Late Quaternary environment of southern Windmill Islands, East Antarctica

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Abstract: Analyses on a sediment core collected from the Windmill Islands, East Antarctica are used to demonstrate that climatic conditions in this region prior to the Last Glacial Maximum were similar to those during the Holocene and that the area was overrun by ice at some stage between 26 kyr BP and the onset of biogenic sedimentation 11 kyr BP. The 10.9 m long core was taken from a marine inlet (epishelf lake) on Peterson Island and is predominantly a sapropel of Holocene age. Material in the lower part of the core includes a till layer laid down during the last glacial in the region and below this till is material which has been dated to 26 kyr BP. Geochemical analyses conducted on the core demonstrate similarities between the Holocene sequence and the preglacial material. The Holocene sequence shows enhanced biogenic production and periods of open water around 4 kyr BP, suggesting a climatic optimum around that time. A subsequent decline in conditions, probably a colder climate with greater extent of sea ice, is evident from 1 kyr BP to the present. The data support results from ice core studies on nearby Law Dome, which suggest there was a period of warming around 11.5 to 9 kyr BP, that recent summer temperatures are low relative to a few centuries ago, and that increasing winter temperatures are the main contributing factor to a recent overall warming in the region.

Received 23 November 2001, accepted 25 July 2002

Key words: Antarctica, climate, Holocene, interglacial environment, marine sediments, Pleistocene

Introduction

Palaeoenvironmental archives across East Antarctica have been established from terrestrial, lacustrine and marine sediments in the sparsely distributed ice-free coastal areas, termed oases. Many gaps in the understanding of the Quaternary environmental development of the region still exist and the information is sparse especially when compared with Northern Hemisphere archives. Windmill Islands is a small oasis on the coast of East Antarctica, with much of its history preserved in its landscape, though to date understanding of its environmental development in the late Quaternary has been limited.

Windmill Islands comprises 75–80 km² of ice-free islands, peninsulas and nunataks on the coast of Wilkes Land (Fig. 1). Law Dome, which abuts the easternmost islands, is an ice dome of 200 km diameter. Its summit is 1395 m a.s.l. and is connected to the East Antarctic ice sheet by a saddle c. 1000 m a.s.l. Oxygen isotope measurements on an ice core from the dome summit indicate that Law Dome remained dynamically independent of the East Antarctic ice sheet and was not overridden by it through the last glacial cycle (Morgan et al. 1997). The Vanderford glacier drains the East Antarctic ice sheet and Law Dome into Vincennes Bay at the southern end of the Islands, along a trough that is up to 1500 m deep (Goodwin 1993). Geology of the southern islands comprises igneous rocks, mostly charnockite and granite and the less rugged northern islands consist of metamorphic rocks, mainly schist, gneiss and migmatite (Blight & Oliver 1977).

The glacial history of the area is not well defined. It is clear that the entire Windmill Islands had been glaciated at some time during the late Pleistocene–early Holocene (Cameron et al. 1959, Hollin & Cameron 1961) then subsequently subjected to fluctuating sea levels. Raised marine features indicate a Holocene upper marine limit of 32 m in the south and 2–3 m less toward the north (Goodwin 1993). Pond sediments close to the marine limit indicate deglaciation in the southern islands by at least 8160 ± 300 14C yr BP (ANU 6401; a correction for marine reservoir effects of -1300 years was applied by Goodwin & Zweck 2000 to give 6860 ± 300 corr. 14C yr BP) and the northern islands by at least 5930 ± 120 14C yr BP (ANU 6399; deemed to not need reservoir correction; Goodwin & Zweck 2000). Goodwin (1993) suggests the earlier deglaciation of the southern islands was due to their proximity to the Vincennes trough, as a rising sea level would have initiated the break up of the floating Vanderford glacier. In the north the ice would have been pinned on the Peterson Bank, which is around 200 m deep, extends up to 80 km north and averages 20 km wide offshore from the north-east coast, hence it would have retreated more slowly and become deglaciated some time later (Goodwin 1993). The northern islands form peninsulas that are connected to the margin of Law Dome by a ramp of ice. Goodwin (1996) suggests the ramp in the
northern parts of Windmill Islands formed during a readvance of the ice sheet sometime after 4000 yr BP and culminating around 2500–2000 yr BP (determined by lichenometry). Goodwin (1996) attributes this 3–4 km readvance to a positive mass balance on Law Dome. Thus it is probable then the whole island region may have been affected. Adélie penguins as well as much other bird life currently populate the Windmill Islands and seals are known to be in the area during breeding season. A radiocarbon date on an Adélie penguin skull found in the north of the islands indicates a minimum age for penguin occupation of the area of 4380 ± 250 14C yr BP (ANU 6403; corrected by -1090 years for marine reservoir effects to 3290 ± 250 corr. 14C yr BP by Goodwin 1993).

The purpose of the research presented here is to enhance this understanding of late Pleistocene and Holocene history in two ways. The first involves sampling the marine sediments at Windmill Islands to at least the marine sediment-till transition, and dating the onset of biogenic sedimentation as a proxy for deglaciation age, which is currently not known accurately for Windmill Islands. The second aim is to use geochemical analyses conducted on the sediment core to infer the sequence of events that occurred, and environmental conditions that were present, to produce the sediment sequence. The basin sampled is anoxic, a theoretically ideal marine environment to sample, since sediments are protected to a large degree from diagenesis. The basin also is enclosed by constricted topography/bathymetry which can preclude or minimize the likelihood of iceberg turbation or similar disturbance, as evidenced by remarkably good preservation of diatoms found in preliminary investigations of a similar sediment core from a nearby site also with these conditions (Cremer et al. 2001).

**Geographical setting**

The sediment core used in this research was retrieved from an inlet on Peterson Island in the south of Windmill Islands (Fig. 1). The 1.5 km long inlet is oriented north–south and has a maximum width around 500 m. It opens to the sea in the north across a c. 3 m-deep sill (Fig. 2). The surrounding hills rise to 78 m a.s.l. A Holocene sea level limit of 32 m was determined on Holl Island, Herring Island, and...
Browning Peninsula (Goodwin 1993), which suggests a similar limit for Peterson Island. The chronology of this sea level highstand is not known precisely. Coraline algae in a raised shoreline 23 m above current sea level at Eyres Bay (Browning Peninsula) yielded a radiocarbon age of 6040 ± 250 14C yr BP (M-1052; Cameron 1964) and this is the only dated in situ marine microfossil from an emergent shoreline in the islands. Numerical modelling by Goodwin & Zweck (2000) estimates the present uplift rate as 3–4 mm yr⁻¹ and an average rise of 5 mm yr⁻¹ for the last 6000 years or so.

Adélie penguin rookeries were established on the rock in the catchment surrounding the coring site at some time during the Holocene, and they will have influenced the biogeochemistry of the sediments at the site. Other rookeries are shown on Fig. 1. The only dates of occupation during the Holocene, and they will have influenced the biogeochemistry of the sediments at the site. Other rookeries are shown on Fig. 1. The only dates of occupation remains unknown.

Methods
To determine the location to be cored, a basic bathymetric profile was made using an echosounder through ice holes drilled around the inlet, and particularly the inlet centre. The deepest place in the inlet was selected for coring since we expected maximum sedimentation rates there, minimal sediment disturbance, and that hiatuses caused by gravitational sediment transport would likely be avoided.

The sea ice was used as a coring platform. A gravity corer was used to obtain an undisturbed near-surface sample, while a piston corer with 3 m barrel and polycarbonate liner was used for the longer sediment sequence. The 3 m core segments overlap by 0.5 m, allowing segment correlation via stratigraphy and biogeochemical proxies. More detail on the coring technique is in Melles et al. (1994). Two gravity cores (PG1430-1 and PG1430-2) and five consecutive piston core segments (PG1430-3 to 7) were retrieved at the site. Field depth of the core was 10.26 m and final correlations led to determination of a total core length of 10.89 m.

Due to high water contents, core segments 1 to 6 were subsampled into 2 cm intervals in the field. The gravity core subsamples from the uppermost 14 cm and every tenth subsample thereafter were stored in plastic vials; other subsamples were stored in sealed plastic bags. Subsamples were refrigerated, not frozen, prior to analysis. The lowest 3 m segment (PG1430-7) was refrigerated, stored in the liner, then opened in the lab, where it was described and photographed. One half was then subsampled at 2 cm intervals and the other half retained in the liner for archival purposes. All 2 cm subsamples were freeze-dried. Water content, as a percentage of bulk weight, was determined on all vial and liner subsamples.

An aliquot of subsample was ground to < 63 µm by planet mill and analysed for total carbon (C), total organic carbon (Corg), total nitrogen (N), total sulphur (S) and organic carbon isotope ratios (δ¹³Corg). C, N and S measurements were made using a CHNS-932 MIKRO (LECO Corporation), while Corg was measured with a Metalyt-CS-1000-S (ELTRA) after treating samples with 10% HCl at 80°C to remove the carbonate. The carbonate content was determined from the difference of organic and total carbon. Crystalline salt was observed in the uppermost samples. In order to avoid influences of variable water contents or pore water salinities on the geochemical variables, the salt content was determined on the remaining fraction of the aliquot ground for geochemical analysis (or the archived aliquot if no material remained). A quantified weight of sample was mixed with a standard quantity of deionised water (generally 30–50 ml) to solution. The salinity of the solution, and thus the percentage of salt, was determined with a salinity meter. The geochemical data were corrected by the following equation:

\[ \text{New Value} = \text{Original value} \times \frac{100}{(100-\text{salinity})} \]

The δ¹³Corg of the organic carbon was determined on carbonate-free samples by combusting with a CHN-O-rapid elemental analyser (HERAEUS), coupled online to a MAT Delta S mass spectrometer (FINNIGAN). The results are given in per mil relative to V-PDB (Vienna-Pee Dee Belemnite).

The grain size distribution of the sediment was measured at 20 cm intervals throughout the core. The organic fraction was first removed by treating the samples for a number of weeks with H₂O₂ with NaOH added to the solution to keep a neutral pH and thus preserve any carbonate. Opal was then removed by boiling with NaCO₃. The coarse fraction (≥ 63 µm) was separated by wet sieving to enable later examination for microfossils. The < 63 µm fraction was concentrated with a centrifuge, dried at 25°C and weighed, then redispersed using 5% Calgon® (sodium hexametaphosphate) and passed through a Malvern Instruments laser particle analyser model 2600C.

Radiocarbon dating was carried out on six samples of calcareous material (shell fragments and echinoids) as well as on bulk organic carbon taken at 14 different depths. In nine of the bulk samples the base insoluble fraction (humic acid free) was dated, and in two of these, the base soluble fraction (humic acid) was dated also. For the other five bulk organic carbon samples only the humic acid fraction (base soluble) was dated. Measurements were made by Accelerator Mass Spectrometry (AMS) at Leibniz Laboratory at University Kiel, Germany, and the ANTARES facility at ANSTO, Australia (Lawson et al.
2000). Selected carbonate fossils were analysed by Charles Hart at the University of Colorado for isoleucine amino acid racemisation (AAR), following the method of Miller (1985).

Results

Hydrology

The core was retrieved from the centre of a c. 100 m wide basin located midway across the inlet. At the coring location the water depth was 25 m below the ice, which at the time of coring (December 1998) was 2.9 m thick. A basic bathymetry consisting of spot depths (Fig. 2) highlights the inlet form and particularly the shallow outlet.

The water column is characterized by a chemocline at 16–18 m water depth where there is a transition to substantially increased amounts of silica and phosphate (Table I). Above the chemocline salinity was 33.1‰, by 22 m depth it was 80‰, and at the sediment-water interface it reached 84.2‰. Oxygen measurements were not made but the H₂S odour of both the bottom water and the sediments indicates there were anoxic conditions at the bottom.

Sediment units

The variation in sediment types through the core is transgressive in nature, with few sharp or clear boundaries. We have defined three sedimentary units, described below, on the basis of sedimentary character and the geochemical proxies (Fig. 3). The boundary between the upper (Unit 1) and middle (Unit 2) units is defined where nitrogen and organic carbon reach values of zero, sulphur reaches a minimum and there is a distinct increase in the fraction of coarse material, indicating a substantially different sedimentation regime. The lower boundary of Unit 2 is then delineated where there are coinciding sharp rises in nitrogen, organic carbon and sulphur contents, as well as a substantial decrease in the fraction of coarse material. Unit 3 begins at this boundary and continues to the base of the core.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Salinity (‰)</th>
<th>Temperature (°C)</th>
<th>Si (µm)</th>
<th>PO₄ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>33.1</td>
<td>-1.6</td>
<td>49.7</td>
<td>4.3</td>
</tr>
<tr>
<td>7</td>
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<td>-1.8</td>
<td>48.1</td>
<td>3.9</td>
</tr>
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<td>33.2</td>
<td>-1.8</td>
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<td>13</td>
<td>33.2</td>
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<td>84.2</td>
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</tbody>
</table>

Fig. 3. Depth versus sedimentary units, geochemical and grainsize parameters, water content and chronology.
2 cm intervals. Within these clusters of sand are abundant biogenic carbonate fragments, including some near complete shells. Geochemical measurements were made on average at 8 cm intervals. The geochemistry shows no clear vertical structure, with some of the larger short fluctuations being coincident with clusters of sand. There is a large biogenic component with Corg values up to 4%. Sulphur values are consistently above 1%.

**Unit 2** from 994 cm to 860 cm consists of a coarse-grained diamicton with very low water content. It is stiff and is poorly sorted at the base, with minor sorting up-core. There is a very low biogenic component in this unit, illustrated by low values of Corg and N. The sulphur content fluctuates between 0% and 1%.

**Unit 1** from 860 cm to 0 cm is a sapropel with jelly-like consistency. It has a very high water content, which steadily increases up-core. Carbonate in this unit is negligible. Corg, N, S and δ13Corg vary considerably. Through most of this unit the organic carbon content is greater than 1% and ranges to 6.9%. Sulphur is above 1% throughout the unit. Near 730 cm there is a notable increase in S, Corg and N. A coincident, more gradual increase near this depth occurs in the δ13Corg. The percentages of organic carbon and nitrogen are consistently high between 730 cm and 230 cm, above which they decline steadily to the surface. A distinct decrease in δ13Corg occurs c. 100 cm and continues to the surface. The Corg/N ratio declines from c. 80 cm to the surface. There is a relatively high ratio of fine-grained as compared to coarse-grained mineral component throughout this unit.

**Core chronology**

Table II shows 14C dates obtained on our samples of shells and bulk sediment and preliminary AAR ratios are given in Table III. In Unit 3 AAR ratios were determined on three marine carbonate fossils. Initial interpretations of these ratios indicate ages of 525 kyr from an echinoid tooth, 120 kyr from a shell and 73 kyr from a limpet (Charles Hart, written communication 2000). These carbonates returned 14C ages indistinguishable from background (Table II). In contrast, the samples of bulk organic carbon, taken within a similar depth range as the shells, yielded two 14C ages of...
33 590 ± 1000 yr BP (KIA8848) and 26 130 ± 950 yr BP (KIA8849) respectively.

There was no material suitable for 14C dating in Unit 2 except some shell fragments which gave an infinite age and are likely there as a result of redeposition. Unit 1 (from 860–0 cm) is undoubtedly Holocene in age. The lowermost date in this unit is at 810 cm. There is a discrepancy between the date made on the base insoluble fraction (8360 ± 60 14C yr BP; KIA8847b) as compared to the date on the base soluble fraction (9170 ± 70 14C yr BP; KIA8847a) which may be due to either some form of contamination, the source of which cannot be confirmed, or due to the low percentage of organic carbon at this sampling depth combined with a water content near 50% causing some mixing or movement of the base soluble fraction to occur. There is one shell in this section of the core at 740 cm and this dated at 4535 ± 40 14C yr BP (KIA8348), which is in close agreement with a bulk sediment date of 4200 ± 60 14C yr BP (KIA8846) at 730 cm indicating that dating of the bulk sediment is a reasonable method to use for chronology determination.

A major problem in using the radiocarbon method to determine ages of samples from the marine environment is the difficulty in quantifying how the initial specific 14C activity differs from that of the contemporaneous atmosphere as a result of ancient carbon circulating in the oceanic water (Stuiver & Braziunas 1993). This is known as the marine reservoir effect. The measured remaining 14C activity of marine samples will reflect both 14C decay, which relates to the sample age, as well as the reservoir 14C activity. In Antarctica the reservoir effect can be quite large - in the nearby Vestfold Hills it is suggested to be of the order of 1300 years (Adamson & Pickard 1986). The age-depth relationship of our samples is clearly not linear and this is in part due to the change over time in the 14C activity of the atmosphere, which then manifests itself as a change over time in 14C activity in oceans and lakes (Stuiver & Braziunas 1993). This reservoir effect is enhanced in the Antarctic region by extended periods of sea ice coverage, preventing exchange of air with the atmosphere, and by supply of glacial meltwater bearing 14C depleted carbon. An enhancement of the reservoir effect in these ways is one probable explanation of the reversal of 14C dates in the uppermost section of our core. This is supported by the exact agreement at 38 cm between the base soluble and insoluble fractions which suggests the samples are not contaminated, and also because there is no significant source in the catchment for reworked terrigenous organic matter which could cause artificially older ages.

To develop a calendar age model we use the method suggested by Stuiver & Braziunas (1993), which considers that a correction for the apparent age anomalies in marine samples is possible when the reservoir–atmosphere offset in specific 14C activity is known. While the change in atmospheric 14C activity over time has been determined through the comparison of the 14C activity in tree rings, where the age of the tree rings is determined by counting them, the reservoir–atmosphere offset is not constant with time and information on its time dependency is lacking. Stuiver & Braziunas (1993) account for this change in offset over time by using a marine calibration curve derived from carbon reservoir modelling. Secular 14C variations in the marine environment are represented in the modelled world ocean marine curve, but this is a world average curve and does not account for regional oceanic differences in specific 14C, which are in part caused by regional differences in upwelling. A region-specific ΔR term which represents the 14C activity differences of regional and world ocean surface layers needs to be specified before calibration. The ΔR term corrects for regional activity differences in the calibration process, and can be determined from 14C ages of marine samples of known historical age. This is a more complex alternative, and in this case more appropriate, approach to the often used method of subtracting an estimated reservoir effect (for example, 1300 ys for samples in Vestfold Hills), and then calibrating with the atmospheric calibration curve.

For Antarctica, derived ΔR terms range from 462 ± 75 for Adélie penguin flesh (M. Geyh, unpublished though see http://depts.washington.edu/qil/marine/refs/131.html or http://radiocarbon.pa.qub.ac.uk/marine/refs/131.html) to 1310 ± 55 for collagen from a Weddell seal (Mabin 1985), with an average of 885 ± 45 (Stuiver & Braziunas 1993). Differences, in part, depend on the material dated with the lower values being associated with the penguin remains and the higher from the seals (see above website for list, or see Stuiver et al. 1981, Mabin 1985, and Whitehouse et al. 1988). Using the average linear sedimentation rate calculated between 89 cm and 730 cm, of 0.21 cm yr⁻¹ we estimate the sample at 89 cm is around 400 years old, the sample at 38 cm is near 180 years old, and the sample at 9 cm is 43 years old. To gain a reasonable age estimate for the sample at 89 cm (the youngest measured 14C date) we use ΔR = 500 ± 100 which fits within the range of values used in the Antarctic region (see Stuiver & Braziunas (1993) for further explanation and tables of marine model 14C ages from AD 1950–9440 BC used to calculate ΔR; also see Stuiver et al. (1998a, 1998b) for updated and extended calibration curve). We suggest the reversal evident in the upper two dates is due to an enhanced reservoir (larger ΔR) caused possibly by more extensive sea ice conditions, however any change over time in ΔR is impossible to quantify without an independent dating method which has not been possible. Table II lists the calibrated dates as generated using the CALIB 4.0 (Stuiver & Reimer 1993) program based on INTCAL98 data (Stuiver et al. 1998a).

Discussion
We have defined three sedimentary units comprising a total core length of nearly 10.9 m. The lowermost Unit 3 is a fine
grained, consolidated sapropel that contains sporadic clusters of sand. Within the sand is a mixed marine fauna with amino acid racemization ratios that suggest ages around 525 kyr, 120 kyr and 73 kyr BP. This indicates that there have been marine conditions nearby during multiple periods in the past, including during and prior to the last glacial cycle (and possibly including Marine Isotope Stage 5). Bulk sediment $^{14}$C assay indicates marine sedimentation of this unit around 33–26 $^{14}$C kyr BP. The older shells with surrounding sand matrix have most likely either been entrained by glacier ice and then deposited from that ice floating on the inlet, or washed into the depression by melt water. The unit composition suggests parts of the Windmill Islands must have been unglaciated during Marine Isotope Stage 3 to enable autochthonous sapropel deposition. Subarial exposure at least of this part of Windmill Islands is contemporaneous with exposure of Bunger Hills c. 450 km away (Gore et al. 2001) and Larsemann Hills c. 900 km to the west (Hodgson et al. 2001). The biogeochemical proxy data indicates the preglacial environment may have been similar to that of the Holocene. The contents of $C_{org}$ N and S, as well as $\delta^{13}C_{org}$ and $C_{org}/N$ in Unit 3 are comparable with those in Unit I suggesting the nutrient supply was similar, and possibly included penguins inhabiting the area. The $C_{org}/N$ ratios are sometimes slightly higher, indicating perhaps a different composition of algae or of collective algae metabolic rates. Fluctuations of $C_{org}$, N, and S in Unit 3 are much greater than in Unit I. This is most likely caused by episodic increases in melt water, bringing in large amounts of clastic sediment, evidenced by large variability in sand contents and presence of shells. Fluctuations in $\delta^{13}C_{org}$ and $C_{org}/N$ suggest that the sediment represents a mix of environments, though the transitional phases are not clearly defined at this sample resolution.

Unit 2 is a glacial diamicton, most likely deposited from the grounded ice during the last glacial period, sometime between 26 $^{14}$C kyr BP and the onset of biogenic sedimentation at the coring site prior to 8.2 cal. kyr BP. The high consolidation of Unit 3 suggests that grounded ice overrode the coring site sometime following c. 26 $^{14}$C kyr BP. The location of the site is such that it would be covered by grounded ice with only a modest 5 km lateral expansion of the Vanderford Glacier. As Goodwin (1993) has proposed that U-shaped valleys on Peterson Island and nearby Holl Island are oriented consistent with formation by an expanded Vanderford Glacier, this scenario for deposition is likely. Furthermore, Morgan et al. 1997 have shown that such an expansion was due to an expansion of Law Dome only, as ice cores extracted from Law Dome show that the East Antarctic Ice Sheet did not expand over Law Dome or Windmill Islands during the Last Glacial Maximum. What remains uncertain though is the timing of the glaciers advance and retreat at the coring site.

The commencement of postglacial sedimentation with biogenic accumulation at the base of Unit 1 at 860 cm is poorly constrained. The oldest $^{14}$C assay in Unit 1 lies at 810 cm, some 50 cm above the base of Unit 1. The minimum age of this sample (Table II) is 8175 cal. yr BP (conservatively using the base insoluble fraction which yielded a younger age than the base soluble fraction). Considering that deposition pre c. 4 kyr BP is steady and at a rate averaging c. 20 cm kyr$^{-1}$, the 50 cm of sediment from 860–810 cm might accumulate in 2500 years. If this inference is accurate, then the biogenic sedimentation of Unit 1 commenced around 10.7 kyr BP. The existence of suitable conditions for the onset of sedimentation at this time is further supported by ice core records from the Law Dome and other East Antarctic sites, which show a clear climatic optimum around the Pleistocene–Holocene transition from 11.5 to 9 kyr BP (Masson et al. 2000). The commencement of biogenic production and sedimentation at this marine site does not necessarily imply the bulk of Windmill Islands was deglaciated, but it does indicate a limited extent of grounded ice to the north and east of Browning Peninsula. The dating of Unit 1 demonstrates that uninterrupted, open marine conditions have prevailed throughout the Holocene. Unit 1 is thus the oldest postglacial sediment yet assessed in Windmill Islands, predating the latest estimates by Goodwin & Zweck (2000) of deglaciation age by some 4 kyr.

An 860 cm long core representing the entire Holocene will, therefore, contain substantial palaeoenvironmental information. Since the primary source for organic matter in this area is biogenic primary production in the water column, it follows that the content of organic carbon and nitrogen in the sediment core will be proportional to the suitability of the environment for biogenic productivity, and will thus reflect the levels of light, temperature and nutrients (Redfield et al. 1963). Anoxic bottom water conditions are indicated by the very high sulphur contents. This hydrological condition during the Holocene and preglacial phase has led to the formation of the sapropel, which has a strong smell of H$_2$S caused by sulphate reducing bacteria (Tissot & Welte 1978 p. 78, Redfield et al. 1963). These anoxic conditions promote organic sediment preservation by preventing decomposition through oxidation. The carbon isotopic composition of organic matter is controlled primarily by biological production but also by carbonate precipitation, respiration of organic matter, and CO$_2$ exchange between water and atmosphere. If algal organic matter ($^{12}$C $>$ $^{13}$C) is buried in the sediments because of anoxic conditions in the bottom water, the surface water becomes enriched in $^{13}$C (McKenzie 1985). In the resulting $^{13}$C enriched waters algal organic matter will then incorporate a larger percentage of $^{13}$C than the previous algal matter. Higher $\delta^{13}C_{org}$ values therefore reflect periods of greater primary production.

The primary productivity indicators show that from the base of Unit I c. 10.7 kyr BP, conditions were sufficient for
some biogenic production to occur. The sulphur values show a rise from zero at the end of the glaciation to 1% or greater with the onset of biogenic sedimentation, and they remained at or above this level through the Holocene. It is unlikely anoxic conditions arose immediately after deglaciation, when glaciers were still present very close to the site and supplying oxygenated melt water, and this transitional phase is likely represented in the core closer to the boundary with Unit 2 where the sulphur content is negligible and sedimentation rates are low such that a gradual transition is not resolved by these data. Following this the high sulphur levels indicate that the site conditions must not have been subjected to major environmental change during this time.

Complicating the interpretation of these data is the changing relative sea level during the Holocene. Goodwin (1993) dated the shoreline of a pond containing marine sediments just slightly below an inferred marine limit of 32 m a.s.l. at 8160 ± 300 14C yr BP (ANU 6401, Goodwin & Zweck 2000). If we calibrate this using the marine curve as described above, we get 8411–7781 cal. yr BP as the time this pond was inundated with seawater. While the relative height of sea level in the period immediately following deglaciation is not known, it is clear that relative sea level must have declined since this time. This higher relative sea level may have had a range of effects. First, the palaeogeography of the inlet and its palaeocurrents would have changed dramatically with water depth at the coring site ranging from the present day 25 m up to 57 m with sea level at the marine limit (32 m above current sea level). Figure 4 illustrates the approximate changing topography of Peterson Island at four time slices associated with the lowering relative sea level. Following deglaciation the coring site lay initially between islets, where seawater would have fluxed freely. As relative sea level lowered, the islets effectively coalesced into the present-day Peterson Island. As the palaeochannels around the coring site closed, and the inlet became progressively isolated, seawater circulation would have slowed. Consequently, sea ice would have been retained in the inlet for progressively longer periods. Finally, the area of land around the coring site has increased, allowing colonization by penguins and potentially the deposition of wind-blown dust and fluvial sediments on the inlet floor.

The δ13Corg and Corg/N show an overall steady rise from the commencement of biogenic production followed by a smaller abrupt increase near 740 cm. Also near 740 cm is the shell dated at 4201–3901 cal. yr BP and a transition to a sustained rise in Corg, N and S reflecting a distinct improvement in environmental conditions and suitability for primary productivity. The more gradual increase in Corg/N suggests that increasing primary productivity caused a depletion in nutrients within the water body, especially in nitrogen, which forced the algae to establish a slightly

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**Fig. 4.** Topography of Peterson Island.

a. Exposed area at 8.2 kyr relative sea level maximum,
b. area above 15 m a.s.l. that would have been exposed
c. 3–5 kyr BP (assuming a change of 3–5 mm yr⁻¹),
d. area above 5 m a.s.l. that would have been exposed
e. 1–1.6 kyr BP (assuming a change of 3–5 mm yr⁻¹),
f. topography today.
different metabolic $C_{org}/N$ ratio than normal (cf. Redfield et al. 1963). A transition to a warm climate thus may be interpreted from high organic carbon accumulation rates in conjunction with increasing $C_{org}/N$ ratios. The magnitude of the transition at 740 cm suggests though there may also be an increase in the preservation rate of the sediment. This would occur if the oxic/anoxic boundary prior to the rise was lower, leading to some fraction of the deposited organic material being decomposed. Sulphur values suggest that sulphate reduction, requiring a lack of oxygen, is prevalent but not to the degree that it is above 740 cm. With an increase in primary production the boundary would then rise, reaching a critical level where the influx of organic material is high enough such that the bottom water is permanently anoxic. Canfield (1994) suggested that sedimentation rate is the determining factor controlling the degradation of organic matter: at a sedimentation rate $> 30$ cm kyr$^{-1}$ most organic material is degraded by anoxic pathways due to the burial rate being above a critical level. The data suggest the section from 740–810 cm accumulated at a rate of 14–17 cm kyr$^{-1}$, whereas above 740 cm, sedimentation rates reached near 200 cm kyr$^{-1}$. This suggests the high flux of organic matter above 740 cm would have contributed to a high preservation rate, enhancing the rise in the $C_{org}$ and $N$. As a result, $C_{org}/N$ and $\delta^{13}C_{org}$ do not show the same sharp rise and $C_{org}/N$ is not significantly different below and above 740 cm.

Supporting the notion of a shift to a warmer climate near 4 kyr BP in the Windmill Island region is the penguin skull dated by Goodwin (1993). The skull has an uncorrected $^{14}C$ age of 4380 $^{14}C$ yr BP, which is comparable to the shell in core PG1430 which dates at 4535 $^{14}C$ yr BP ($4201–3901$ cal. yr BP). Conditions must have been conducive to occupation by penguins, requiring access to open water for most of the summer. Furthermore, this peak is concurrent with warm conditions implied by a readvance of the Law Dome ice margin suggested to have occurred soon after c. 4 kyr BP (Goodwin 1996).

Following this major climatic improvement in the mid-Holocene, the $C_{org}/N$ ratio stabilized. We interpret all available data from this period to indicate that climatic conditions continued to be favourable to primary production and that this primary production was in equilibrium with the nutrient supply. A greater proportion of finer grained material in the interval 500–300 cm (c. 1.2–2 kyr BP) suggest longer periods of open water and less sea ice, or possibly less terrestrial erosion. Over the last c. 1000 years a decrease in the biogeochemical proxies, including a decrease in the $C_{org}/N$ ratio, indicates that climatic conditions have become less favourable, probably cooler together with a longer duration of sea ice cover.

The effects of the changing palaeogeography are not clear as regional temperature changes have acted to moderate them, both enhancing and opposing them over time. The organic carbon, nitrogen and the grain size ratio data show a gradual decline since c. 1 kyr BP, possibly as a consequence of the closure of the c. 5 m a.s.l. sills to the west, northwest and east of the coring site. While occupation of the catchment by penguins would constitute an ongoing nutrient source, sea ice may have persisted in the inlet for longer periods, leading to a lower primary productivity than while the sills were submerged. The Law Dome ice core indicates a drop in atmospheric temperature around 1000 years ago, and lasting several hundred years, to some of the lowest values for the Holocene (Delmotte et al. 1999). An abrupt and brief warming occurred c. 600 years ago, after which there was a general decline, ending in the Little Ice Age at 1750 AD (Morgan & van Ommen 1997). The combined influence of these cooler temperatures with the emergence of the sills acting to lock in the sea ice is the most likely explanation for the inferred decrease in biogenic productivity over the last c. 1 kyr BP.

Morgan & van Ommen (1997) describe a differing trend in summer as opposed to winter $\delta^{18}O$ is apparent in the Law Dome ice core between the mid 1800s and now. In winter there is a distinct warming inferred, whereas the summer data, on average, infers cooler temperatures during the last two centuries relative to the two centuries before that. The impact of cooler summers in this region can be significant for biological production with the growing season being considerably shortened. The level of exchange of CO$_2$ with the atmosphere in an environment with greater and longer coverage of sea ice would also decrease. This may in part explain the enhanced reservoir effect implied by the radiocarbon dates on the uppermost samples which would have been deposited during this period of cooler summers.

Conclusion

In summary, the 10.89 m sediment core from Peterson Island in the Windmill Islands demonstrates that the environment during a period prior to the Last Glacial Maximum was similar to that during the Holocene. The site was overrun by ice following 26 $^{14}C$ kyr BP and the onset of biogenic sedimentation at c. 11 kyr BP dictates the minimum age for deglaciation in this area. We infer that enhanced biological production is linked with longer periods of open water around 4 kyr BP suggesting a climatic optimum around that time. A decline in conditions, probably a result of a cooler climate creating greater extent and duration of sea ice, is evident from 1 kyr BP to the present. Our data also support proxy temperature data from ice core studies which showed that recent summer temperatures are low relative to a few centuries ago and increasing winter temperatures are the main contributing factor to a recent overall warming in the region.

Acknowledgements

We thank the Australian Antarctic Scientific Advisory
Committee (ASAC grant 1071), German Alfred Wegener Institute for Polar and Marine Research, University Co-op Bookshop and the Australian Institute for Nuclear Science and Engineering (AINSE 97/038R) for financial support and the Australian Antarctic Division for logistic support. We thank Charles Hart for the AAR determinations and Donna Roberts for access to unpublished geochemical data. We thank Ian Goodwin and Yngve Kristoffersen for constructive reviews. We also thank Ute Bastian for technical assistance at AWI and Michael Woolley and Chris Morgan for their substantial assistance in the field.

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