LATE QUATERNARY HISTORY OF THE BUNGER HILLS, EAST ANTARCTICA

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Abstract: The Bunger Hills protrude from the inner continental shelf of East Antarctica and comprise a complex area of deglaciated hills and marine inlets (101°E and 66°S). The ice sheet expanded northwards and submerged the hills during the Last Glaciation. The limited glacial erosion, and thick glacial deposits in the northwestern part of the hills suggests the last ice sheet did not extend far onto the continental shelf and was little thicker than the highest hills (163 m). Glacial retreat was caused by rise of sea level which flooded the major inlets before 7.7 Ka. Sea level rise caused relatively rapid collapse of the ice sheet margin without systematic retreat of the ice edge. Several ice-dammed lakes, with eroded shore terraces, existed during the period of deglaciation. Raised beaches occur extensively in the inlets up to 7.5 ± 1 m above the modern wave and sea ice limits. Middle and late Holocene (post 5.6 Ka) uplift occurred at 1.4 m/1000y. Beach morphology suggests wave action may have been more important during the middle Holocene and that sea ice has increased in the late Holocene. The low altitudes of the beaches suggest a thin ice cover of >155 m and <400 m. Similar evidence from Vestfold Hills and Windmill Islands points to the margin of the East Antarctic ice sheet having been thinner than postulated by Hollin (1962) and Hughes et al. (1981). Within Bunger Hills two sets of moraines occur marginal to the Edisto Ice Tongue and Apfels Glacier, the Older and Younger Edisto Moraines dated to after 6.2 ka BP and the last few centuries. In the south the end moraine located at the junction of the ice sheet, hills and perennial snow-wedge represents the Antarctic ice margin since at least 5.6 Ka.

Key words: Bunger Hills, deglaciation, raised beaches

Introduction

The Bunger Hills (101°E, 66°10'S) form the most extensive oasis in East Antarctica being 952 km² in area with 482 km² land (Wisniewski, 1983). The region consists of a complex of islands and inlets on the inner shelf. In the southeast the ice sheet abuts the hills but does not submerge them. In the west the Apfels and Scott glaciers flow westwards and northwards onto and across the inner continental shelf; the latter in a 700–1300 m-deep trough. The floating Edisto Ice Tongue extends north eastwards before it grounds on Thomas Island. The Shackleton Ice Shelf with Mill Island ice dome (ca. 350 m) extends from the Scott to the Remenches glaciers in the north. The sea penetrates beneath the Shackleton Ice Shelf from depths of 177 m to 1042 m on the outer continental shelf to over 100 m within the Edisto Channel and Kakanon Inlet (GEBCO 5.13, 1981; Grigor'ev and Yevtseyev, 1966). The small Remenches outlet glacier bounds the area in the east (Fig. 1).

The hills form a line of summits 130–150 m high in the south that deflect the ice flow to west and east. The hill summits decline northwards and reflect a preglacial erosion surface. The southern hills contain several fault-oriented glacial lakes, the largest being Figurnoe extending to 137 m bsl. The southern hills consist of gniss, granite and migmatite. Thomas Island, which also consists of migmatite, and Charnockite Peninsula form the central part of the region (Ravich and Solov'ev, 1966). The northern part includes Geographers Island, the Mariner Islands and islands that underpin the Shackleton Ice Shelf.

Last Glaciation Ice Expansion and Retreat

During the Last Glaciation the Antarctic ice sheet engulfed most of the oasis. The ice flow was mainly from southeast to northwest in the sector 275°–335° with a mean of 310–320°. Topography had little influence on the direction of regional ice flow which was the same on Thomas Island and Charnockite Peninsula as in the southern hills. The only variation was in the northeast where the Remenches Glacier expanded westwards (275°) over part of the Highjump Archipelago. The Apfels and Scott glaciers did not expand eastwards, and there is no evidence for northward expansion of ice towards the Shackleton Ice Shelf and outer continental shelf (Fig. 2).

The ice flow pattern was determined from the distribution of striae, roches moutonnées, orbicular granitoid, charnockite, conglomerate and sandstone erratics throughout the west-central part of the region. The charnockites have been derived from Charnockite and Kashalot islands and the eastern part of the oasis, but the granitoïds and sediments do not crop out within the area and have been transported northwestward from sources beneath the ice sheet.

The ice sheet covered the highest points in the southern hills (163 m) and submerged the region. How far the ice extended to the north, how thick it was in the north and northwest, is debatable. There is some circumstantial evidence that suggests the ice only just covered the area during the Last Glaciation and did not extend to the shelf edge. Thick glacial drift occurs on the northwestern parts of Thomas and Geographers islands and seems inconsistent with the northward movement of thick erosive ice. The topography appears to be only superficially modified by glacial erosion which has accentuated the major lineaments of the pre-glacial landscape. The highest summit of the

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Taylor Islands (121 m), that projects through the Scott Glacier, exhibits very poorly developed roche moutonnée surfaces but is covered with a mantle of migmatite blocks of 1–3 m size. These blocks appear to have been formed by dilation of the bedrock which exhibits the development of tafoni, desquamation flaking and iron case-hardening of boulders to a greater degree than elsewhere in Burger Hills. The evidence suggests that the highest Taylor Island was either a nunatak during the last expansion of ice across the region or was deglaciated at an early stage.

There is no systematic pattern of retreat moraines with associated outwash plains or terraces developed in Burger Hills from which the pattern of deglaciation can be determined. Although there are considerable areas of hummocky drift on northwestern Thomas Island and on western Geographers Island, these deposits appear to have been formed by the stranding of residual ice on the islands when the ice sheet margin collapsed in the deep inlets (>100 m) during the Holocene transgression. As the ice sheet margin collapsed the Scott Glacier found an outlet northeastwards in the Edisto Ice Tongue. The Shackleton Ice Shelf became established in the north, and the Apfels and Remenchus glaciers became separately defined in the southwest and east. The Antarctic ice sheet edge retreated approximately to its present limit defined by the end moraine which was formed before 5.6 Ka (Adamson and Colhoun, 1992).

During deglaciation ice-dammed lakes were impounded long enough for shoreline terraces to be cut and beaches deposited. The largest occurred in western Fish Tail Bay and had shorelines at 23 m and 20 m. Another formed in Lake Dolgoe with a shoreline at 29 m; 16 m above present lake level. A third formed in the valley north of Lake Shchel, with beaches at 23 m and 15 m. Other minor lakes developed near the continental ice sheet margin (Colhoun and Adamson, 1989).

Near the ice sheet margin in the south and east rock surfaces are mainly ice smoothed and drift free. In the west central part of the southern hills and on central Thomas Island thin drift occurs on the valley floors and adjacent hillslopes are drift free. The thickest glacial deposits occur in the west and northwest between Vertolyetny Peninsula and Geographers Island (Adamson and Colhoun, 1992).
Raised Beaches and Their Significance

Raised marine landforms occur on Geographers Island, Thomas Island, Charnockite Peninsula, Kashalot Island, on the northern shore of the southern hills, on the Krylaty and Vertolyetnyy peninsulas and within the Transkriptii Inlet. Shoreline features include erosional and depositional forms developed under the influence of both wave action and sea ice. Erosional forms include marine rock platforms, sea cliffs and parallel-sided, wave-eroded chasms. Depositional forms include beach terraces with beach ridges and small deltas. Sea ice has formed many ice pushed block lines. Fossil marine limits are shown in bays by the contact between the beach and moraine deposits. On headlands the effects of wave-washing has cleaned off the glacial drift and sea ice pushing has aligned boulders at the lower limit of drift.

The modern and fossil marine limits were measured at many localities. Depending on exposure and effects of sea ice ramping, modern marine limit occurs up to 1–3 m above HWM (high-water mark). The raised beaches extend to 9–
Fig. 3. Raised beaches in the western part of Kapakon and Transkriptsiin inlets, Bunger Hills showing heights of the marine limit above HWM.
10 m above modern HWM and 7.5 ± 1 m above the modern marine limits. Within Transkriptii Inlet the beaches are lower not exceeding 6.2 m above HWM and 5 m above the modern marine limit, indicating that Transkriptii Inlet became marine later than the Edisto and Kapokon inlets (Fig. 3; see Colhoun and Adamson, 1992 for other maps of raised beaches).

Fossils of *Laternula elliptica* King and Broderip were obtained from several beaches and from marginal shear moraines at the terminus of the Edisto Ice Tongue on Thomas Island. The radiocarbon dating (Table 1, Figs. 1 and 3) shows that the region had been transgressed before 7.7 Ka and had attained approximately its present size by 5–5.6 Ka. No *Laternula* shells were found within Transkriptii Inlet which because of melting ice and lake drainage is relatively fresh to 88 m depth (Kaup et al., 1989).

The fossil marine limits and radiocarbon dates obtained from Ostrovnya Bay, Ice Axe Bay and northern Krylaty Peninsula indicate an uplift rate of 1.4 m/1000y during the middle and late Holocene (Colhoun and Adamson, 1992).

The results confirm the findings of Rozycki (1961) who studied the raised beaches of Fish Tail and Ostrovnya bays, and concluded that the highest sea level during the last 6 Ka was 7–9 m above present HWM. Observations at the eastern end of Geo Bay, on the southern side of Thomas Island (Fig. 1), showed that ice pushed block shorelines formed near the fossil and present marine limits are separated by a sloping beach face of water worn sand and gravel. The sequence is compatible with Rozycki’s (1961) interpretation that the coast may have been less icebound in middle Holocene times than at present. However, at Fish Tail Bay West (Colhoun and Adamson, 1992), the site of Rozycki’s observations, it was noted that the centre of the bay was characterised by a continuously sloping wave-washed surface that extended from the fossil marine limit at 9.4 m to the modern sea ice pushed boulder line at 1.75 m (Fig. 4). About 15 low-amplitude beach ridges occur on the surface but there is only one ice pushed boulder line at 5.2 m. In contrast three distinct terraces bounded to seaward by ice pushed block lines occur at the eastern end of the beach and merge gradually with the wave-washed beach surface towards the centre of the bay. Although the coasts may have been less ice bound in middle Holocene times, it is also possible that the pattern of ice pushed forms and wave-washed sand and gravel surfaces may reflect local differences in beach exposure.

### Table 1. Radiocarbon dates.

<table>
<thead>
<tr>
<th>Location</th>
<th>Material &amp; Age Details</th>
<th>Age (yr BP ± Error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Younger Edisto Moraine,</td>
<td>Shell fragments from till</td>
<td>1510 ± 100 BP Beta 17528 corrected – 200 yr BP</td>
</tr>
<tr>
<td>Thomas Island</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Older Edisto Moraine,</td>
<td>Shell fragments from till</td>
<td>7540 ± 100 BP Beta 17529 corrected – 6.2 ka BP</td>
</tr>
<tr>
<td>Thomas Island</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head of Edisto Inlet,</td>
<td>Fragments of <em>L. elliptica</em> in beach sand</td>
<td>8950 ± 490 BP Beta 15828 corrected – 7.7 ka BP</td>
</tr>
<tr>
<td>Thomas Island, main access probably from Edisto Channel</td>
<td>amongst morainic bounders. Max. beach height 6.8 m, sample height 2.8 m.</td>
<td></td>
</tr>
<tr>
<td>North Coast Bay, Thomas Island, Edisto Channel</td>
<td>Fragments of <em>L. elliptica</em> in beach sand. Max. beach height 6.9 m, sample height 3 m.</td>
<td>4960 ± 120 BP Beta 17526 corrected – 3.7 ka BP</td>
</tr>
<tr>
<td>Elliptica Lake, Thomas Island, access from Edisto Channel</td>
<td>Shells of <em>L. elliptica</em> in growth position. Approx. ML 10.5 m, sample height 4 m.</td>
<td>5630 ± 90 BP Beta 15830 corrected – 4.3 ka BP</td>
</tr>
<tr>
<td>Geo Bay, Thomas Island, Kapokon Inlet</td>
<td>Fragments of <em>L. elliptica</em> in beach sand. Max. beach height 6 m, sample height 2.6 m.</td>
<td>6010 ± 100 BP Beta 17525 corrected – 4.7 ka BP</td>
</tr>
<tr>
<td>Chamrockite Peninsula, Kapokon Inlet</td>
<td>Fragments of <em>L. elliptica</em> from beach sands. Max. beach height 7 m, sample height 1.3 m.</td>
<td>6210 ± 100 BP Beta 17524 corrected – 4.9 ka BP</td>
</tr>
<tr>
<td>Shhel Inlet, Kapokon Inlet</td>
<td>Fragments of <em>L. elliptica</em> from beach sand. Max. beach height (not the ML) 3 m, sample height 2 m.</td>
<td>6880 ± 160 BP Beta 15831 corrected – 5.6 ka BP</td>
</tr>
<tr>
<td>Ostrovnya Bay, Kapokon Inlet</td>
<td>Fragments of <em>L. elliptica</em> from sandy mud at head of bay. Max. beach height 8.5 m, sample height 2.2 m.</td>
<td>6500 ± 130 BP Beta 17527 corrected – 5.2 ka BP</td>
</tr>
<tr>
<td>Ice Axe Bay, Kapokon Inlet</td>
<td>Shells of <em>L. elliptica</em> in growth position. Max. beach height 8 m, sample height 3-3.5 m.</td>
<td>6900 ± 120 BP Beta 15829 corrected – 5.6 ka BP</td>
</tr>
<tr>
<td>North of Krylaty Peninsula, Kapokon Inlet</td>
<td>Shells of <em>L. elliptica</em> in growth position. Max. beach height 8.6 m, sample height 5.2 m.</td>
<td>6250 ± 140 BP Beta 15832 corrected – 5 ka BP</td>
</tr>
</tbody>
</table>

Correction of 1300 yrs based on values determined for Vestfold Hills by Adamson and Pickard (1986).

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Fig. 4. Upper: Profile of raised beach morphology at Ice Axe Bay showing gravel beach ridges, ice-pushed boulder lines and thermal contraction cracks. Middle: Profile of raised beach at Fish Tail Bay West with similar features shown. Lower: Profile of raised beach north of Krylaty Peninsula. Note the multiple low ridges of approximately equal spacing and height.

The low altitude of the raised beaches at Bunger Hills allows some deductions on the probable thickness of the Antarctic ice sheet over the inner continental shelf during the Last Glaciation by comparison with other areas. The age of the Last Glaciation Maximum for this sector of the East Antarctic coast is not known but may be presumed to be about 18–20 Ka. Also, the date of deglaciation of the region is not known though it has been suggested as being over 10 Ka (Shumskiy in Wisniewski, 1983), a date now confirmed by Bolshiyanov et al. (1991). The amount of isostatic depression of the coastal zone during the Last Glacial Maximum and relative position of sea level are also not known. Using a viscoelastic Earth model Clark and Lingle (1979) suggested that relative sea level in the Windmill Islands was
only 1.5 m below present at 16 Ka. The maximum altitude of raised beaches on the Windmill Islands near Casey Base (111°E, 65°30'S) is 30 m and the lowest raised beach reported at 23 m is dated at 6050 ± 250 y BP (M 1052) (Cameron and Goldthwait, 1961). If the Windmill Islands were isostatically depressed at maximum glaciation by an amount equivalent to sea level fall (100 m, Clark et al., 1978) minus 1.5 m (Clark and Lingle, 1979), then assuming an ice density of 0.9 and mantle density of 3.3 the raised beaches at 23 m and 30 m allow estimates of ice thickness of 445 m and 471 m if postglacial uplift is complete.

If relative sea level in the Burger Hills was also only slightly below present at maximum glaciation and isostatic depression was approximately equivalent to the 100 m of post glacial sea level rise for the East Antarctic region suggested by Clark et al. (1978) then the average ice thickness over the inner shelf is estimated at 389 m, say 400 m.

If, however, sea level fall was greater being around 121 ± 5 m as suggested for Barbados by Fairbanks (1989), then the estimates for ice thickness over Burger Hills would be 465 m and for Windmill Islands 521–547 m. At Vestfold Hills (78°E, 68°S) raised beaches occur at similar altitudes to Burger Hills and do not exceed 10 m above the modern marine limit (Adamson and Pickard, 1986). This implies similar ice thickness to Burgeo Hills. The contrast in height of the raised beaches at Windmill Islands with Burgeo and Vestfold hills probably reflects the proximity of the Law Ice Dome and large Vanderford Glacier.

In Canada, Andrews (1968, 1970) has used a different method of estimating ice thickness. He demonstrates from 19 dated uplift curves that the percentage of uplift per 1000 years following deglaciation is the same for each site though the absolute uplift rate varies. He also showed that by 4 Ka after deglaciation 80% of the uplift has occurred and that by 10 Ka the smoothly decelerating process of uplift is complete. Applied to Burgeo Hills, which are now known to have been deglaciated before 10 Ka (Bolshiyanyov et al., 1991), the 7.5 m of beach uplift during the last 5.6 Ka represents 17.7% of uplift. Such a value suggests a total uplift of 42.4 m and an estimated ice thickness of 155 m. That the ice may have been only 155 m or less in thickness at maximum glaciation is compatible with the inference that the highest summit of the Taylor Islands at 121 m remained a nunatak.

These estimated values for ice thickness from East Antarctica are generally considerably less than the 500–1000 m postulated by Denton et al. (1975) and Hughes et al. (1981). These authors used Hollin’s (1962) model of the extent of ice in East Antarctica at maximum glaciation and also extrapolated from the Ross Sea in West Antarctica where they considered that 500 m of ice extended to the edge of the continental shelf. This thickness of ice in the Ross Sea was questioned by Drewry (1979) who thought that the ice was much thinner and did not extend to the shelf edge. Recently Denton et al. (1989) have presented Maximum and Minimum models of ice thickness for the Ross Sea. The Maximum Model shows over 1200 m of grounded ice adjacent to the southern Ross Sea coast and 100–200 m near the shelf edge, with an average thickness of 700–800 m. The Minimum Model shows grounded ice of 1000–500 m in the inner Ross embayment with the central and outer embayment occupied by shelf ice. Hollin (1962) envisaged approximately 1000 m of ice over the inner shelf and 500 m of ice on the outer shelf of East Antarctica. Our findings suggest that maximum ice thicknesses on the inner shelf were about 400 to 475 m and may have been considerably less, and that the similarity of sea level to present at maximum glaciation would have prevented the extension of thick ice over the outer shelf where water depth exceeds 1000 m in places.

Recent extensive reconnaissance studies have been made of the raised beaches of Victoria Land from Cape Adare to McMurdo Sound (Mabin, 1986; Kirk, 1991). In northern Victoria Land no beaches exceed 5 m altitude, but in southern Victoria Land maximum beach height increases from 20 m at Terra Nova Bay to 32 m at Cape Ross before decreasing to present sea level in the inner part of McMurdo Sound. The isobases of uplift focus on the mountains of Victoria Land rather than the Transantarctic Mountains and the low altitudes attained by the beaches suggest much less ice in the Ross Sea than suggested by Hughes et al. (1981). These observations are in accord with our view derived from East Antarctica that the thickness and extent of ice over the continental shelf during the Last Glaciation Maximum was probably much less than previously thought.

Ice Margins and Moraines

After deglaciation a variety of ice margins were developed in the western part of the oasis and have fluctuated slightly in extent from time to time. Northwest of Geographers Island the southern margin of the Shackleton Ice Shelf impinges on the bays and forms a series of arcuate marginal moraine ridges that conform with the outline of the coastal bays. Southwest of Geographers Island the floating ice is thicker, being part of the Edisto Ice Tongue that extends northwards from the Scott Glacier. The grounded ice has formed two belts of linear moraines; an outer and older series of rounded moraines up to 15–20 m in height, and an inner younger series of sharp-crested moraines that are still ice cored and up to 10 m high (Figs. 2 and 3).

The major part of the Edisto Ice Tongue has been grounded on the western end of Thomas Island for some time and has formed two series of moraines like those on the southwest coast of Geographers Island. As the ice passed onshore on Thomas Island the ice incorporated marine sediment within the morainic debris. Shell fragments from the Older Edisto Moraines gave a radiocarbon age of 7540 ± 100 y BP (Beta 17529) and from the Younger Edisto Moraines of 1510 ± 100 y BP (Beta 17528). Accepting an Antarctic sea water correction of 1300 y (Adamson and Pickard, 1986), the dates suggest the Older Edisto Moraines formed after 6.2 Ka and the Younger Edisto Moraines during the last few centuries. Recent Spot satellite images (1991) show that the eastern end of the Edisto Ice Tongue adjacent to Thomas Island has collapsed since 1986 which stresses the ephemeral nature of moraine development at the grounded ice margin.

Similar marginal moraines occur adjacent to the Vertolyetny Peninsula where the southern margin of the Edisto Ice Tongue grounds, on Kainii Island in Transkriptisi Inlet against which the Apfels Glacier terminates, and at a
few localities on the western coast of the southern hills south of Cape Khordern (Fig. 1).

The Apfels Glacier and margin of the Antarctic ice sheet impinge on the Southern Hills in the south and southeast. The Apfels glacier flows slowly (ca. 100 m/y) west northwards to join the Scott Glacier but the Antarctic ice sheet is blocked by the hills except in the east where it descends to Kapakon Inlet. The Apfels ice margin appears to have maintained the same position against the hills for a long time, to judge by the lack of evidence for fluctuation in the small ice-marginal lakes. A distinct end moraine has been formed within 100 and 200 m of the edge of the Antarctic ice sheet where it is blocked by the hills and the perennial snow wedge (Fig. 2). The moraine consists of a broad ridge of boulders on the ice surface, and its configuration follows around the spurs and into the cols between the hills. The radiocarbon date for Shchel Inlet of 6680 ± 160 y BP (Beta 15831; corrected 5.6 Ka) indicates that the ice sheet edge has been in approximately its present position since at least middle Holocene times. Three kilometres east of the head of Lake Figunee the margin of the ice sheet passes through a col in a large recumbent fold, and recently formed ice-cored moraine has been deposited on top of a weathered rock surface stained brown by hydrated iron oxide. To what extent these features are local to the col or whether they imply slight readvance of the ice sheet margin is difficult to assess.

Conclusions

The Buonger Hills were glaciated during the Last Glaciation by the northwestern expansion of the edge of the Antarctic ice sheet over the oasis. Deglaciation was caused by collapse of the ice sheet edge over the deep marine inlets on the inner continental shelf during the Holocene transgression. The limited glacial erosion, thick glacial deposits in the northwest and the low altitude of the raised beaches all suggest that the region was not covered by a very thick ice sheet during the Last Glaciation and that ice probably did not extend to the edge of the deep-water outer continental shelf. The raised beaches post-date 7.7 Ka. The oasis was approximately its present size by 5.6 Ka and the Antarctic ice sheet had established its present margin by this time. It is suggested that during the Last Glaciation ice thickness and extent in coastal East Antarctica were very much less than has been hypothesised by Hollin (1962) and Hughes et al. (1981).

Marginal adjustments in shelf ice boundaries, and the grounding of floating ice tongues and outlet glaciers descending to tide water, have formed marginal moraine ridges in the western part of the area. An older series appears to post-date 6.2 Ka and a younger ice cored series appears to have formed in the last few centuries.

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