pickard 1986). Maximum beach and sample heights are given because *L. elliptica* usually grows in water of more than 3 m depth.

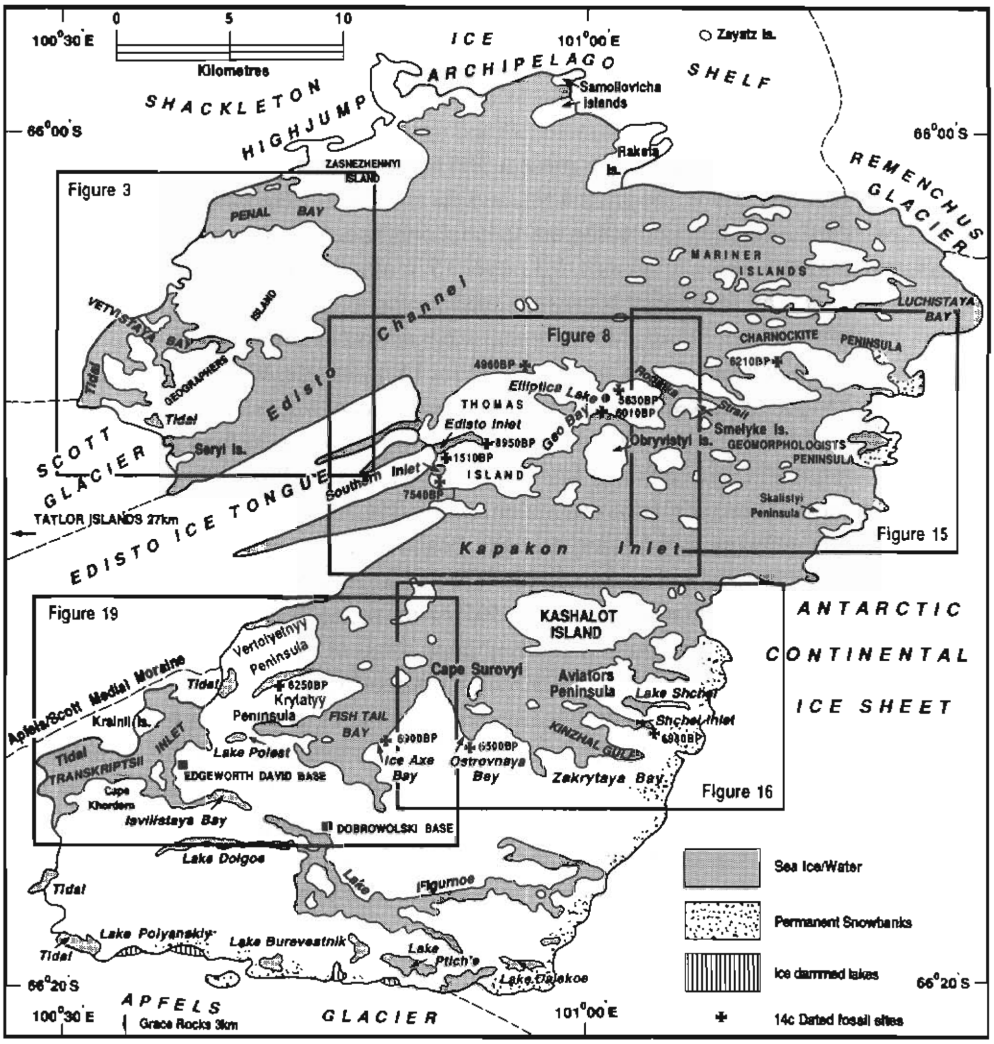

Figure 2. Location of Figures 3, 8, 15, 16, 19.

Table 1. Radiocarbon dates.

Younger Edisto Moraine, Thomas Island	Shell fragments from till	1510 ± 110 yr BP Beta 17528 corrected ~ 200 yr BP
Older Edisto Moraine, Thomas Island	Shell fragments from till	7540 ± 100 yr BP Beta 17529 corrected ~ 6.2 ka BP
Head of Edisto Inlet, Thomas Island, main access probably from Edisto Channel	Fragments of *L. elliptica* in beach sand amongst morainic boulders. Max. beach heights 6.8 m, sample height 2.8 m.	8950 ± 490 yr BP Beta 15828 corrected ~ 7.7 ka BP
North Coast Bay, Thomas Island, Edisto Channel	Fragments of *L. elliptica* in beach sand. Max. beach height 6.9 m, sample height 3 m.	4960 ± 120 yr BP Beta 17526 corrected ~ 3.7 ka BP
Elliptica Lake, Thomas Island, access from Edisto Channel	Shells of *L. elliptica* in growth position. Approx. ML 10.5 m, sample height 4 m.	5630 ± 90 yr BP Beta 15830 corrected ~ 4.3 ka BP
Geo Bay, Thomas Island, Kapakon Inlet	Fragments of *L. elliptica* in beach sand. Max. beach height 6 m, sample height 2.6 m.	6010 ± 100 yr BP Beta 17525 corrected ~ 4.7 ka BP
Charnockite Peninsula, Kapakon Inlet	Fragments of *L. elliptica* from beach sands. Max. beach height 7 m, sample height 1.3 m.	6210 ± 100 yr BP Beta 17524 corrected ~ 4.9 ka BP
Shchel Inlet, Kapakon Inlet	Fragments of *L. elliptica* from beach sand. Max. beach height (not the ML) 3 m, sample height 2 m.	6880 ± 160 yr BP Beta 15831 corrected ~ 5.6 ka BP
Ostrovnaya Bay, Kapakon Inlet	Fragments of *L. elliptica* from sandy mud at head of bay. Max. beach height 8.5 m, sample height 2.2 m.	6500 ± 130 yr BP Beta 17527 corrected ~ 5.2 ka BP
Ice Axe Bay, Kapakon Inlet	Shells of *L. elliptica* in growth position. Max. beach height 8 m, sample height 3–3.5 m.	6900 ± 120 yr BP Beta 15829 corrected ~ 5.6 ka BP
North of Krylatyy Peninsula, Kapakon Inlet	Shells of *L. elliptica* in growth position. Max. beach height 8.6 m, sample height 5.2 m.	6250 ± 140 yr BP Beta 15832 corrected ~ 5 ka BP

2. Explanatory description of the marine features

The raised marine features will be described for (1) Geographers Island, (2) Thomas Island, (3) Charnockite Peninsula, (4) the mainland coast east of Cape Surovyi and Kashalot Island, (5) the mainland coast west of Cape Surovyi (see section 2.5), (6) the Krylatyy and Vertolyetnyy Peninsulas, and (7) the Transkriptsii Inlet. The coverage is not complete but includes most major features of the coast.

2.1 Geographers Island

The visit to Geographers Island was brief and less detail was collected than from other areas partly due to the relatively thick snow cover (Figure 3). Most of western Geographers Island is covered with thick moraine deposited by north-westerly moving Antarctic ice. Kettle lakes and enclosed depressions are numerous. Rock outcrops have been moderately fractured by frost action and surfaces show moderate iron oxidation and tafoni development. Solifluxion processes are active and perennial snowbanks blanket most of the eastern half of the island. A deep snow trench in the eastern part of the island represents a shallow marine inlet. Tide cracks are shown on air photographs of the northern part of the snow trench. Penal Bay has multi-year sea ice, and snow almost completely blankets Zasnezhennyi Island.

Most raised marine forms occur adjacent to the very shallow bays on the north-western and western sides of the island. In the bays several beach terraces extend to 9 m above HWM (Figure 4) and are cut into the moraine deposited from the continental ice sheet. There is strong evidence for sea ice ramping on the beaches. Sea ice blocklines and ice floe depressions occur on the larger, more exposed beaches which though largely icebound in 1986 have also experienced wave action. Small kalottenberg and ice ramped ridges demonstrate the effects of sea ice pushing (Figures 5 and 6). All the raised beach deposits between 5.3 m and 9 m and sea ice push features up to 6.5 m are formed on deposits of continental moraine in areas outside the rounded ridges of the Older Edisto Moraines and sharp-crested Younger Edisto Moraines.

Around Belyi Island and Vetvistaya Bay sea ice has ramped the floor deposits into several distinct ridges that are convex to the south-east and resemble moraines. On the adjacent coast ice pushed ridges conform with the coastal outline. They appear too large to be sea ice pushed ridges and only occur between the ice shelf edge and the main raised beaches (Figure 7). The distribution suggests they were formed by shelf ice penetrating the bay entrances and pushing directly onshore, as does the Edisto Ice Tongue on Thomas Island. If correct this interpretation suggests that the ice shelf margin has recently retreated slightly north-westwards.

None of the beaches on Geographers Island is dated. However, as the altitudes of the beaches are as high as those on Thomas Island the dating from Thomas Island of 7540 ± 100 yr BP (6.2 ka) for the Older Edisto Moraines and 1510 ± 110 yr BP (200 yr) for the Younger Edisto Moraines indicates that marine transgression affected Geographers Island as early as any area in Bunger Oasis. The field data imply that glacier and shelf ice abutted Geographers Island throughout the Holocene and that parts of the shelf ice edge have retreated recently.

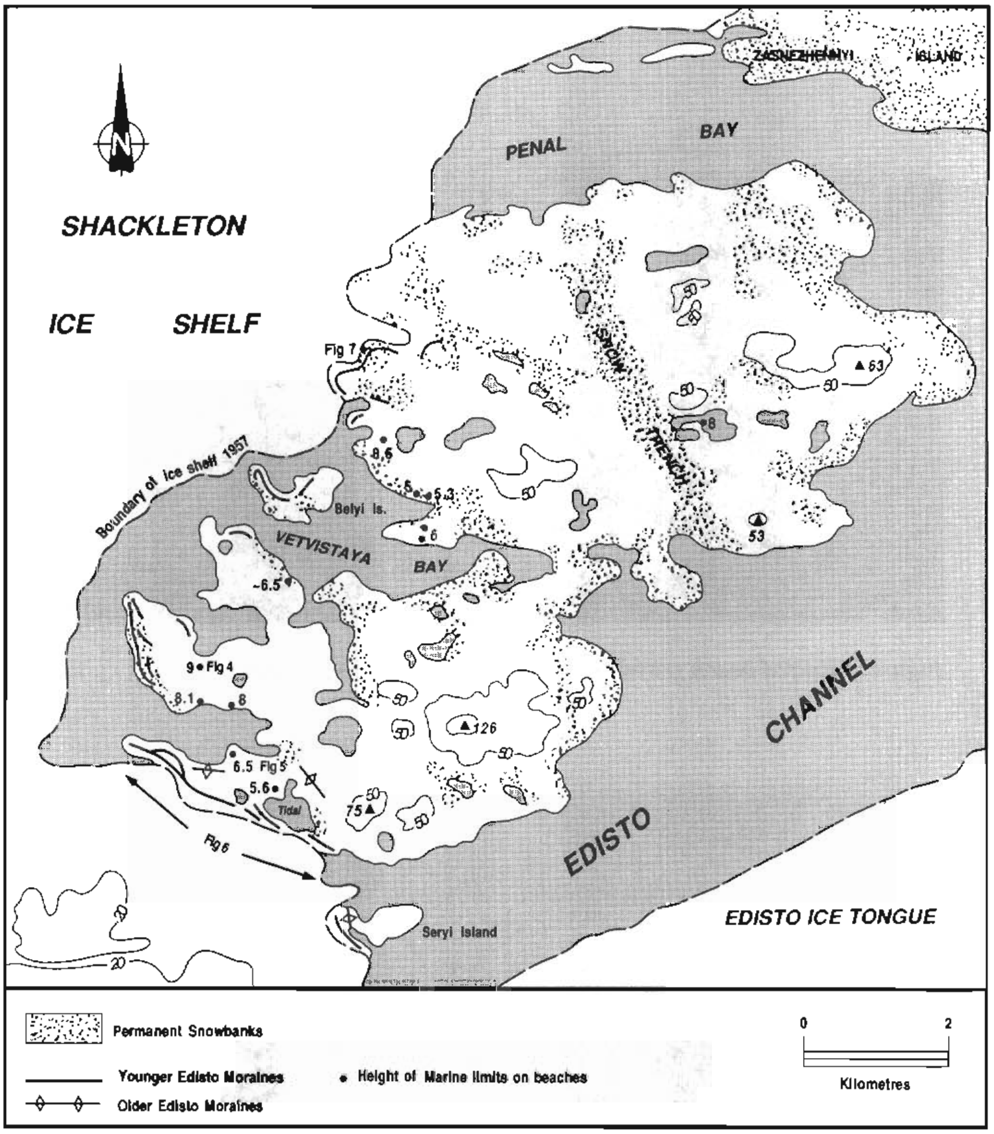

Figure 3. Map of raised beach sites on Geographers Island.

Figure 4. Raised beach gravels extending to 9 m on Geographers Island.

Figure 5. Sea ice pushed boulder ridge forming part of kalottenberg at 6.5 m on Geographers Island.

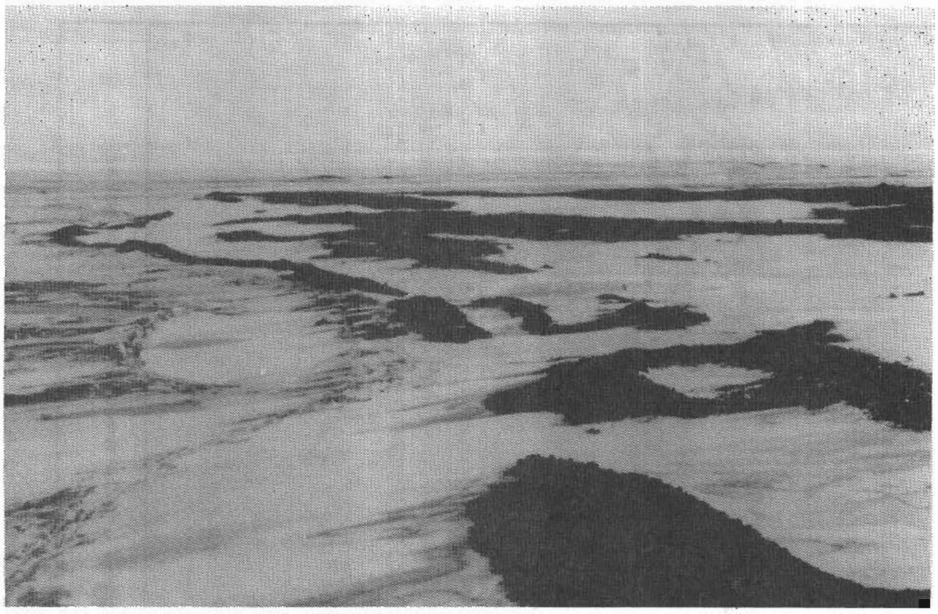

Figure 6. Younger Edisto Moraine formed between shelf ice edge and south-western shore of Geographers Island.

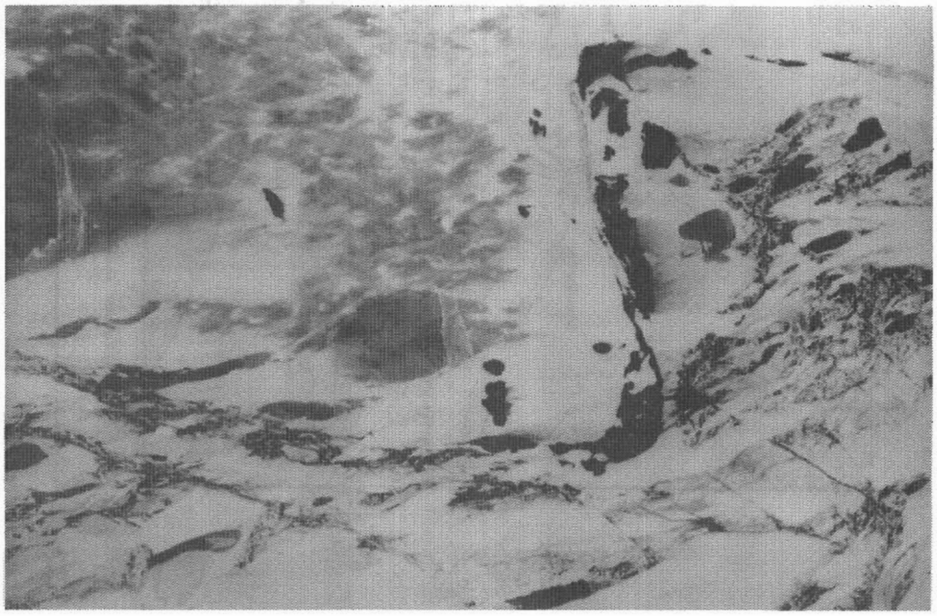

Figure 7. Shelf-ice pushed moraine ridges, Geographers Island.

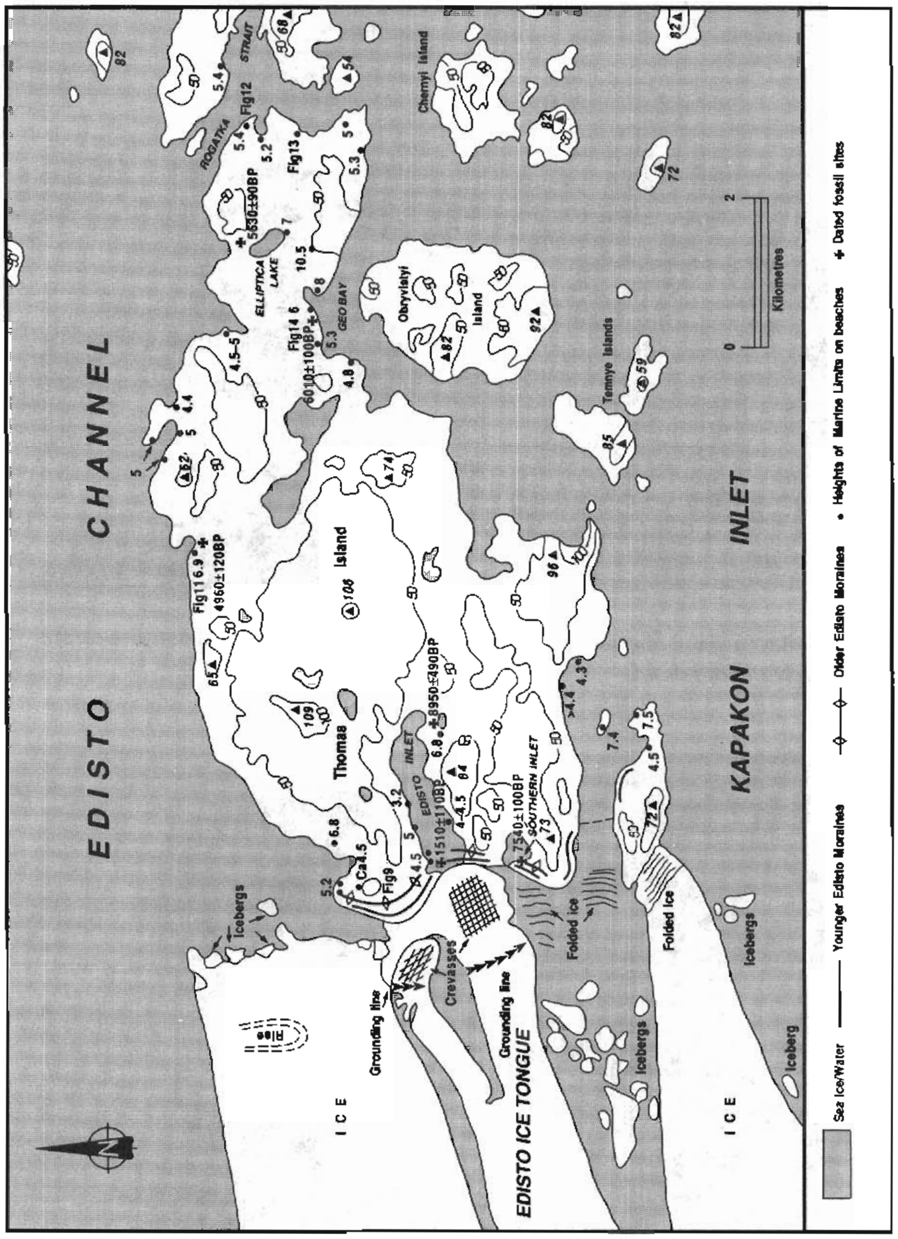

Figure 8. Map of raised beach sites, Thomas Island.

2.2 Thomas Island

Much detail was obtained from Thomas Island which occurs adjacent to the floating Edisto Ice Tongue and between Edisto Channel and Kapakon Inlet. The question of the long term stability of the ice tongue with respect to marine transgression was examined.

Small beaches occur in the bays at all levels above the modern limit of sea ice ramping (~2 m) to 8 m. A value of 10.7 m south of Elliptica Lake (Figure 8) is the highest for Bunger Hills but it may not be very accurate as it had to be surveyed over a long distance from the north coast.

At the western end of Thomas Island the sea entered Edisto Inlet to 6.8 m and Southern Inlet to 8 m before the Older and Younger Edisto moraines were formed (Figure 9). Most beaches within Edisto Inlet occur between 3.2 and 5 m above HWM, and form narrow terraces of sand and gravel backed by low cliffs/rock slopes. They appear to have been formed by wave as well as sea ice action. The small lake at the head of Edisto Inlet has been cut-off by isostatic uplift and the inlet head has a reversible tidal flow over a rock bar. Some beach limits are modified by snow patch erosion. West of the lake *Laternula* shell fragments occur in sand within a lag of wave-washed morainic blocks. These provide the earliest date for marine transgression of 8950 ± 490 yr BP (Beta 15828), 7.7 ka corrected for seawater.[3] Marine access could only have occurred if the western exit of Edisto Inlet was not blocked by land ice. This suggests that part of the Edisto Ice Tongue was afloat west of Thomas Island while the Older Edisto Moraines were constructed at the grounded ice margin. Similar moraines are dated to 7540 ± 110 yr BP (6.2 ka) (Beta 17529) at Southern Inlet. It appears, therefore, that the grounded margin of the Edisto Ice Tongue expanded onto Thomas Island sometime after 6.2 ka BP, and that the initial marine transgression occurred on retreat of the Antarctic continental ice.

North-western Thomas Island resembles Geographers Island with beaches developed in small embayments on thick deposits of continental moraine. The beach surfaces show the effects of both wave action and sea ice ramping, and extend to 6.8 m altitude outside the Older Edisto Moraines. A beach with a ML at 5.2 m is cut into the distal side of the Older Edisto Moraine ridge adjacent to Edisto Channel (Figure 10). For the sea to have entered Edisto Inlet by 7.7 ka BP to at least 6.8 m and Southern Inlet to 7.8 m requires that the Edisto Ice tongue terminated at least slightly further west than the position it had when it constructed the Older Edisto Moraines at about 6.2 ka BP.

At maximum transgression the sea flooded *Elliptica Lake*[4] from the north to a height of about10.5 m and almost divided the island. The water level was at least 7 m deeper than present lake level until after 5630 ± 90 yr BP (about 4.4 ka) (Beta 15830), when isostatic recovery cut the sea connection.

Occasional sea ice pushed boulder lines occur on the north coast beaches of Thomas Island. However, most beaches have gently sloping surfaces that extend up to marine limits

[3] Due to the large error and seawater correction this date could be as young as 6.7 ka.

[4] Informally named for the extensive beds of *in situ Laternula elliptica* shells at the northern end of the lake.

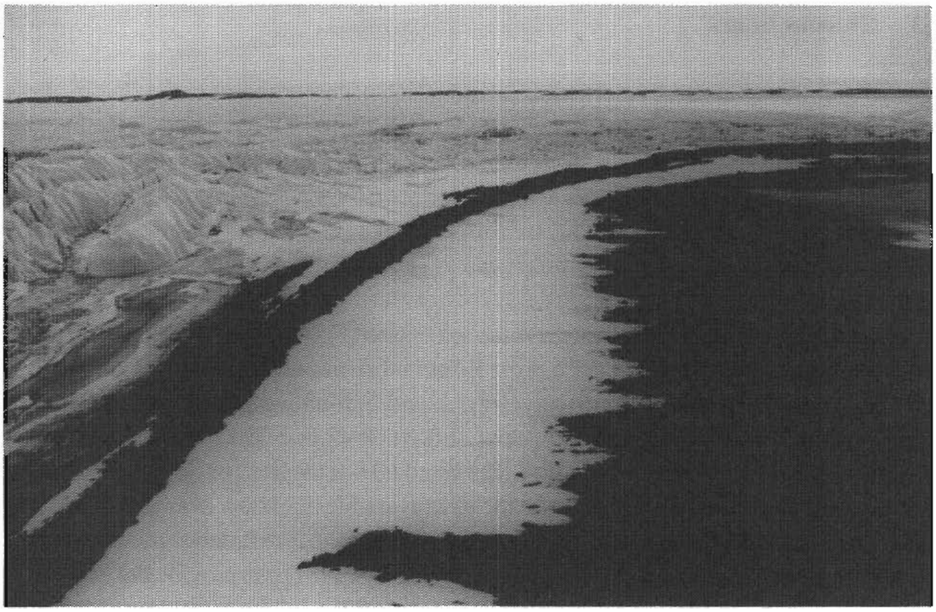

Figure 9. Older and Younger Edisto Moraines, Thomas Island.

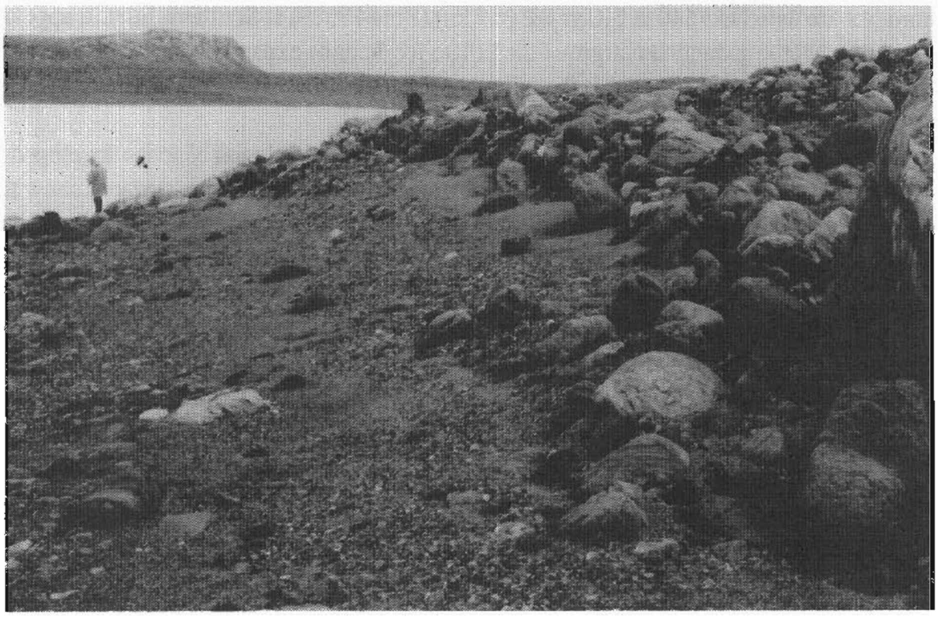

Figure 10. A shoreline cut at 5.2 m in the Older Edisto Moraine, north-west Thomas Island.

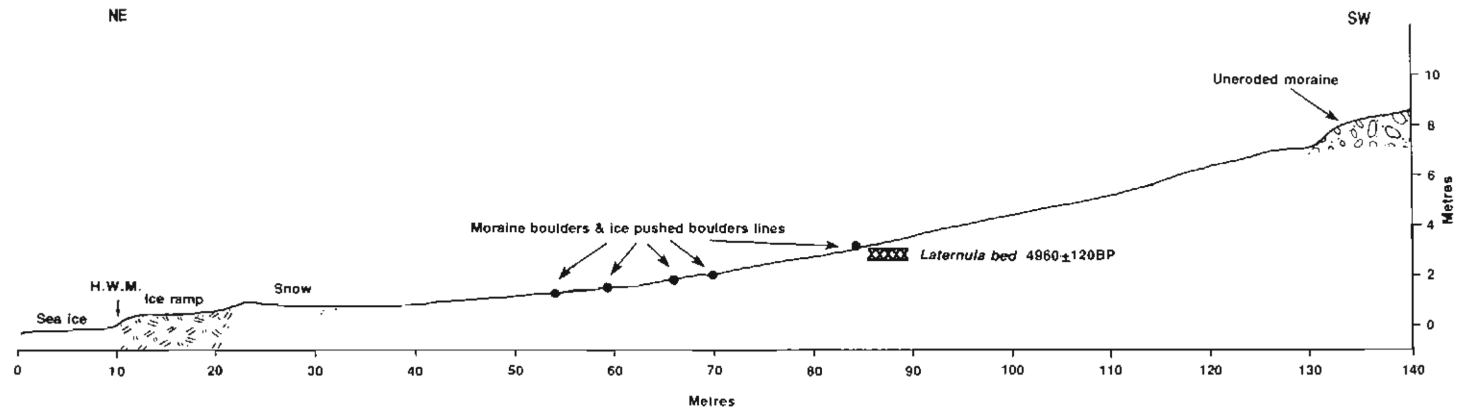

Figure 11. Middle north coast Thomas Island beach profile.

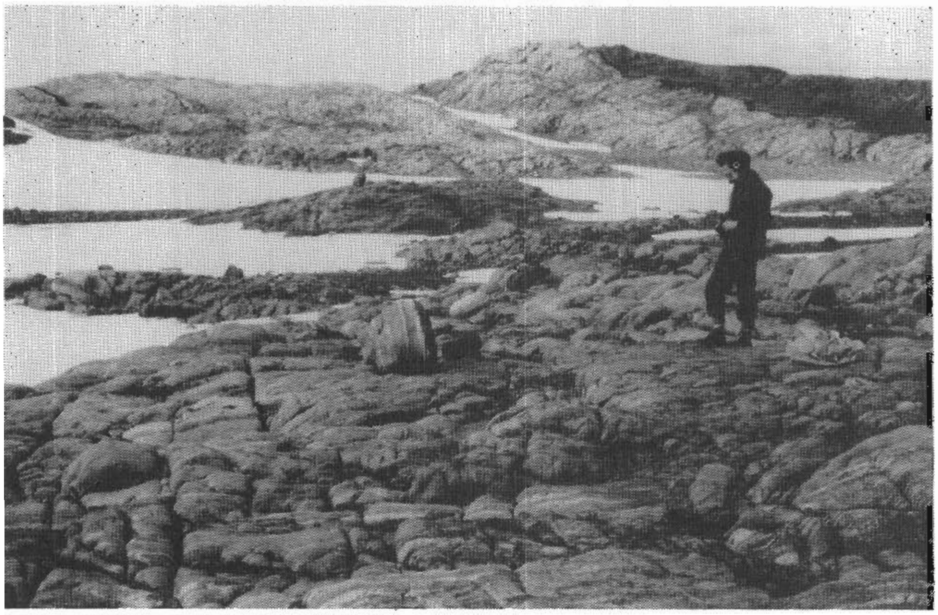

Figure 12. Wave-washed rock and aligned boulders at lower limit of moraine, north-east Thomas Island.

formed between 4.4 m and 6.9 m as low cliffs in moraine or rock (Figure 11). Wave action during summer from the open water Edisto Channel was the dominant process and formed gravel beaches with 1–5 cm size clasts in a matrix of medium to coarse sand and granules. Occasional large boulders washed from the moraine remain on the beach surfaces. In addition, the low headlands of the central north coast exhibit extensive areas of wave-washed rock. On the mid north coast a 40 cm thick bed of *Laternula* shells was found 2.8 m to 3.2 m above HWM where the ML is at 6.9 m. A radiocarbon age of 4960 ± 120 yr BP (about 3.7 ka) (SUA 17526) was obtained. At the eastern end of Thomas Island wave erosion has stripped the moraine from the headlands up to at least 12 m (Figure 12). Former stacks 4–5 m high have been strongly wave-eroded and a 4 m deep fossil geo (Figure 13) has been excavated into the cliff along a dolerite dyke. The eastern end of Thomas Island is exposed to strong north-east and south-east winds that generate strong wave action when the ice of Rogatka Strait is broken up by strong tidal currents.

Observations on the south coast centred on *Geo Bay*[5]. This bay is more protected than the eastern end of Thomas Island, particularly from the strong south-easterly storms. Beaches occur around the bay up to 8 m. The most complex sequence occurs at Geo Bay East where ice pushed block shorelines occur at 7 m and 8 m. A sloping beach face of water-worn sand and gravel that is slightly modified by snow patch melt occurs at 3.5 m to 5.5 m and ice pushed ridges are formed at 0.5 m and 1.7 m above the high tide ice crack. The sequence

[5] Informally named for a small fossil geo in the cliffs to the west.

suggests that conditions varied from icebound to open water with a return to icebound conditions. The changes may relate to climatic variation from colder and less stormy, to warmer and windier with a return to colder conditions. It seems that any climatic changes likely to manifest themselves in variations of beach morphology would be revealed in the more protected bays like Geo Bay East rather than on exposed sections of coast as the forms would be best preserved in the bays. The contrast between sea ice pushed and aligned block shorelines and open water wave formed beach terraces is also very well seen in the central part of Geo Bay (Figure 14).

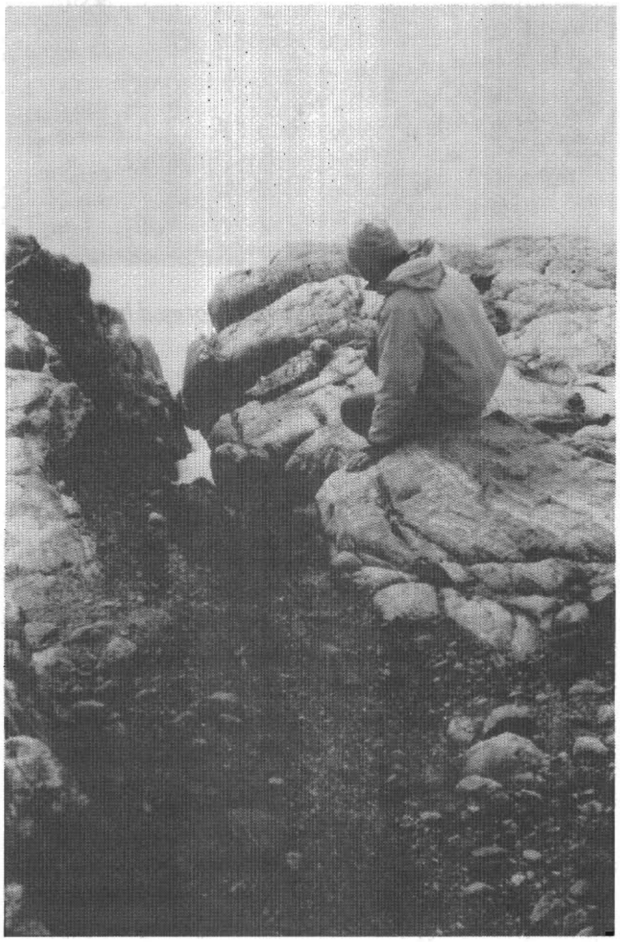

Figure 13. Fossil geo 4 m deep excavated along a dolerite dyke, eastern Thomas Island.

Figure 14. Sea ice pushed block shoreline and wave formed beach terrace central Geo Bay, Thomas Island.

2.3 Charnockite Peninsula

Most of Charnockite Peninsula has a cliffed coast. Beaches are of limited extent and consist of subrounded to subangular gravels and medium-coarse sand deposits, the former usually above the latter (Figure 15). The beach deposits occur below 5.4 m except in the inlet in the centre of the peninsula where they attain 7 m. Because of extensive snow patches, recent solifluxion and steep rock slopes at the back of the pockets of beach, it was not possible to define the ML in open bay situations. However, the limit was certainly over 5.4 m and probably around 7 m.

The shallow inlet near the centre of the peninsula was formerly more extensive before isostatic uplift isolated three small shallow lakes at 30–40 cm, 4 m and 5.3 m above the high tide ice crack in the north-west. West of the highest lake, beach sands and gravels extend to 7 m and the ML is masked by an extensive snow bank. Between the highest and middle lakes there is dead ice moraine with enclosed depressions that measure 5 x 3 m to 3 x 2 m overlain by beach sand. The moraine was still ice cored when invaded by the sea. At the eastern end of the middle lake shell fragments occur in the lake beach sand. The middle lake is barred by a boulder sill at 3.5–4 m, across which a small stream flows towards the lowest lake. On the northern bank of the stream a 1.5 m high section of medium sand contains abundant *Laternula* which gave a ^{14}C age of 6210 $\pm$ 100 yr BP (4.9 ka) (Beta 17524).

Charnockite Peninsula is tied to the Antarctic ice sheet in the east by a large snow bank. To the south Geomorphologists and Skalistyi Peninsulas protrude westwards from the ice sheet and have steep cliffed coasts. No beach deposits were observed from the air. To the north the Mariner and adjacent islands to the east as far as Luchistaya Bay have also steep, mainly cliffed coasts and the lower ground is extensively blanketed by perennial snow banks. No beaches were observed from the air.

The evidence from Charnockite Peninsula and adjacent areas shows that the Holocene transgression probably attained about 7 m and that it transgressed dead ice moraine in the centre of the peninsula as recently as 4.9 ka BP. The absence of beaches from the peninsulas to the south and islands to the north, compared with their extensive development on Thomas Island and on the mainland coast further west, suggests ice retreat eastward after 4.9 ka BP, and separate definition of the eastern margin of the Antarctic ice sheet, the shelf ice at the head of Luchistaya Bay and the Remenchus Glacier.

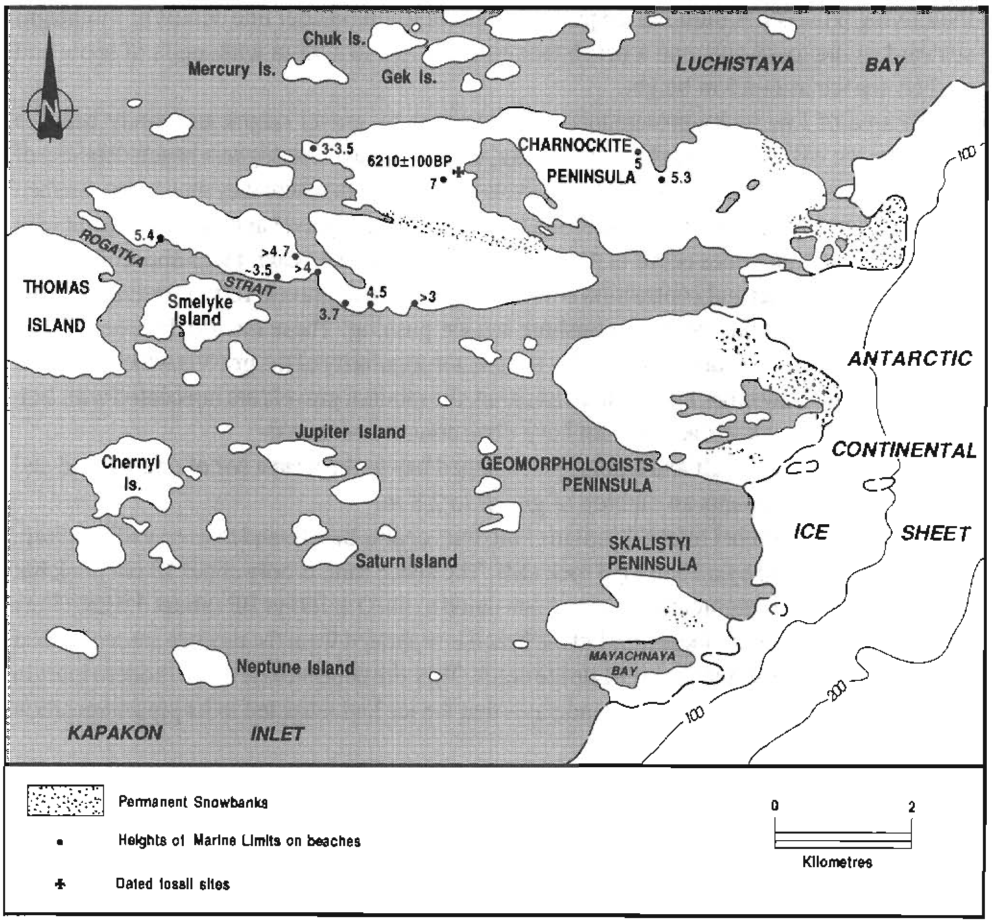

Figure 15. Map of raised beach sites Charnockite

2.4 The mainland coast east of Cape Surovyi and Kashalot Island

This area includes beaches formed at Ostrovnaya Bay, on the inlets and low headlands of this predominantly cliffed coast and on Kashalot Island (Figure 16). Most of the mainland coast was icebound in 1986 and appeared to have been for many years.

At the head of Ostrovnaya Bay a series of beaches 235 m wide (Figure 17) extend to a ML at 8.5 m where an ice pushed boulder line is packed against a 1 m high scarp in moraine. Solifluxion lobes partly mask the scarp and have flowed onto the highest beach surface which consists of a lag of 1–5 cm gravels over 80 cm+ of medium coarse sand and permafrost. Eighty metres seaward an ice pushed gravel and aligned boulder ridge has a crest at 5.4 m. A second beach face with gravel over sand slopes seawards at 5–7° and has been eroded by a snow bank into a hollow at 2.2 m where large well-preserved *Laternula* fragments were found and dated to 6500 ± 130 (about 5.2 ka) yr BP (Beta 17527). The *Laternula* fragments occurred in pockets of greenish grey fine sand and appeared to be very little disturbed from their living position. A third sea ice pushed ridge crest and boulder line occurs at 3 m height seaward of the fossil site, and a beach face slopes down to a 95 m wide mass of snow and pushed sea ice at 1–1.5 m height.

An area of low rocky prominances tied together by gravel ridges and sandy beaches occurs on the eastern side of the entrance to Zahrystaya Bay. The highest beach deposits of medium coarse sands and 1–10 cm size gravels occur at 8.5 m where they abut a low, washed rock outcrop. In addition, bars of subrounded to subangular gravel and beach deposits with sea ice pushed blocklines occur at 4.5 m, 3.5 m and 3 m. The beach faces above 3 m have deep, polygonal, thermal contraction cracks. Angular beach gravels form ridges at 2 m and 1.5 m, and clearly relate to strong onshore sea ice pushing. These modern beaches can be distinguished from the raised beaches by the greater angularity of the gravels which suggests that the coast is now more icebound. In addition, the modern gravels are not coated with iron oxides and the beach surfaces do not have deep contraction cracks.

Between Kinzhal Gulf and a horseshoe-shaped bay to the west a bar of coarse sand and 1–5 cm gravel surmounts an outcrop of gneiss to 2.8 m.

At the head of Shchel Inlet a thin skin of medium coarse beach sand rests on a till platform to 3 m and is backed by a 10 m high rock cliff. The beach sand is only about 10 cm thick but contains *Laternula* fragments that have been dated to 6880 ± 160 yr BP (about 5.6 ka) (Beta 15831). The ML was not identified but the beach is separated from the modern sea ice pushed beach material 1 m above the high tide ice crack. This site occurs close to the modern margin of the Antarctic ice sheet. The date indicates that the ice had retreated to its present position before 5.6 ka BP.

On a low rocky headland at the western end of Magnetologists Strait small beach ridges are well represented. On the eastern side the ML is at 8.8 m with lower ridges at 7.1 m and 1.4 m. On the western side the ML occurs at 8.6 m with lower ridges at 6.9 m, 4.5 m, and 1.6 m. The 1.4 m and 1.6 m ridges are modern being due to sea ice ramping. In contrast, the higher beaches are the product of both sea ice ramping and open water wave action.

At the head of the next inlet to the east a beach extends to 8.6 m and washed rock to about 10 m. The beach surface is highly disturbed by contraction cracks and mud boils. Also, at the

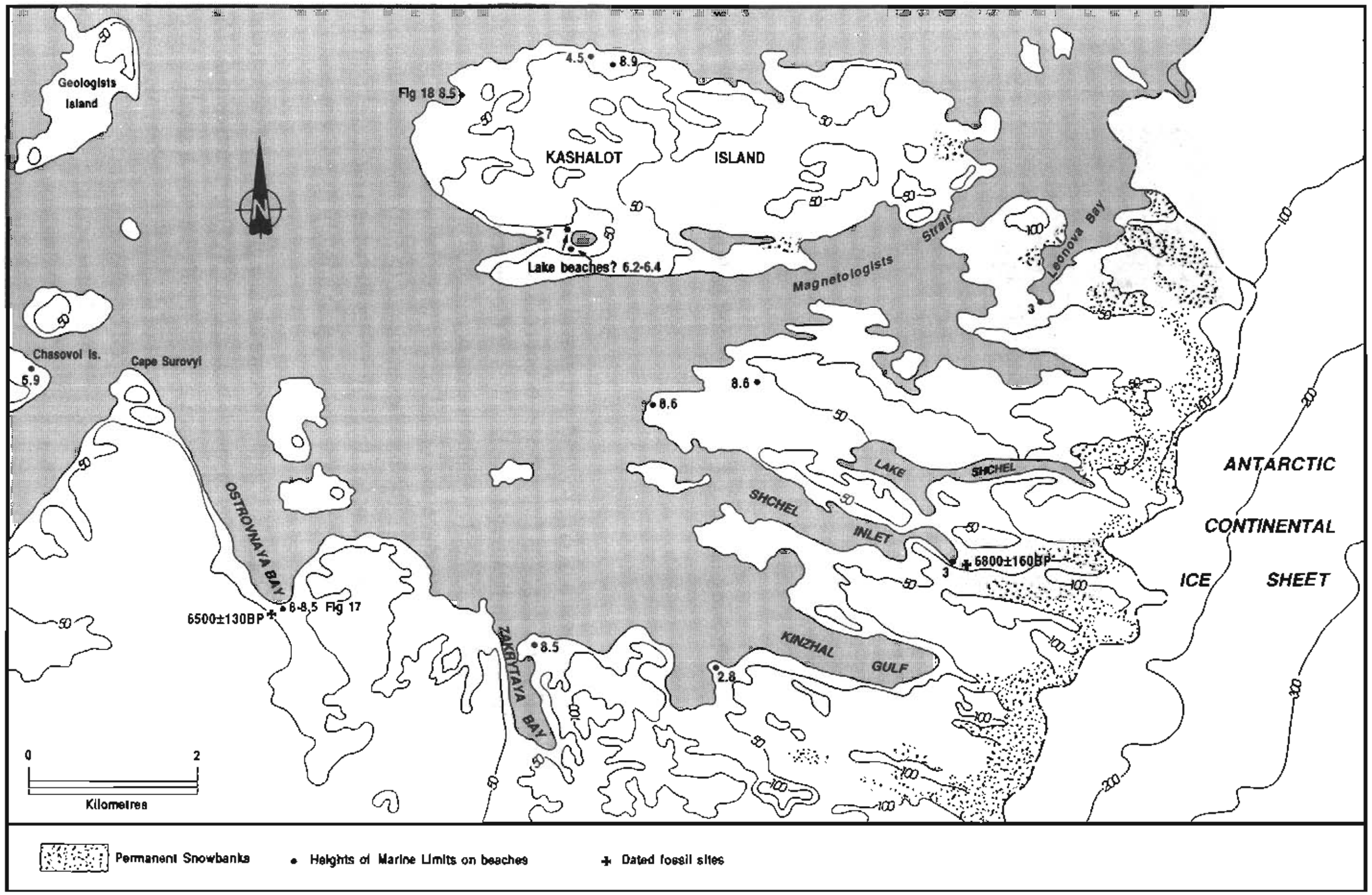

Figure 16. Map of mainland coast beach sites east of Cape Surovyi.

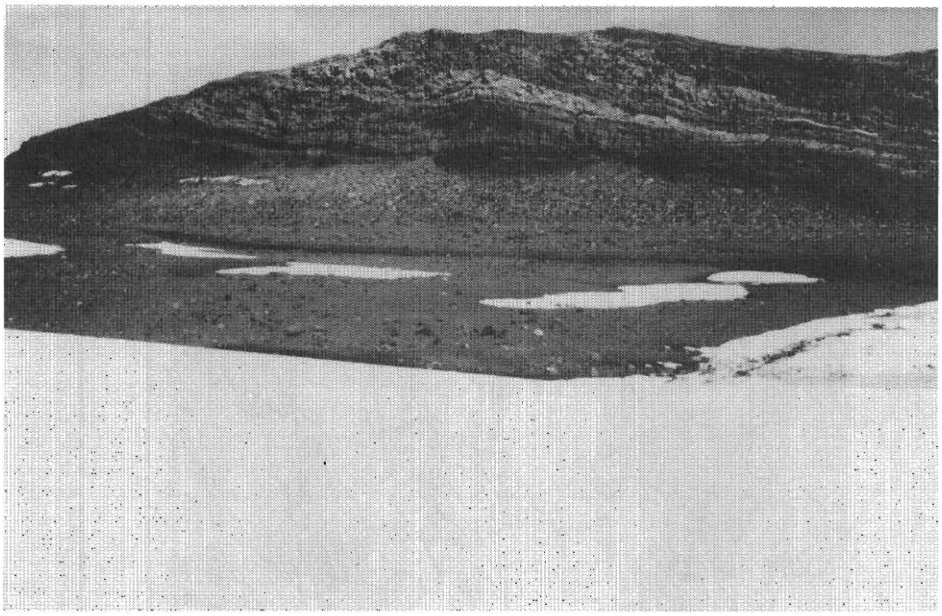

Figure 17. Ostrovnaya Bay showing ML at 8.4 m. Snow patch hollow on right is site of Laternula *fragments.*

head of Leonova Bay a small beach of coarse sand and gravel extends to 3 m height and is partly covered with solifluxion deposits from the adjacent rock slope.

The field evidence therefore indicates that the beaches of the eastern part of the mainland coast were formed largely under icebound conditions with occasional open water conditions particularly at Ostrovnaya Bay to produce the broad beach faces between the ice pushed ridges. Open water seems to have affected the beaches at higher (>3 m) more than those at lower altitude. The sea had transgressed Shchel Inlet by 5.6 ka BP which indicates that this section of the Antarctic ice sheet margin had retreated to approximately its present position by mid-Holocene times.

Most of Kashalot Island is cliffed and snow banks obscure the low ground at the eastern end. Beach sequences were recorded in the south-west, north-west and north of the island (Figure 16).

In the south-west a small lake is separated from a west-facing bay by a small area of moraine with 0.5 m to 2 m size boulders. West of the crest of the moraine debris at 8.1 m a beach face slopes at 6° from 7 m height to a well-developed beach ridge crest at 4.8 m. The beach consists of subangular gravel of 1–3 cm size and medium to coarse sand. A lower beach ridge crest occurs at 3 m. Between the two beach ridges contraction cracks occur on the surface and the beach deposits consist of subrounded to subangular gravels of 3–10 cm size and medium to coarse sand. Between the 3 m ridge and the modern sea ice pushed boulder line and ridges up to 1.5 m, the beach consists of small gravel and medium to coarse sand. The gravel is subrounded indicating some open water wave action. It is not clear if the sea overtopped the moraine at maximum transgression and entered the lake. The ML of 8.5 m and 8.9 m at Kashalot north-west and Kashalot north indicate that it could have done. Locally there are depressions 5 m in diameter on the surface of the boulder moraine which appear to have been formed by deflation of the sandy matrix.

Within the lake basin there is a well developed shore terrace with an upper limit of ice packed boulders at 6.2 m to 6.4 m height. The deposits of the shore terrace west of the lake between 6.2 m and 5 m height consist of a lag of surface gravels 2–6 cm in size over well sorted and bedded medium sands with distinct reddish brown iron-rich horizons that were not found in any marine beach-face sediments. The terrace appears to have been formed by the lake before it fell to its present level of 1.3 m. Polygonal contraction cracks also occur in the lake terrace surface which suggests that water level has remained low for a long time.

A very clear ML is preserved at 8.5 m on north-west Kashalot Island (Figure 18). A flat-topped beach terrace 30 m wide of 1–5 cm size subrounded gravel and medium to coarse sand terminates abruptly against moraine that extends for 70 m to an 8 m high rock bluff. The beach sediment is waterlaid and is cut by polygonal contraction cracks. A distinct sea ice pushed boulder line occurs at 7.8 m. Below this, an 80 m wide beach of subrounded gravels and medium to coarse sand slopes at 6° down to the modern sea ice foot which occurs at 1 m. The surface of the broad terrace shows many washed-out moraine boulders, several minor ridges due to ice pushing and undulations produced by ice grounding, ground-ice heaving and dissection by meltwater. A pit dug at 6.5 m showed that the upper part of the beach consisted of well rounded cobbles. The field evidence shows that both open water wave deposition and sea ice ramping were important in the formation of this sequence.

On the north of Kashalot Island another very clear ML occurs at 8.9 m with a 10 m wide storm beach of rounded cobbles of about 10 cm size abutting uneroded moraine. At the eastern end of the bay the beach is 60 m wide and slopes at 9° to a 20 m wide zone of washed-out morainic boulders. The beach consists of waterlaid subrounded to subangular gravels and medium to coarse sands. Contraction cracks intersect the surface. At the western end of the bay the beach declines from 4.5 m against a 10 m high gneiss bluff to the modern sea ice foot and beach at 1.5 m. Three sea ice pushed block lines occur on the 10° beachface but the sediment has mainly been wave deposited indicating that open water was formerly more prevalent on the exposed northern coast of Kashalot Island than today.

2.5 The mainland coast west of Cape Surovyi

The mainland coast west of Cape Surovyi includes the south-eastern and south-western shores of Fish Tail Bay. Open water developed in the southern part of the bay in 1986 and appeared to do so each year (Figure 19).

The most easterly site occurs at *Ice Axe Bay*[6] (Figures 20 and 21) where a line of sea ice pushed boulders packed against uneroded moraine marks the ML at 8 m. An undulating beach surface slopes seawards for 160 m and has been dissected by surface streams and snowmelt. The deposits consist of subrounded to subangular gravels of 1–5 cm size on well

[6] Informally named due to the finding of an old ice axe on the beach.

Figure 18. Raised beach terrace with ML at 8.5 m on north-west Kashalot Island. Note: undulations due to stranded floe ice in 30 m wide high terrace and distinct sea ice pushed boulder line below the fossil sea stack.

sorted and stratified medium to coarse sands. The beach is seamed with contraction cracks. An eroded bank at 3–3.5 m revealed abundant *Laternula* in growth position at right angles to the slope of the bank. The shells were dated to 6900 ± 120 yr BP (about 5.6 ka) (Beta 15829) (Figure 22). Because the shells grew orthogonal to the bank rather than the beach surface indicates that the bank must have been eroded underwater. On the south-western part of the bay a gravel bar at 2.6 m dams a small lagoon. The bar consists of subangular to subrounded gravels of 3–10 cm size. Below the bar a sea ice pushed boulder line occurs at 2 m. A snow ridge masks the modern beach deposits of well sorted, medium to fine sand. Below 1 m there are two low sea ice pushed ridges adjacent to the present shore. Although the sea was covered with rotting ice in January 1986 and not subject to wave action, nevertheless most of the beach deposits appear to have formed under open water conditions.

In the southern inlet of Fish Tail Bay beach deposits occur at > 6.7 m and a ML occurs at 8.3 m. In both areas the beach surfaces are partly masked by solifluxion from the adjacent slopes, and consist of gravel and sand. Lake Sredneye 1 km to the west and at 6 m altitude was noted to be salt which suggested a marine origin. This interpretation is supported by the chemical analysis of Kaup et al. (1989) which gives high values for Na, Cl and other cations.

At Fish Tail Bay East (Figure 19) a clear ML occurs at 8.3 m where a steeply-sloping beach face of 6–7° is cut into moraine. There are no major beach bars or sea ice pushed ridges below the ML in the centre of the bay and the beach face slopes gently to the modern beach. A minor terrace extending across the bay at 1.6 m represents the limit of modern sea ice

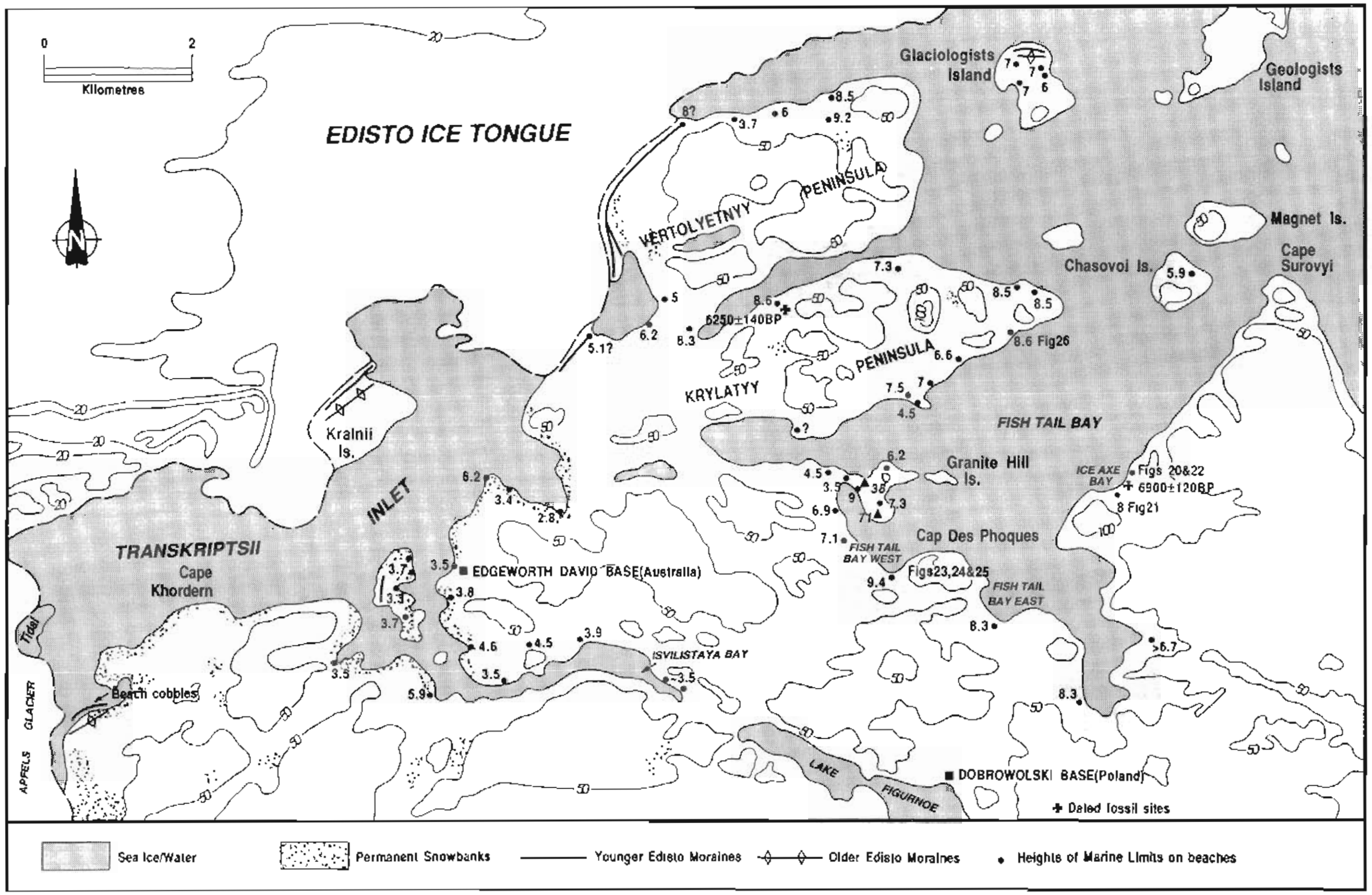

Figure 19. Map of raised beach sites around Fish Tail Bay, Krylatyy and Vertolyetnyy Peninsulas, and Transkriptsii Inlet.

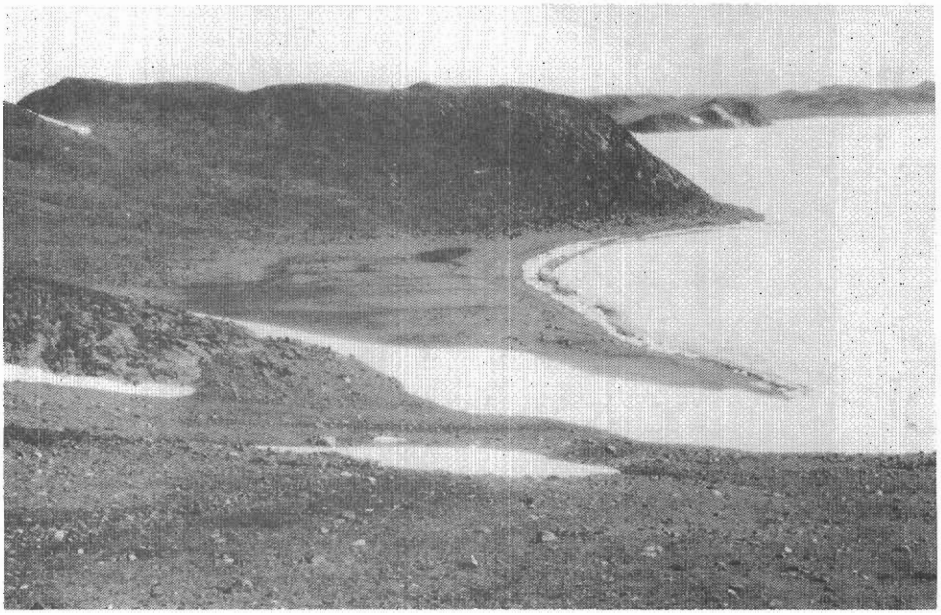

Figure 20. Raised beaches at Ice Axe Bay.

pushing. Below 1.2 m the modern beach is sandy and passes under a snow bank at 1 m. A distinct terrace occurs at 3.5 m in the south-eastern part of the bay. The main raised beach consists of subangular to subrounded 1–5 cm gravels on medium to coarse sand and granules. There are extensive areas of washed-out morainic boulders on the lower part of the beach. In the upper part, 50–70 cm deep depressions with 10–15 cm high gravel ridges on their south-west side were formed by stranded ice floes under the influence of north-easterly wave effects. The beach surface exhibits contraction cracks, sorted stone nets, wind truncated boulders and tafoni. The beach appears to have been formed predominantly under open water conditions but still preserves evidence for ice stranding during seasonal break up in Fish Tail Bay.

Fish Tail Bay West includes three small bays in the inlet south of Granite Hill Island. The eastern bay preserves the broadest beach sequence (Figure 23). In the centre of the bay a ML is formed at 9.4 m by crescent-shaped embayments formed by wave action and by the effects of sea ice pushing against uneroded moraine. A 20 m wide beach terrace contains depressions formed by ice floe stranding and consists of subrounded to subangular 2–10 cm gravels in medium to coarse sand (Figure 24). Below this the main beach slopes at ~8° down to the modern sea ice pushed boulder line at 1.75 m. The surface is characterised by many (about 15) minor 10–20 cm amplitude beach ridge undulations formed by wave action but there is only one minor sea ice pushed boulder line at 5.2 m. A large beach ridge occurs at 3.5 m. The beach consists of 2–5 cm size subrounded gravels on medium to coarse sand, and exhibits occasional contraction cracks. The modern beach consists of medium sand and subangular 2–10 cm rock fragments that occur inside a 1 m high ice ramp with thrust-up sand and angular gravel.

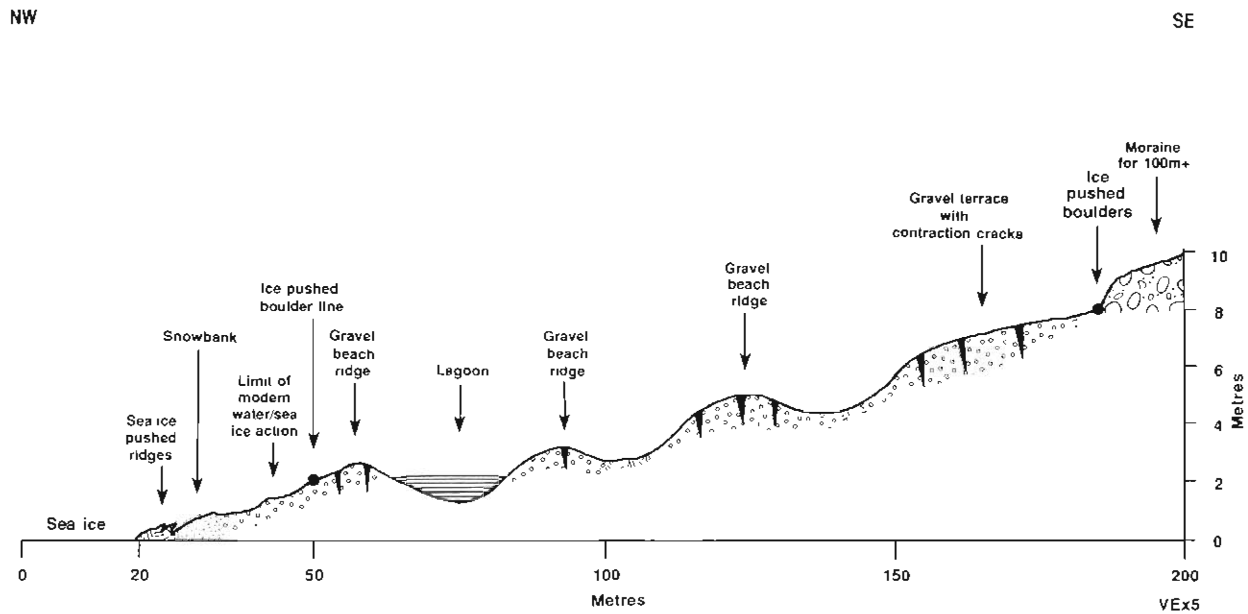

Figure 21. Profile of raised beach forms at Ice Axe Bay. Laternula *in adjacent section at 3.0-3.5 m 6900±120BP*

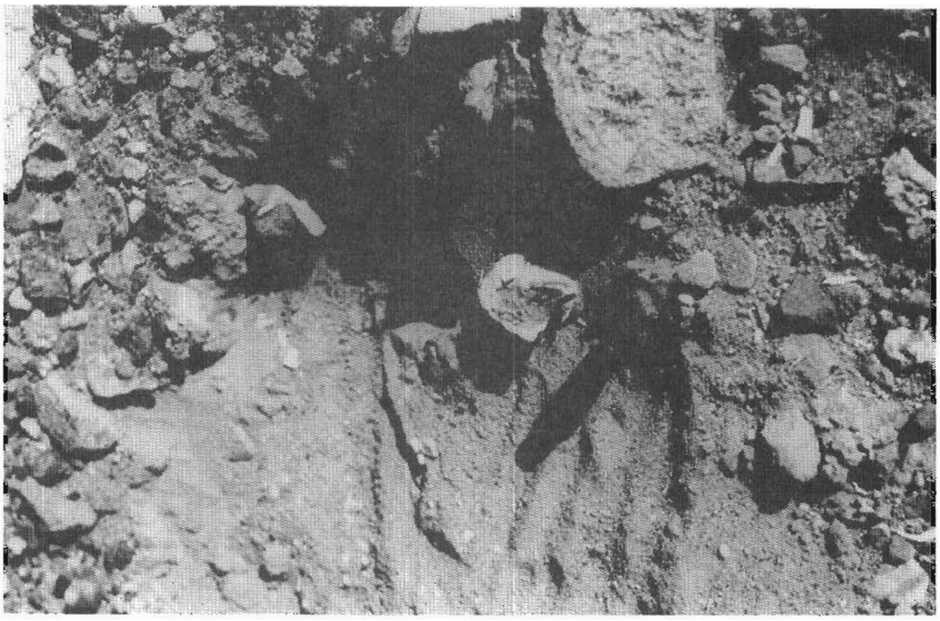

Figure 22. Laternula elliptica *in growth position, Ice Axe Bay.*

In contrast to the uniform slope in the centre of the bay the eastern end exhibits at least three terraces bounded to seaward by ice pushed block lines (Figure 25). From the eastern end to the centre of the bay the distinct terraces merge to form the sloping surface of the main beach with only traces of the blocklines remaining.

The evidence suggests that the beach forms developed under varying conditions of wave and sea ice action. The 20 m wide upper terrace seems to have been formed by waves acting in association with many stranded ice floes. The terraced eastern part of the beach suggests that sea ice and ice floes were more prevalent in this area which was more protected by Cap Des Phoques from north-east and east winds than the centre of the bay where the undulating main beach surface was mainly formed by open water wave action. The uniformity of slope and ridge crest heights suggests that the beach sequence was constructed during regression caused by a uniform rate of isostatic uplift.

The central and western parts of Fish Tail Bay West give much less information with ML's cut in moraine at 7.1 m and 6.9 m respectively. These values are probably slightly too low as measurement was difficult from the sea ice pushed margin. The central part of the bay appears to have been the area described by Rozycki (1961) (see discussion and conclusions).

The peninsula west of Granite Hill Island comprises a series of rock hills linked to the mainland by deposits of moraine and beach. Strong sea ice pushing within the complex of small embayments at the western end of Fish Tail Bay has produced gravel bars and beach deposits at many levels (Figure 19). South-west of the 38 m high hill a ML occurs at 9 m with a coarse sand and granule beach washed from moraine that passes laterally into a large sea ice pushed boulder ridge with 1 m to 1.5 m blocks. Lower bars occur at 4.5 m, 3.5 m and 2 to 1 m, the last being modern. Between the 38 m and 71 m high hills enclosed depressions

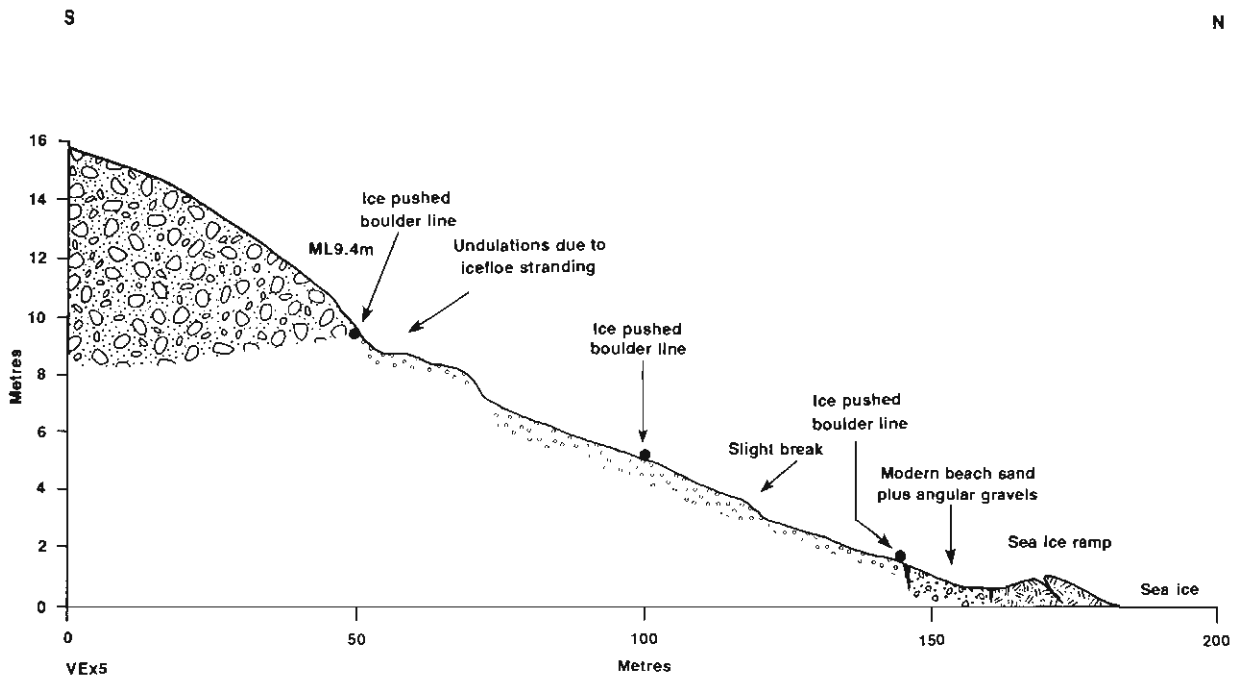

Figure 23. Profile of raised beach forms on the eastern side of Fish Tail Bay West.

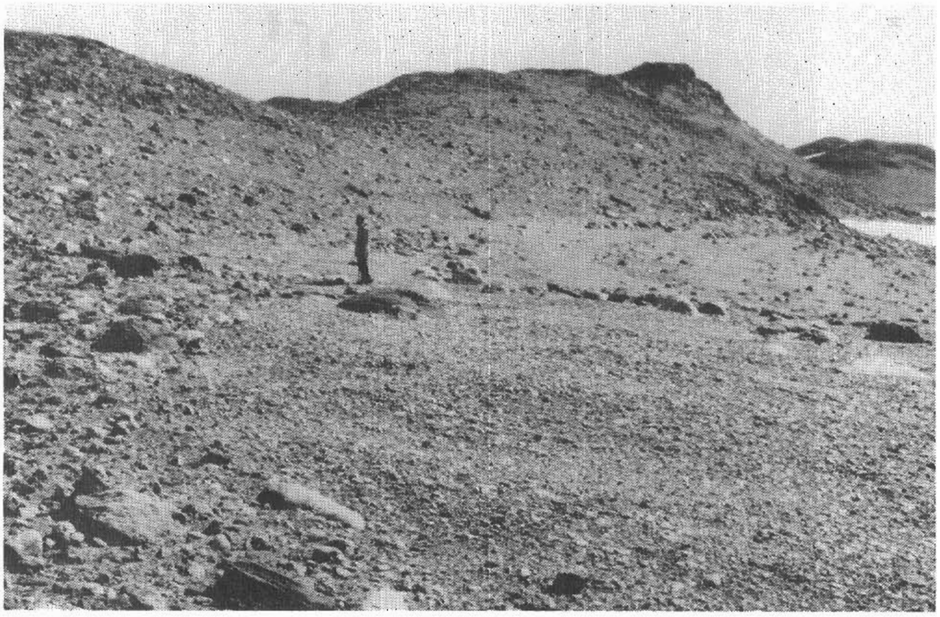

Figure 24. Marine limit at 9.4m in Fish Tail Bay West, showing depressions near the shoreline due to ice floe stranding.

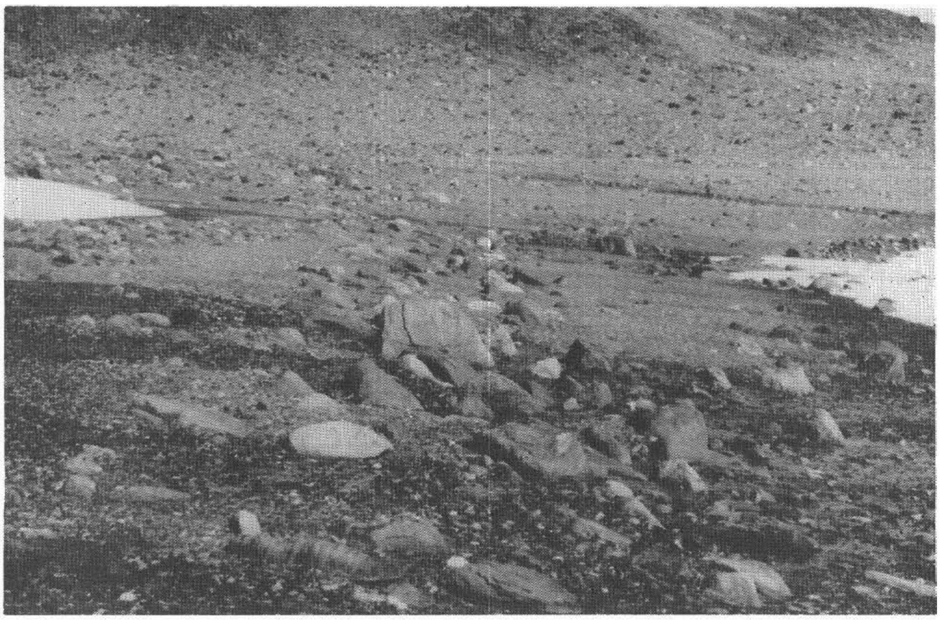

Figure 25. Sea ice pushed block shoreline towards eastern end of Fish Tail Bay West.

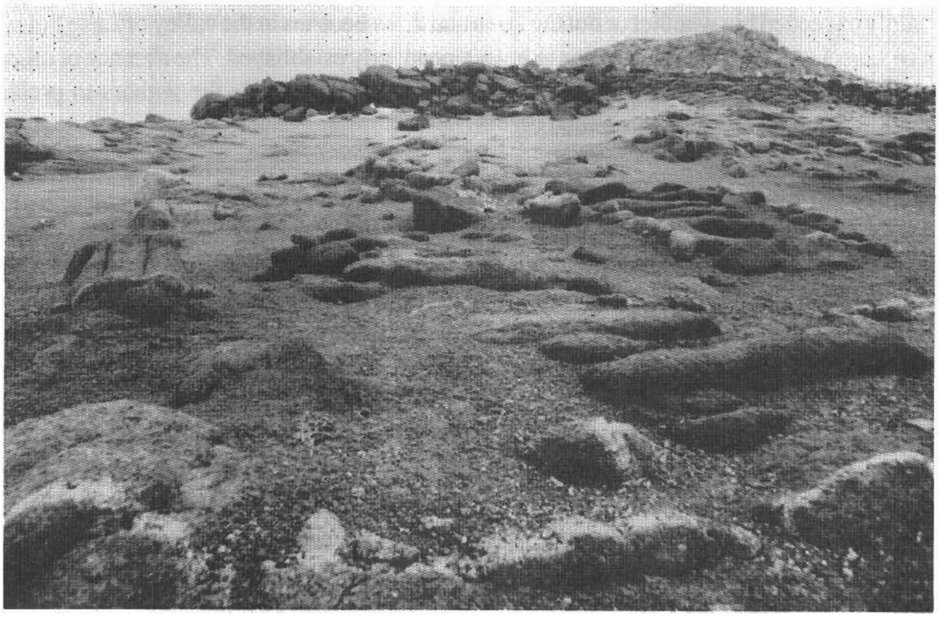

Figure 26. Irregular inner part of marine rock platform cut in mafic granulite with low cliff behind, Krylatyy Peninsula

in the moraine suggest that ice was present when the sea transgressed to 9 m. A ML of 7.3 m occurs in the moraine northeast of the 71 m high hill and the beach consists of 2–5 cm gravel and coarse sand formed by washing of the moraine. North of the lagoon modern sea ice pushed boulders occur to 1 m with gravel ridges at 1.7 m and 3.5 m. North of the adjacent hill to the east a beach has been cut in moraine at 6.2 m and the rock has been wave-washed to 9 m. At the western end of the peninsula there are extensive washed rock areas and beach terraces at 3.5 m and 4.5 m.

The combined evidence from Fish Tail Bay points to transgression to about 9 m above HWM and 7–8 m above the modern ML. The coastal landforms of this exposed area of headlands and bays have been formed by both wave and sea ice action while the land has been uplifted. Sea ice action appears to be more prominent at lower levels.

On either side of western Fish Tail Bay and in the valley of Lake Polest to the west Colhoun and Adamson (1989) noted a well-formed shore line at 20 m altitude which they attributed to formation in a glacial lake. They also noted that Lake Polest (surface 6 m) was highly saline and that sandy beaches occurred at 20 m and 23 m at its western end. Recently Kaup et al. (1989) have shown the lake to have a high salt content and have suggested a marine origin with isolation due to isostatic uplift. Colhoun and Adamson (1989) interpreted the 20 m and 23 m beaches and associated shore lines as having formed in a glacial lake because the beach deposits contained no shell fauna and the extent of the shorelines was abruptly terminated in western Fish Tail Bay where the inferred lake could have been dammed by an ice margin. The threshold of access for marine water to the Lake Polest Valley is about 12 m. The chemical evidence of Kaup et al. (1989) indicates that this level was certainly exceeded but whether or not the 20 m and 23 m beaches in the valley of Lake Polest can be associated with the sea remains to be independently established. The absence of other unequivocal marine beaches at such altitude in Bunger Hills leads the authors to prefer retention of the glacial lake interpretation.

2.6 The Krylatyy and Vertolyetnyy Peninsulas

The southern coast of Krylatyy Peninsula is characterised by extensive areas of washed rock and rock platforms formed on biotite-rich granulites. A western promontory extending southwards to the narrows at the western end of Fish Tail Bay shows extensive washed rock and a low-level, small beach that was inaccessible below a steep snow bank.

A second promontory extends south-eastwards mid-way along the peninsula. On the western side gravel bars at 7.5 m and 4.5 m connect hills of rock that have been washed to 10–11 m on the coastal cliff. On the eastern side wave washing of rock and moraine have produced deposits of coarse sand and granules that extend to a cliff notch at 7 m to 7.6 m. Above this lies a 5–10 m wide terrace at 20 m that is not marine and forms the northern shoreline of Glacial Lake Fish Tail (Colhoun and Adamson 1989). Further east a small platform cut in granulite extends to 6.6 m against slightly degraded moraine.

Near the eastern end of the peninsula a 100 m wide platform is cut in granulite and extends to a low cliff of granulite and granite at 8.6 m. Moraine has been cleaned off the cliff face for a further 2–3 m. The upper part of the platform is irregular (Figure 26) but the central part is smooth and slopes at 5° towards a snowpatch adjacent to the sea ice. Occasional morainic boulders 1–2 m in size rest on the platform.

The southern coast of Krylatyy Peninsula is the only area in Bunger Hills where marine platforms cut in rock were observed. Several factors appear to have contributed to their formation. Firstly, the very coarse granulite has a strongly foliated structure that permits easy disintegration. Secondly, exposure to south-easterly storms facilitates wave erosion and sea ice rafting when Fish Tail Bay is seasonally open. Thirdly, the low-lying rock surface is frequently wet allowing frost and perhaps salt action to enhance the disintegration.

On the north-east of Chasovoi Island a beach extends to a limit of 5.9 m cut into moraine. The 85 m wide beach consists of subangular to subrounded 1–10 cm gravels and medium to coarse sand in its upper and lower parts with a 35 m broad zone of washed-out morainic boulders towards the middle. The beach slopes 4° towards a 40 m wide snow patch and sea ice pressure ridge. The beach surface has contraction cracks and minor gullies.

Raised beaches occur at four sites north of Krylatyy Peninsula. At the eastern end a beach occurs on either side of a low granite headland. Below the 2 m cliff a narrow platform slopes seaward at 12°. To the north is a fossil sea stack with a large (5 m x 3 m x 2.5 m) ice pushed boulder on its eastern side. The exposed eastern beach is 70 m wide and slopes seawards at 10° from a ML cut in moraine. The beach surface is mainly washed-over moraine. West of the stack and platform an 80 m wide beach slopes from a ML at 8.5 m seaward at 7–8° to the modern beach and ice foot at 1.6 m. This beach consists of subangular to subrounded gravels and medium coarse sand where relatively protected, and washed-out moraine boulders further west. Both beaches are single, seaward-sloping surfaces that have been exposed to open water wave action.

On the mid-north coast a 50 m wide beach of washed-over moraine, 1-5 cm gravel and medium to coarse sand slopes seaward at 8° from a ML of 7.3 m that is modified by snowmelt erosion and masked by soliflusion.

The third site on the northern side of Krylatyy Peninsula provides some of the best data fro sea level change in Bunger Hills (Figure 27). The site lies inside a bar of moraine debris that crosses the inlet between Krylatyy and Vertolyetnyy Peninsulas and causes reversible tidal flow. Inside the moraine the water is salt but the variation in level of the tidal prism (about 30 cm) is not sufficient to produce sea ice tide cracks. A very clear ML limit occurs at 8.6 m in moraine above HWM on the modern beach which was determined to be 0.3 m above the control level of the moraine bar. The 120 m wide beach slopes seawards at 6°, and consists of eight broad beach bars that are almost equally spaced (Figure 28). The bars have an amplitude of 0.7 m to 1 m and consist of 2–8 cm gravels and medium to coarse beach sand. Linguoid structures formed by wave action trend obliquely across the bars towards 200–225°. These ridges are 0.7–1.5 m wide and 0.2–0.3 m high. They are asymmetrical with wave-proximal and wave-distal slopes of 5–7° and 10–15° respectively. The gravel of the proximal slopes has a medium sand matrix but there is no matrix in the surface layer of gravels on the distal slope. Only a single sea ice pushed blockline occurs at about 3 m in the beach sequence. A stream has cut a 3 m deep section through the fossil beach deposits. In the west bank 32 m from the ML and at 5.2 m height abundant articulated *Laternula* bivalves were found in growth position. They gave a radiocarbon age of 6250 ± 140 (about 5 ka) yr BP (Beta 15832). Below the fossil beach the modern beach has a rippled sand surface and is divided by the stream from a small recurved sand and gravel spit that trends westwards. The modern stream has built a small delta within the fossil beach deposits and the delta presumably commenced formation when the moraine bar was uplifted sufficiently to reduce tidal effects.

At the head of the inlet between Krylatyy and Vertolyetnyy Peninsulas a wide 80–100 m low-gradient beach extends to a ML at 8.3 m in low cliffs of eroded moraine. The beach consists of extensive areas of washed-out moraine, 2–10 cm beach gravels and well sorted medium sand.

No important marine deposits were observed on the southern side of Vertolyetnyy Peninsula and Geologists Island was not visited. However, very clear relationships occur between the raised beaches and the Older and Younger Edisto moraines on Glaciologists Island (Figure 19). Beaches are cut into moraine deposited by the Antarctic ice sheet on the western, northern and eastern sides of the island up to 6–7 m. In the west a lower beach occurs at 5.8 m. The 7 m beach on the northern side is notable as it is a large round-crested shingle ridge that lies above extensive washed-out moraine on a 100 m wide beach that is separated from the rounded and sharp-crested lateral moraines of the Older and Younger ice limits of the floating Edisto Ice Tongue. The field evidence shows that marine transgression and partial uplift preceded the maximum expansion of the Older Edisto ice advance, as also observed on Thomas Island.

On the northern shore of the Vertolyetnyy Peninsula the beach deposits have been formed in association with the partially grounded ice margins of the floating Edisto Ice Tongue. The Older Edisto ice margin is identified by small and fragmented low ridges of rounded moraine and the Younger Edisto ice margin is recognised by sharp-crested ridges of presently or recently ice-cored moraines.

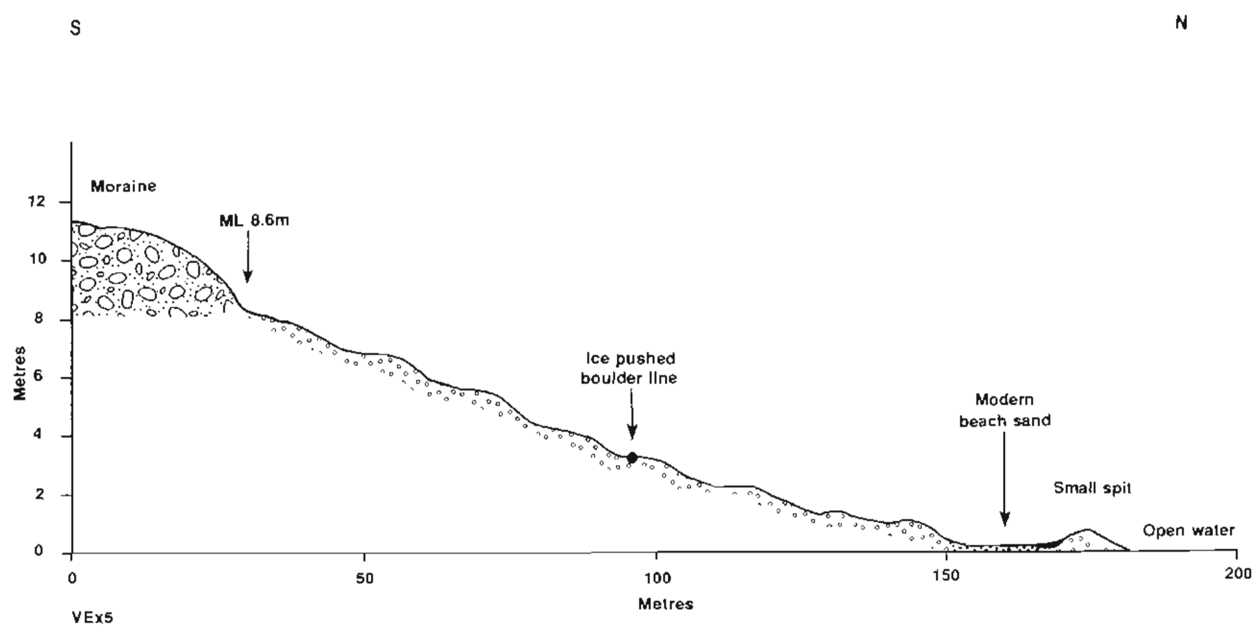

Figure 27. Profile of beach forms north of Krylatyy Peninsula.

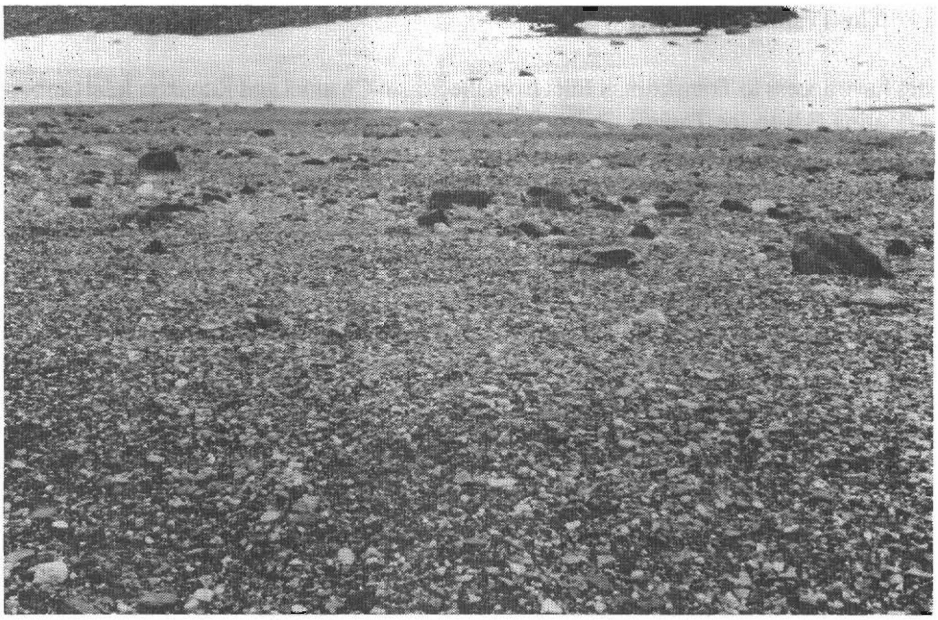

Figure 28. Sloping gravel beach with multiple ridges north of Krylatyy Peninsula.

Near the eastern end of the peninsula the sea attained a ML of 9.2 m cut into moraine of the Antarctic ice sheet. A gravel beach with medium-coarse sand matrix slopes at 6° down to a cobble ridge at 7 m with 5–15 cm clasts. The seaward slope of the cobble ridge is very steep (20–25°). The beach then declines at 5° to a snowbank and sea ice pushed ridge at 1.5 m. The sharp-crested Younger Edisto Moraines occur 200 m distant, on the other side of the frozen inlet.

Further west a 135 m wide beach extends from the icefoot and snowbank at 1.5 m up to two cobble ridges at 7–7.5 m and 8–8.5 m at the ML. The ridges consist of subangular cobbles of 10–15 cm size. The highest ridge extends inland around a shallow lake and abuts a 2–3 m high washed rock cliff.

Close to the limit of the Edisto Ice Tongue marine deposits were identified at 3.7 m, at 6 m but the upper limit was modified by solifluxion, and possibly at 8 m though the effects of weak meltwater flow along lateral channels made the differentiation of marine and glacifluvial sands and gravels difficult.

South-west of the Vertolyetnyy Peninsula a small sea inlet, blocked to the west by the Edisto Ice Tongue, shows a beach terrace that extends to 6.2 m on its eastern and south-eastern shore. The beach slopes at 10° and consists mainly of angular and subangular 2–10 cm size gravels which are subrounded near their upper limit. A sea ice pushed blockline occurs at about 5 m. Washed surfaces of coarse sand and small angular gravels occur at 5.1 m and 3.8 m height adjacent to the older and younger moraines at the southern end of the inlet. However, these deposits have also been modified by marginal meltwaters.

2.7 The Transkriptsii Inlet

Tides have access to Transkriptsii Inlet from the Edisto Channel and Kapakon Inlet beneath the floating Edisto Ice Tongue. Raised beaches occur in the northern part of Transkriptsii Inlet which is covered with thick ice and in Isvilistaya Bay where the ice breaks up seasonally in the inner part of the bay (Figure 19).

On the south-western shore of the large bay north of Edgeworth David station a beach limit rises from 2.8 m at the bay head to 3.4 m on the eastern side of the headland. The beach slopes at 7–8° towards the bay and exhibits several lines of sea ice pushed boulders and depressions with low ridges around them in the beach deposits indicating the presence of stranded ice floes. The marine limit is masked by solifluxion in places. Contraction cracks occur on the beach and boulders show moderate development of tafoni. On the headland boulder ridges occur at 0.7 m, 1.7 m, 3.0 m and 5.5 m with a beach extending to 6.2 m height. They show the effect of very strong ice pushing. The beach slopes towards Transkriptsii Inlet and consists of subangular to subrounded gravels on medium-coarse sand.

A narrow beach occurs at Edgeworth David station up to 3.5 m. It consists of subangular to subrounded gravel and medium-coarse sand. The limit is partly masked by solifluxion and snowmelt erosion. A similar beach occurs in the bay south of Edgeworth David with a clear ML at 3.8 m even though partly modified by solifluxion and snowmelt erosion. The beach consists of 2–8 cm subangular to subrounded gravels, medium-coarse sand and washed-out morainic boulders. Contraction cracks occur on the surface and ice pushed boulders occur at the base of the low cliff at the ML.

Beaches occur on the small island lying offshore from Edgeworth David. On the eastern side beaches extend to 3.7 m height, are cut into moraine, slope at 8° and consist of 2–8 cm gravels and medium-coarse sand. In the south-east a beach crosses the narrow neck of land at 3.7 m where it is cut into moraine deposited by the Antarctic ice sheet. On the western side of the island a 10 m broad and 4 m high moraine marks the margin of a former advance of the Apfels Glacier. No breaks occur further south in the Trasnkriptsii Inlet which is covered with ice that is probably at least centuries old. However, rounded beach cobbles were found in the Apfels Moraine 4 km to the west-south-west indicating that beaches had been formed further south in the Transkriptsii Inlet at an earlier time (? interglacial).

Rozycki (1961) cites the recording of fragments of marine shells by Voronov (1959) from the moraine surface near Dobrowolski station at a height of 40 m. He tentatively suggests that the shells were derived by glacial action from older marine deposits. If so, then it is likely that Lake Figurnoe was transgressed by the sea prior to the last glaciation. The presence of shells at high level could even be of pre-Pleistocene age as suggested by the occurrence of Pliocene age shells at Marine Plain in the Vestfold Hills (Pickard et al. 1988).

Beach deposits occur at several localities within Isvilistaya Bay which becomes a very shallow estuary towards the entrance to Lake Figurnoe. An extensive beach extends to 3–5 m in an inlet on the southern shore close to the western end of the bay. The 100 m wide beach consists of gravel, medium-coarse sand and washed-over moraine. The material is strongly sorted into stone nets. The beach surface is modified by contraction cracks, frost heaving and dissection. The upper limit is masked by solifluxion and snowmelt. A higher terrace of gravel occurs at 7.5 m but its origin as a beach was not confirmed.

In the inner part of Isvilistaya Bay a small beach of gravel and coarse sand extends to about 5.9 m on the southern shore but the limit·is degraded by solifluxion and snowmelt erosion. On the northern shore a beach occurs up to 4 m surrounding a small lake and ice pushed boulders occur to 5 m. The beach consists of gravel and medium-coarse sand, and at one place the surface is interrupted by thermokarst depressions of 3 x 2 m size. West of this extensive beach a small cliff notch occurs on a low headland at 3.5 m, while to the east a fossil cliff notch occurs on a low headland at 3.5 m, while to the east a fossil beach extends to 3.9 m and modern ice-ramping occurs to 1.5 m. At the head of the bay two shallow lakes occur within the morainic boulders and minor fragments of beach occur on the northern slope at about 3 m.

Today the tidal influence extends beneath the ice of Transkriptsii Inlet to the most south-westerly part of the Bunger Hills at Lake Polyanskiy where it meets the Apfels Glacier flowing from the main Antarctic ice sheet.

No *Laternula* fossils were found in any of the beaches in Transkriptsii Inlet. All the beaches found had ML's of less than 6.2 m and most are less than 4.5 m. Kaup et al. (1989) found that Transkriptsii Inlet has an 88 m deep layer of low salinity water of 0.4–1.2 g/l below which it increases sharply to 22 g/l to 29 g/l at 93 m and 104 m depth. While the inlet is clearly connected with the other marine inlets the relatively deep freshwater surface layer due to outfall from Lake Figurnoe and ice melting would inhibit the development of a marine fauna in shallow water.

3. Discussion and Conclusions

This discussion summarises the evidence for former higher relative sea levels in the Bunger Hills as demonstrated by the field data, establishes the validity of 7.5 ± 1 m, as the dated Holocene ML, and compares the findings with other work at Bunger Hills and in East Antarctica. The data is then considered with respect to the post glacial marine transgression and inferred ice thickness during the last glacial maximum in East Antarctica. The conclusions on Bunger Hills and East Antarctica are compared briefly with some results from the Ross Embayment of West Antarctica.

The derived beach boulders in the Apfels Moraine on the eastern side of Transkriptsii Inlet south of any recorded Holocene raised beaches and the marine shell fragments near Dobrowolski station on Lake Figurnoe and south of any known Holocene fossil site suggest that the southern part of the Bunger Hills was transgressed by the sea prior to the last glaciation to a greater extent and altitude than during the Holocene. Such transgression could have been either Pleistocene interglacial or late Tertiary in age and the Antarctic ice sheet margin was probably further south than present.

The two major inlets of Edisto Channel and Kapakon Inlet were formed by transgression beneath the largely floating Shackleton Ice Shelf (Lazarev et al. 1965) to the east and west of Mill Island as post glacial sea level rose and the land remained isostatically depressed. The two inlets were connected by Rogatka Strait between Thomas Island and Charnockite Peninsula, and by flow beneath the floating Edisto Ice Tongue.

The survey showed the widespread occurrence of beaches above modern marine limits in open bays adjacent to Edisto Channel and Kapakon Inlet. It also showed that regression from this limit had produced forms developed by wave action and sea ice pushing at all altitudes down to present marine limits. The best sites were Ostrovnaya Bay, Ice Axe Bay and the northern shore of Krylatyy Peninsula where the differences between the maximum Holocene ML and present ML are 7.3 m, 7 m, and 8.3 m respectively. The average of 7.5 ± 1 m is taken as the best estimate of higher relative sea level for the region though locally beach forms occur up to about 9 m.

The lower altitudes attained by beaches within Transkriptsii Inlet suggest that the eastern margin of the Apfels Glacier retreated later than the opening of Kapakon Inlet. Also, the absence of beaches from the islands north of Charnockite Peninsula and from Geomorphologists and Skalisti Peninsulas suggests that the snout of the Remenchus Glacier and associated shelf ice have only retreated recently from the eastern part of the oasis.

Examination of the beaches below 7.5 ± 1 m altitude, particularly with reference to whether the deposits and surface forms resulted from wave action or sea ice pushing, indicated that the major areas where seasonal open water developed were Edisto Channel, Rogatka Strait and Fish Tail Bay. Although it is to be expected there would be variation in sea ice limits with the warmth and storminess of the summer season, much of the remainder of the area seems to have remained icebound during summer. Also, there was no evidence for break-up of ice in Transkriptsii Inlet for a very long time except in the shallows of Isvilistaya Bay. Examination of the surface sediments and ice pushed ridges on many beaches e.g. Geo Bay East on Thomas Island, suggested that open water wave action was stronger in the past than at present, and that sea ice effects have increased. This suggestion is also supported by the erosion of the fossil geos at the eastern end of Thomas Island. To what extent these features imply milder climatic conditions in the middle than the late Holocene, and how the evidence for an increase in sea ice in the major inlets during the late Holocene relates to the postulated recent retreat of shelf and glacier ice in the east is difficult to determine.

The oldest radiocarbon date is from the head of Edisto Inlet where the assay was 8950 ± 490 yr BP (Beta 15828). This sample was very small and gave a high standard error. By deducting twice this error and applying the 1300 year sea water correction, the age could be as young as 6.7 ka BP rather than 7.7 ka BP which the seawater correction alone would imply. The date of 6880 ± 160 yr BP (Beta 15831) at Shchel Inlet indicates that the oasis was extensive and that the Antarctic ice sheet had retreated to approximately its present position by about 5.6 ka BP. The minimum age of attainment of maximum relative sea level is best obtained by combining the radiocarbon dates and height values of the ML for the three best sites at Ostrovnaya Bay, Ice Axe Bay and northern Krylatyy Peninsula. This gives an average corrected age of 5.25 ka BP and indicates an uplift rate of at least 1.4 m/ka during the middle and late Holocene.

Rozycki (1961) has previously examined the raised beaches of Ostrovnaya and Fish Tail Bays. He reported ML of 7 to 9 m and in a profile and detailed description of the bay referred to here as Fish Tail Bay West described three terraces above the modern beach at 1.5 m, 4.5 m and 7 m. He interpreted the highest ridge adjacent to the 7.5 m ML as having been formed by wave action under open water conditions in the bay but with some effects of floating ice. He noted an increasing influence of sea ice in the beach formation below 4.5 m down to the 1.5 m beach which along with the modern beach he regarded as having been formed when the coast was largely icebound. He described the beach forms as well developed on the western side and less so on the eastern side of the bay. He considered that northerly to north-easterly winds (waves) were dominant in beach formation though in a footnote he indicates that easterly winds are dominant in the oasis. The present observations suggest that the contrast between the western and eastern sides of the bay results from protection by the headland of Cap des Phoques against easterly winds and south-easterly storms.

By comparison with ages suggested for Ross Sea deposits (Hough 1950) Rozycki attributed the age of the Bunger beaches to about 6 ka BP and argued that the evidence for greater wave action on the higher than on the lower beaches indicated that at least the summer climate was warmer during middle Holocene times than recently. While it is necessary to be cognisant of probable short term variations in the breakup of sea ice in different parts of the inlets that would cause variations in beach morphology, nevertheless the present observations support Rozyckis' view.

A recent geochemical study by Kaup et al. (1989) identified a number of lakes of high salinity mainly located between Kapakon and Transkriptsii inlets. Apart from Fish Tail Bay and Transkriptsii Inlet which are clearly sea inlets, they suggested that six other isolated lakes were of marine origin. The highest on the Vertolyetnyy Peninsula occurs at 39 m. Since no conclusive evidence for raised beach forms occurs above 10 m the geomorphological and geochemical data do not seem to concur on a marine origin. Examination of the geochemical data (Table 1 pp. 351–352 in Kaup et al. 1989) reveal very high Na and Cl values for Lake

Polest (8500 mg/l Na and 12500 mg/l Cl) and Lake Sredneye (12500 mg/l Na and 19200 mg/l Cl). Lake Polest occurs at 6 m with a marine threshold from Fish Tail Bay of slightly below 12 m and Lake Sredneye occurs at 6 m. The altitude of these lakes is consistent with a probable marine origin even though the threshold to Lake Polest is slightly higher than the highest raised beach features recorded. None of the other lakes of inferred marine origin including those at higher altitude have Na values above 1750 mg/l (range 200–1750 mg/l) or Cl values above 3100 mg/l (range 405–3100 mg/l) which for both ions is nearly an order of magnitude less. To explain the differences in concentration of Na, Cl and other salts between the high-salinity lakes Polest and Sredneye and the other lower salinity lakes, the authors suggest that the salinity of the higher altitude lakes probably reflects the concentration of cyclic salts over a long period. The cyclic salts would be derived mainly from the western part of Kapakon Inlet and Fish Tail Bay which become open water in summer. These bays are affected frequently by extremely strong winds of easterly origin during the passage of polar low pressure systems. It is also possible that a small part of the salt may derive from rock weathering.

There are few studies in East Antarctica to compare the present results with. West of Bunger Hills the most extensive area where isostatically raised beaches have been observed and dated is Vestfold Hills. Adamson and Pickard (1983) noted that Davis was built on an old beach at about 10 m height. During the return voyage from Bunger Hills the authors called at Davis and were able to confirm that the broad beach in the bay north of Davis had a ML of 9 m and was very comparable with the widely developed beaches at Bunger Hills (Figure 29). During a brief traverse the terraces adjacent to lakes Dingle and Stinear were

Figure 29. Raised beach terrace cut in moraine 9 m height north of Davis, Vestfold Hills.

examined, and a flight was made across the area. The authors did not observe any evidence for Holocene raised beaches above 10 m as previously reported and dated by Adamson and Pickard (1983, 1986) and Zhang and Peterson (1984).

Recently Bronge (1989) has cored Nicholson Lake and has recorded marine diatoms from the lower part of the sediments deposited between 6.3 and 4.3 ka BP. Bronge records the level of Nicholson Lake as 12.3 m while the Vestfold Hills 1:50 000 map (1982) records the level as 9 m. Whatever the precise altitude, the record is important because only marine diatoms have been recorded at Nicholson Lake whereas three species of marine shell have been found between 2.4 m and 5.5 m height around Watts Lake further north in the same inlet. It seems that Nicholson Lake was only just invaded by the Holocene sea at the head of the protected inlet. Although the heights need to be confirmed there is relatively little difference in altitude between Nicholson Lake and the beach north of Davis. The data obtained so far from the Vestfold Hills like the Bunger Hills indicate the occurrence of Holocene raised beaches up to 9–10 m altitude only, and the intrusion of seawater into Nicholson Lake and Lake Polest respectively at the head of narrow inlets where the seawater may have transgressed thresholds as high as 12 m.

Further west Gillieson (1990) has studied lake sediments in the Larsemann Hills but has not found evidence of Holocene raised beaches even though Tertiary marine deposits have been found. (Gillieson, pers. comm. 1990). West of Mawson, Adamson has observed Holocene raised beaches from the air but their altitudes and ages have not been determined.

East of Bunger Hills the only record of isostatically raised beaches is for the Windmill Islands and peninsulas adjacent to Casey. Here Løken (1959) observed ML's cut in moraine, gravel beach terraces and rock benches between 22.9 m and 30.1 m. A radiocarbon date of 6050 ± 250 yr BP (M 1052) was obtained from a beach at 23 m (Cameron and Goldthwait 1961) and is a minimum age for deglaciation. The date is presumably not corrected for Antarctic seawater so the age may be nearer 4.7 ka BP. Although the work was clearly reconnaissance, what is surprising is that from 14 sites no beaches were recorded below 22.9 m which is quite different from the records for Bunger and Vestfold Hills. New research is needed on the Windmill Islands before the implications of the higher beach levels can be fully evaluated.

The maximum extension of ice during the last glaciation in Antarctica is regarded as having occurred about 18 ka BP with associated minimum world eustatic sea levels of about 120 m (Hughes et al. 1981, Fairbanks 1990). Rise in sea level from melting of the North American and Fennoscandian ice sheets (Hollin 1962) caused the major rise in Holocene sea level and deglaciation of coastal Antarctica. However, very little is known concerning the timing of retreat of the east Antarctic ice sheet or of relative sea levels in the Antarctic regions during maximum glaciation and the Holocene transgression.

Domack, Jull and Donahue (1991) have indicated that by 10.7 ka BP marine conditions occurred in Prydz Bay to within 30 km of the coast. Adamson and Pickard (1986) show that by 8.26 ka BP the sea had entered Lebed Lake and Colhoun and Fitzsimons (unpublished) show that by 8.56 ka BP (9860 ± 110 yr BP SUA 2924) the sea had penetrated along the margin of Sørsdal Glacier to Sigma Cove. Domack, Jull, Anderson, Linick and Williams (1989) show that the ice retreated from the Mertz and Ninnis outlet glacier troughs on the continental shelf off Wilkes Land during the middle Holocene after 9 ka BP and before 2.5 ka BP.

The age of deglaciation at Bunger Hills is not known though it has been suggested as between 15 and 6 ka BP with a probable date of about 10 ka BP (Shumskiy 1957, Wisniewski 1983). This paper records marine transgression to the head of Edisto Inlet by 7.7 ka BP which is a minimum age of deglaciation for the oasis, and full deglaciation to the present edge of the Antarctic ice sheet by 5.6 ka BP.

No direct information is available for relative sea levels on the continental shelf north of Bunger Hills at maximum glaciation or during the earliest part of the post glacial transgression. Some idea of the probable relative sea levels and timing of change can be gained from the predictions of Clark, Farrell and Peltier (1978) and Clark and Lingle (1979). These authors use a spherical viscoelastic Earth model, allow for eustatic sea level fall, allow for fully compensated isostatic loading of the shelf by an ice mass of 500 m and allow for attraction of water by the ice mass at maximum glaciation. They suggest that 75 m of the postglacial sea level rise was due to the melting of Northern Hemisphere ice sheets and 25 m to Antarctic ice. By estimating marine transgression rate, land uplift rate, loss of water attraction by the removal of ice mass and water loading of the ocean basins and continental shelf during deglaciation Clark and Lingle (1979) calculated that sea level at Windmill Islands (Wilkes) was only 1.5 m below present at 16 ka BP, that submergence occurred between 16 and 5 ka BP and that emergence occurred after 5 ka BP.

Similar conditions at Bunger Hills would have resulted in a sea level at maximum glaciation only slightly below present. Submergence would have occurred between 16 and 6–5 ka BP followed by emergence. Such relatively high sea level conditions during glacial maximum could have limited the extension of ice onto the deep continental shelf. The submergence between 16 and 6 ka would have caused ice retreat and the extant raised beaches would have been formed mainly after 6 ka BP. The calculation for the Windmills Islands appears to fit the evidence obtained from Bunger Hills though the ice thickness at maximum glaciation does not appear to have been as great at Bunger Hills.

Clark and Lingle (1979) conclude that if the Antarctic ice sheet was approximately the same size as today at 18 ka BP then beaches younger than 5 ka BP would only be raised 2–4 m above present sea level. The occurrence of ML's of 7.5 ± 1 m with a maximum threshold of 12 m to Lake Polest at Bunger Hills, and 9–10 m with a threshold of 9–12 (?) m to Nicholson Lake at Vestfold Hills, suggest that ice thickness and isostatic depression were much less than would be required by the extension of 500-1000 m of ice onto the continental shelf as suggested by Denton et al. (1975) and Hughes et al. (1981) for the Ross Sea. The higher raised beaches at Windmill Islands between 23 and 30 m suggest the ice was slightly thicker than at Bunger Oasis, perhaps due to the proximity of the Law Ice Dome. Because the field data is confined to middle and late Holocene raised beaches and information on relative sea level at previous times can only be estimates, precise calculation of ice thickness at maximum glaciation is difficult.

If at maximum glaciation sea level was only slightly below present sea level (~1.5 m as suggested for Windmill Island) there would have been a very close balance between eustatic sea water withdrawal, and position of the depressed land. Since sea level rose by 100 m due to return of meltwaters after deglaciation, Clark and Lingle (1979), it would require a maximum ice thickness of only 400 m to effect fully compensated isostatic depression and subsequent recovery, having regard for the present altitude of the raised beaches (based on an ice density of 0.9, mantle density of 3.3). Such an ice thickness is suggested as a maximum figure.

In Arctic Canada Andrews (1968, 1970) examined uplift curves from 21 sites. He found that similar percentage values for uplift for each 1 x 10^3 years following deglaciation occurred even though the absolute uplift values varied from place to place. He showed that 4 ka after deglaciation 80% of uplift had occurred and that by 10 ka the smoothly decelerating process of uplift was complete.

In Bunger Hills it is evident that the beaches have been emerging during the last 6 ka. This is inferred from the relative uniformity of slopes from the ML to tidewater or high tide ice crack on many of the larger beach sequences. In addition, the radiocarbon age at Shchel Inlet of 6880 ± 160 yr BP (Beta 15831), or about 5.6 ka BP, indicates that the Antarctic ice sheet edge has been at or perhaps slightly south of its present position during this period. The Antarctic ice sheet edge is considered to be approximately in a steady state adjacent to the high ground of the southern Bunger Hills with minor fluctuation taking place on the marginal outlet glaciers to east and west (Adamson and Colhoun 1991). If the interpretations that uplift is still continuing and that the Antarctic ice sheet edge has been stable for the last 6 ka are correct then the Canadian analogue implies that only the last 10 ka need be considered further.

Assuming 10 ka as the age of deglaciation of Bunger Hills (the limiting age for application of Andrews model) and using only the three best dated sites at Ostrovnaya Bay, Ice Axe Bay and Krylatyy Peninsula with an average of about 5.25 ka BP, then 7.5 m would represent 17.7% of the uplift and give a minimum total uplift figure of 42 m. This suggests an average ice thickness of around 154 m at maximum glaciation.

The estimates based on the suggested position of glacial maximum sea level at Windmill Islands, where isostatic recovery has been 15 m greater than at Bunger Hills (50 m of ice load), or on the Andrews model for Canada suggest very different ice thicknesses of 400 m and 154 m respectively. Neither figure, regarded as probable maximum and minimum values, approaches the 500 m thickness suggested by Denton et al. (1975) and about 500-1000 m thickness of the Hughes et al. (1981) model for extension of the ice sheet onto the outer continental shelf of East Antarctica. A figure of half as much ice over the Bunger Oasis with very limited extension onto the continental shelf seems more appropriate given the limited degree of glacial erosion of the Bunger Hills (Adamson and Colhoun 1991).

The similar altitudes of the raised beaches at Bunger and Vestfold Hills and slightly greater altitude at Windmill Islands (15–22 m) suggests that ice thickness on the east Antarctic coast at maximum glaciation was much less than postulated by Denton et al. (1975) and Hughes et al. (1981) who extrapolated from the Ross Sea where they considered that 500 m of ice extended as far as the edge of the continental shelf. Drewry (1979) on the basis of radio echo-sounding, marine sediment and glacial geological evidence suggested that the Ross Sea ice was much thinner than suggested by Denton et al. (1975) and Hughes et al. (1981). Recently Denton et al. (1989) have given two extreme reconstructions of ice in the Ross Sea for the maximum glaciation. The minimum reconstruction shows ice thicknesses from >1000 m to <500 m surrounding the inner part of the Ross Embayment with the central and outer embayment occupied by shelf ice to the continental edge. The maximum and preferred reconstruction shows a declining ice gradient from 1300 m adjacent to the foot of the Transantarctic Mountains to under 100 m at the edge of the continental shelf where the ice grounded. Over the central part of the basin the ice was 600–800 m thick.

Examination of raised beaches in the Ross Sea basin was formerly confined to measurement and dating at single sites or limited extents of coastline. Recently Mabin (1986) and Kirk (1991) have made extensive reconnaissance studies of the altitudes of raised beaches along the Victoria Land coast from Cape Adare to McMurdo Sound. Their findings show that no beaches occur above 5 m in the northern part of Victoria Land but that in southern Victoria Land beach altitudes increase from 20 m at Terra Nova Bay to a maximum of 32 m at Cape Ross before decreasing to sea level in the inner part of McMurdo Sound. Mabin (1986) and Kirk (1991) both conclude that the altitudes of the beaches are too low to support the ice thickness inferred by the Hughes et al. (1981) model and suggest that the last glaciation ice cover was much thinner than indicated by the model. In addition, it can be noted that the altitude pattern given implies that isostatic uplift patterns were focussed on ice masses centred on the mountains of Victoria Land and not in the southern part of the Ross Sea Basin and Transantarctic Mountains as would be required by a south to north thinning ice sheet throughout the Ross Sea Basin. The low altitudes of raised beaches and limited ice thickness inferred has strong similarities with the Bunger Hills and east Antarctic areas, and strongly suggests that ice thickness and extents over the coastal areas and continental shelves of West and East Antarctica during maximum glaciation were much less than is currently suggested on the basis of glaciological and geophysical reconstructions.

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