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Circum-Antarctic coastal environmental shifts during the Late Quaternary reflected by emerged marine deposits

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Abstract: This review assesses the circumpolar occurrence of emerged marine macrofossils and sediments from Antarctic coastal areas in relation to Late Quaternary climate changes. Radiocarbon ages of the macrofossils, which are interpreted in view of the complexities of the Antarctic marine radiocarbon reservoir and resolution of this dating technique, show a bimodal distribution. The data indicate that marine species inhabited coastal environments from at least 35 000 to 20 000 yr BP, during Marine Isotope Stage 3 when extensive iceberg calving created a 'meltwater lid' over the Southern Ocean. The general absence of these marine species from 20 000 to 8500 yr BP coincides with the subsequent advance of the Antarctic ice sheets during the Last Glacial Maximum. Synchronous re-appearance of the Antarctic marine fossils in emerged beaches around the continent, all of which have Holocene marine-limit elevations an order of magnitude lower than those in the Arctic, reflect minimal isostatic rebound as relative sea-level rise decelerated. Antarctic coastal marine habitat changes around the continent also coincided with increasing sea-ice extent and outlet glacial advances during the mid-Holocene. In view of the diverse environmental changes that occurred around the Earth during this period, it is suggested that Antarctic coastal areas were responding to a mid-Holocene climatic shift associated with the hydrological cycle. This synthesis of Late Quaternary emerged marine deposits demonstrates the application of evaluating circum-Antarctic phenomena from the glacial-terrestrial-marine transition zone.

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Introduction

Antarctic coastal areas contain marine sediments and fossils which have emerged above sea level during the Late Pleistocene and Holocene. These emerged marine deposits, some of which have been studied since early in the 20th century (Anderson 1906, Ferrar 1907, David & Priestly 1909, Debenham 1920), exist around the continent in environmental zones that are directly influenced by the prevailing glacial, marine and climate conditions. The purpose of this review article is to assess the coastal deposits in relation to circum-Antarctic environmental shifts that may have occurred during the Late Quaternary.

Most of the Antarctic coastline is occupied by ice shelves, ice streams, ice walls and outlet glaciers (Table I). These glacial systems are, in turn, influenced by the relative dynamics of the adjacent ice sheets which vary from the land-based East

Table I. Coastal types around the Antarctic margin[1].

coastal type	coastline distance (km)	coastline %
ice shelves	14 110	44
ice walls	12 156	38
ice streams and outlet glaciers	3954	13
ice-free areas	1656	5
Total	31 876	

[1] Modified from Drewry *et al.* 1982.

Antarctic Ice Sheet (Drewry 1975, Jacobs 1992) to the marine-based West Antarctic Ice Sheet (Mercer 1978, Denton *et al.* 1989, Alley & Whillans 1991) to the ice masses in the Antarctic Peninsula region (Sugden & Clapperton 1980, Rott *et al.* 1996). Because Antarctic coastal areas are directly impacted by these different ice sheets, any coastal environmental shifts which are synchronous around the continent would suggest an overriding imprint of climate change.

There also are climate feedbacks from the Antarctic ice sheets that influence adjacent coastal areas in a circumpolar context. Cold dry air masses over Antarctica create a zonal pressure gradient in the atmosphere that generates the polar vortex around the continent (Schwerdtfeger 1984, King & Turner 1997). This cyclonic circulation in the atmosphere, in turn, influences oceanic circulation and drives the Antarctic Circumpolar Current (Deacon 1937). The influence of these atmospheric processes also is reflected in the circumpolar band of snow accumulation within 500 km of the coastline, which has accumulation rates that are an order of magnitude higher than than on the polar plateau (Giovinetto & Bentley 1985). The Antarctic ice sheets also exert an influence on sea-ice production, water mass formation and Antarctic marine ecosystem processes around the continent (Deacon 1982, Smith 1990).

Even though ice-free areas occupy only 5% of the coastline (Table I), there are hundreds of Late Quaternary beach deposits in the circumpolar environmental zone (Table II). Late Quaternary marine deposits also occur in terrestrial 'oases' in East Antarctica (Korotkevich 1971, Pickard 1986, Hiller *et al.* 1988, Borman & Fritzsche 1995) as well as on ice-shelf surfaces in the Ross Sea (Baroni 1990, Kellogg *et al.* 1990). Marine fossils, which have been radiocarbon dated from these emerged deposits, provide a circumpolar framework for determining whether there have been synchronous environmental changes in Antarctic coastal areas during the Late Quaternary. Such circum-Antarctic environmental shifts may reveal past climate imprints and global feedbacks which have influenced the evolution of the Antarctic ice margin.

Circum-Antarctic emerged marine deposits

Marine sediments

Emerged marine sediments (which occur from the marine limit down to the present sea level) are influenced by the characteristics of the coastline as well as the prevailing environmental conditions. Around Antarctica, coastline types include bedrock coasts, ice-cliff coasts, ice-cored moraines and rocky/sandy coasts (Nichols 1968). The latter type includes alluvial areas with deltas, moraines, talus and elevated beach coastal plains. Development of these marine platforms occurs in embayments, regions with multi-year sea ice and

Table II. Circum-antarctic distribution of Late-Quaternary raised beach deposits from different coastal sectors of Antarctica.

Location of raised beaches	Sector	No. of sites[1]	Reference
James Ross Island	57–59°W	4+	Ingólfsson *et al.* 1992, Hjort *et al.* 1997
South Shetland Islands	58–62°W	83	John & Sugden 1971, Curl 1980, López-Martínez *et al.* 1992, 1996, Tatur *et al.* 1997
Hope Bay	63–64°W	1	Birkenmajer 1993
Marguerite Bay	66–70°W	17	Nichols 1960
Alexander Island	74–76°W	1	Sugden & Clapperton 1980
Ross Island	166–168°E	6	Speden 1962
Beaufort Island	166–167°E	3	Stuiver *et al.* 1981, Kirk 1991
Dailey Islands	165–166°E	1	Kirk 1991
Franklin Island	168–169°E	1	Stuiver *et al.* 1981
West McMurdo Sound	163–164°E	29	Speden 1962, Nichols 1968, Stuiver et. al 1981, Kirk 1991
Victoria Land Coast (76–75°S)	161–164°E	13	Kirk 1991
Terra Nova Bay	163–166°E	19	Orombelli *et al.* 1990, Baroni & Orombelli 1989, 1991
Capes Adare and Hallett	170–172°E	6	Kirk 1991
Scott Island	179°W–180°E	1	Kirk 1991
Windmill Islands	110–111°E	13	Goodwin 1993
Bunger Hills	100–102°E	12	Adamson & Colhoun 1992
Gaussberg	89–90°E	2	Zhivago & Esteev 1970
Rauer Islands	77–78°E	1	Yevteyev 1962
Vestfold Hills	78–79°E	16	Pickard 1985
Syowa coast	38–40°E	40	Yoshida 1983, Hayashi & Yoshida 1994, Maemoku *et al.* 1997
Prince Olav Coast	41–45°E	5	Yoshida 1983, Hayashi & Yoshida 1994

[1] Areas of the emerged deposits range from tens of square metres to hectares.

other sheltered areas, as well as in exposed coastal areas which are impacted to a greater extent by waves, wind and seasonal ice floes.

Permafrost, along with land and sea ice are specific to the polar regions in influencing the formation and preservation of emerged marine sedimentary deposits (Nichols 1961a, 1961b). These emerged beaches have ridges, swales, cusps, deltas and strandlines (Fig. 1). However, because of the strong influence of ice, many of the polar beaches become pitted over time and sometimes terminate abruptly because ice was present when they were formed. Polar beach ridges also can be influenced by 'ice push' or sediment deposition from stranded ice. Moreover, Antarctic coastal areas may be veneered by solifluction, fluvial and aeolian deposits.

Strandlines are particularly important because they provide time horizons that may be related to glacial isostatic and eustatic sea-level processes (Andrews 1970) as well as regional and local environmental conditions in Antarctic coastal areas. For example, in West McMurdo Sound, changes in the prevailing storm direction during the Late Quaternary are reflected by the relative orientations of proximal strandlines (Fig. 2a). Additional information about the relative magnitude

Fig. 1. Strandlines of emerged marine sedimentary deposits along Marble Point (77°26'S, 163°153'E) in West McMurdo Sound, Antarctica. Orientations and elevations of individual strandlines as well as their rock deposits reflect relative sea-level changes and variable storm impacts. Photograph by the United States Geological Survey (TMA 3061) from an altitude of 10 000 feet in 1993.

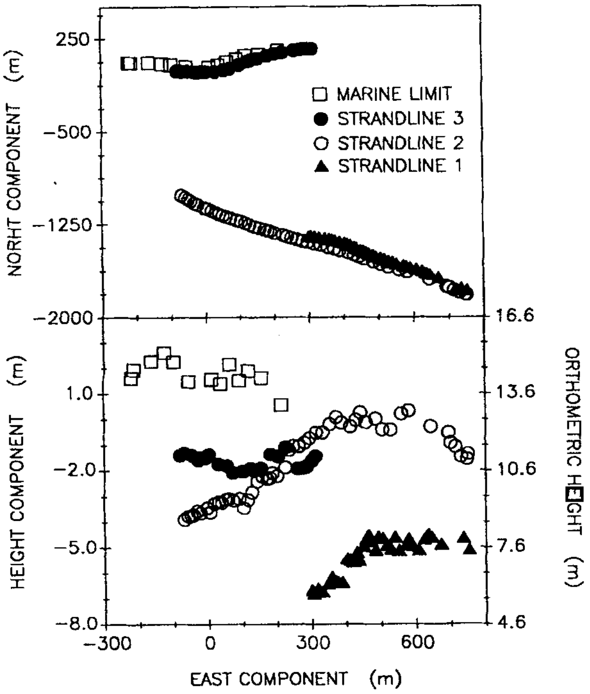

Fig. 2. Holocene storm beach strandlines south of Marble Point, Antarctica, adjacent to dated (6120–6430 ^{14}C yr BP) macrofossil deposits (Stuiver *et al.* 1981). Elevations along the sea-level strandlines were measured with Global Positioning System (GPS) technology using dual-frequency Trimble 4000 SSE receivers. These kinematic surveys were conducted by walking along individual strandlines and then post-processing positions relative to the static site (77°27'3.237"S, 163°44'46.385"E, 12.64 m a.s.l.) near South Stream (Berkman *et al.* 1998). **a.** GPS positions along the east and north axes of the strandlines relative to the static site showing changes in strandline orientation over time; **b.** GPS positions along the east and height axes of the strandlines relative to the static site showing changes in strandline elevation gradients over time. Orthometric heights represent elevations above sea level (Berkman *et al.* 1998).

of these Holocene storm impacts is contained in elevation gradients along individual strandlines, which can vary by up to 4 m in height within one kilometre (Fig. 2b).

In a general sense, lithologies in these Antarctic coastal areas may be contrasted between 'low-energy' and 'high-energy' marine deposits. Low-energy marine deposits, which occur in sheltered coastal areas, are composed of relatively fine-grained sediments (Fig. 3a). Here, beach sediments may consist of poorly sorted medium to coarse sands and pebble gravels underlying an armour of subangular detritus left on the surface by deflation of the matrix by strong winds. High-energy coastal areas which are exposed, by contrast, form deposits with large cobbles and boulders (Fig. 3b). Rounding of the clasts in marine deposits, unlike the angular sediments which exist at higher elevations along rocky coasts, provide a key criterion for identifying the marine limits around Antarctica (Nichols 1968, Arche *et al.* 1996). Seaward of the marine limit, the Late Quaternary age of these emerged sediments can be confirmed by associated marine fossils.

Marine fossils

Species that are incorporated into emerged marine deposits come from different habitats and represent different ecological conditions in the Antarctic coastal zone: saline lakes, sites on top of ice shelves, ornithogenic soils from avian rookeries and raised beach sediments. Emerged marine species include those which are restricted to the marine environment during

Table III. Number of marine fossil taxa identified in Holocene beaches from different coastal sectors of Antarctica[1,2].

Taxa	0–60°W	60–120°W	120–180°W	180–120°E	120–60°E	60–0°E
Algae	1				36	1
Protozoa				14	18	22
Bryozoa				2		
Porifera				2	4	
Annelida				4	7	2
Mollusca	3	1		21	15	3
Echinodermata	1			5		1
Arthropoda		1		7		1
Pisces				1		
Aves	2			2	4	1
Mammalia	3			3	4	2

[1] Based on data from: Cameron & Goldthwaite (1961), Speden (1962), Cameron (1964), Meguro *et al.* (1964), Nichols (1968), Shotton *et al.* (1969), John & Sugden (1971), Korotkevich (1971), Webb & Wrenn (1975), Omoto (1977), Curl (1980), Chapman-Smith (1981), Stuiver *et al.* (1981), Clapperton & Sugden (1982), Adamson & Pickard (1983), Yoshida (1983), Zhang & Peterson (1984), Pickard (1985), Adamson & Pickard (1986), Hiller *et al.* (1988), Baroni & Orombelli (1989, 1991, 1994a), Adamson & Colhoun (1992), Ryan *et al.* (1992), Ingólfsson *et al.* (1992), Goodwin (1993), Verkulich & Hiller (1994), Emslie (1995), Hjort *et al.* (1997).

[2] Gaps in the taxonomic data, to some extent, reflect an investigator bias rather than the absence of emerged fossils within coastal areas.

their lifetime (such as marine flora, benthic invertebrates, fish and whales) as well as those which can move onto land independent of sea level (such as birds and seals).

Most of the Antarctic fossils deposits below the Late-Pleistocene/Holocene marine limit occur in low-energy coastal environments. These Late Quaternary species, which are distinct from Pliocene deposits that also occur in Antarctic coastal areas (Speden 1962, Chapman-Smith 1985, Pickard *et al.* 1988, Berkman & Prentice 1996), have been identified from at least 150 different taxonomic groups (Table III: see Berkman 1994a for taxonomic list). The delineation of lakes in East Antarctica as former marine systems (Burton 1981) also has been confirmed by the observation of marine fossils such as molluscs, sponges, foraminifera, polychaetes and algae in emerged banks and sediment cores (Pickard 1985, Pickard *et al.* 1986, Fulford-Smith & Sikes 1996, Melles *et al.* 1997). Emerged marine fossils have been found in all sectors of Antarctica except the region from 120° to 180°W (Table III: Berkman 1997). Two of the most useful marine fossil groups for interpreting paleoenvironmental conditions in ice-free Antarctic coastal areas are calcareous invertebrate and avian assemblages.

The most abundant, widespread and best preserved emerged marine macrofossils around Antarctica are calcareous benthic invertebrates. The circumpolar scallop (*Adamussium colbecki*) and clam (*Laternula elliptica*) have been the among the most studied (Fig. 4a & b) with more than 65 papers on the biochemistry, physiology, population biology, ecology and geology of these two species (review in Berkman in press).

In contrast, mobile marine species are not constrained by sea level and may be found far from the coast. For example, mummified crabeater seals (*Lobodon carcinophagus*) have been reported more than 50 km from the coastline at elevations above 1000 m (Péwé *et al.* 1959). Similarly, snow petrels (*Pagodromoa nivea*), have been found in rookeries over 300 km from the ocean (Hiller *et al.* 1988). The occupation of snow petrel and Adélie penguin rookeries (*Pygoscelis adelie*), however, are strongly influenced by their access to open water and provide proxies for interpreting past sea-ice

Fig. 3. a. Low-energy beach with sand deposits in Explorers Cove (78°38'S, 166°25'E), western McMurdo Sound. The Dry Valley Drilling Project (DVDP) core 8–10 at the mouth of Taylor Valley, shows recent glacial meltwater erosion of the Holocene delta which has been prograding into the marine environment. Photograph was taken by P.A. Berkman during the 1986–87 summer. **b.** High-energy beach with cobble and boulder deposits along the coast of False Bay (62°43'S, 60°22'W), Livingston Island. A push moraine from a recent glacial pulse is visible on the rounded beach deposits. Photograph was taken by J.López-Martinez during the 1993–94 summer.

Fig. 4. Abundant *in situ* fossil deposits of **a.** the infaunal clam, *Laternula elliptica*, from a raised beach west of Lake Zakuro at Langhovde along the Syowa Coast in East Antarctica; **b.** the epifaunal scallop, *Adamussium colbecki*, from an emerged delta at South Stream in western McMurdo Sound. Both of these calcareous marine benthic invertebrates have circumpolar distributions as fossils in raised beaches and living assemblages in adjacent marine habitats (Berkman in press). The photographs were taken by M. Havashi and P.A. Berkman, respectively.

coverage. Abandoned Adélie penguin rookeries have been identified along the Windmill Islands in East Antarctica (Goodwin 1993), along the coast of Victoria Land in the Ross Sea (Baroni & Orombelli 1994a), and in the Antarctic Peninsula region (Tatur 1989, Emslie 1995, Tatur *et al.* 1997). Stomach oil deposits from snow petrel fossil breeding colonies also have been found in the Untersee Oasis (Hiller *et al.* 1988) and Bunger Hills (Verkulich & Hiller 1994) of East Antarctica.

Beyond responding to sea level and ice sheet impacts over time, emerged fossils reflect the ambient environmental conditions that existed when the species were alive. Palaeoecological interpretations can be derived from the growth patterns and geochemistry of individual shells as well as the diversity, longevity, distribution, and abundances of entire assemblages. Modern analogues, which commonly live in adjacent marine environments around the continent, provide experimental baselines for assessing past environmental conditions (Berkman 1997).

Radiocarbon dating in the Antarctic marine ecosystem

Ultimately, the value of any paleoenvironmental proxy is constrained by its dating and the accuracy with which it can be placed in an historical context. The most reliable chronologies are derived from sedimentary, glacial and biogenic deposits which continuously accumulate over known time intervals. The principal age control for Late Quaternary events is derived from the radioactive decay of ^{14}C to stable ^{12}C (conventional half-life is 5568 yrs). With the advent of accelerator mass spectrometry (which requires less than a milligram of carbon as opposed to several grams for

Table IV. Reservoir corrections which have been proposed for radiocarbon dating biotic deposits from the Southern Ocean.

radiocarbon reservoir correction (yrs)	sample collection location	reservoir correction derivation[1]	reservoir correction application	Reference
750	Antarctic Peninsula	post-bomb shells	Antarctic Peninsula, general	Sugden & John 1973
800–3000	Syowa coast	post-bomb seawater and various marine species	general	Omoto 1983
850 ± 300	Weddell Sea	post-bomb penguins and marine algae	10°W to 40°E, general	Hiller *et al.* 1988
850	South Shetland Islands	pre-bomb and post-bomb whale and seal bones	whales and seals, South Shetland Islands	Clapperton & Sugden 1988
850–1450	McMurdo Sound	post-bomb molluscs	general	Stuiver *et al.* 1976
940	Antarctic Peninsula	pre-bomb and post-bomb seals and whales	general	Curl 1980
>1000	Bunger Hills	marine sediments	marine sediments	Melles *et al.* 1994
>1000	Antarctic Peninsula	pre-bomb whalebones	whalebones	Gordon & Harkness 1992
1065–1760	Ross Sea	pre-bomb penguins and seals	penguins and seals	Mabin 1985, 1986
1090	Ross Sea	post-bomb penguins	penguins	Whitehouse 1988, Goodwin 1993
1100	Syowa coast	post-bomb marine organisms & seawater	marine organisms, Syowa coast	Hayashi & Yoshida 1994
1120	Syowa coast	post-bomb marine organisms	general	Yoshida & Moriwaki 1979, Yoshida 1983
1130	circumpolar	pre-bomb and post-bomb penguins	penguins	Berkman 1997
1200	McMurdo Sound	post-bomb seal	general	Olsen & Broecker 1961
1200	Antarctic Peninsula	post-bomb calcareous marine species	Antarctic Peninsula	Domack 1992
1200–1300	Hope Bay	pre-bomb penguins	marine organisms, Antarctic Peninsula	Björck *et al.* 1991
1250–1300	Antarctic Peninsula	various pre-bomb and post-bomb marine species	Antarctic Peninsula	Gordon & Harkness 1992
1300	Victoria Land coast	pre-bomb seal and penguin	general	Stuiver & Braziunas 1985
1300	Vestfold Hills	post-bomb molluscs & marine sediment	general	Adamson & Pickard 1986
1300	East Antarctica	various post-bomb marine species	East Antarctica	Verkulich & Hiller 1994
1300	circumpolar	pre-bomb and post-bomb calcareous marine species	calcareous marine species	Berkman & Forman 1996
1400	circumpolar	pre-bomb and post-bomb molluscs	molluscs	Berkman 1994a
1400	circumpolar	various pre-bomb and post-bomb marine species	shells, seals and penguins	Gordon & Harkness 1992
1424	circumpolar	pre-bomb and post-bomb seals	seals	Berkman 1997
1700	Wilkes Land coast	marine algae	sediment cores along Wilkes Land coast	Domack *et al.* 1991
5000	Wilkes Land coast	foraminifera	sediment cores along Wilkes Land coast	Domack *et al.* 1991
5020–5500	Wilkes Land coast	post-bomb sedimentary calcite and organic carbon	sediment cores along Wilkes Land coast	Domack *et al.* 1989

[1] Pre-bomb and post-bomb time periods are relative to calendar year 1950.

conventional dating), radiocarbon dating can be used for effectively determining the ages of organic materials that have lived during the last 45 000 yrs (Geyh & Schleicher 1990, Kitagawa & van der Plicht 1998). However, the accuracy of radiocarbon age determinations beyond 35 000 yars is questionable because of contamination and other factors when there is less than 1% of the original ^{14}C remaining.

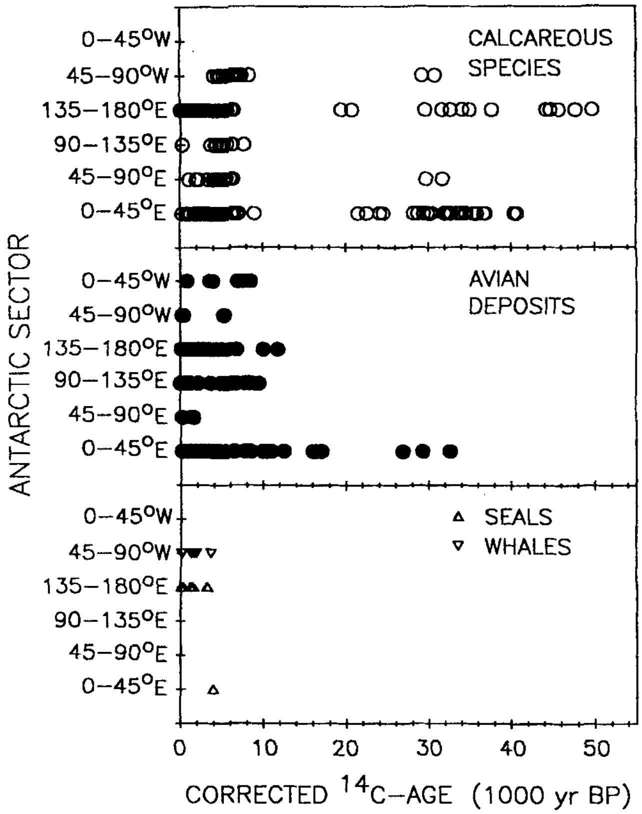

Fig. 5. Radiocarbon-dated emerged marine fossil deposits (calacareous marine species, primarily mollusc shells; avian deposits; and whale and seal deposits) from the Late Quaternary around Antarctica. The data are presented in relation to different Antarctic coastal sectors: **0–45°E** (Meguro *et al.* 1964, Yoshida 1970, 1973, 1983, Moriwaki 1974, 1976, Omoto *et al.* 1974, Omoto 1976, 1977, 1978, Nogami 1977, Hiller *et al.* 1988, Hayashi & Yoshida 1994, Igarashi *et al.* 1995); **45–90°E** (Adamson & Pickard 1983, Zhang *et al.* 1983, Pickard & Adamson 1983a, 1983b, Pickard & Seppelt 1984, Pickard 1985, Zhang & Peterson 1984, Hiller *et al.* 1988); **90–135°E** (Cameron & Goldthwait 1961, Adamson & Colhoun 1992, Verkulich & Hiller 1994, Melles *et al.* 1997); **135–180°E** (Péwé *et al.* 1959, Olsen & Broecker 1961, Nichols 1968, Hendy *et al.* 1969, Stuiver *et al.* 1976, 1981, Speir & Cowling 1984, Whitehouse *et al.* 1988, Kellogg *et al.* 1990, Baroni *et al.* 1991, Baroni & Orombelli 1994a, 1994b, Hall 1997); **0–45°W** (Hiller *et al.* 1988, Lintinen & Nenonen 1997); **45–90°W** (Shotton *et al.* 1968, 1969, Sugden & John 1973, Hansom 1979, Curl 1980, Sugden & Clapperton 1980, Rabassa 1983, Barsch & Maubacher 1986, Ingólfsson *et al.* 1992. Hjort *et al.* 1997, Tatur *et al.* 1997). All of the radiocarbon dates have been corrected by subtracting the 1300-yr age of the pre-bomb Antarctic marine radiocarbon reservoir (see text).

The validity of Late Pleistocene radiocarbon ages can be assessed by measuring the ratios of amino acids which convert from the L-configuration when an animal is living to the D-configuration after it dies (Wehmiller 1982, Miller & Brigham-Grette 1989). For example, previous measurements (Clapperton & Sugden 1982, Hansom & Flint 1989, Ingólfsson *et al.* 1992, Martinez-Macchiavello *et al.* 1996) show that there is a direct relationship between the D/L ratios and radiocarbon ages of calcareous marine organisms in the Antarctic Peninsula region: recent molluscs (zero age) had D/L ratios of 0.011 ± 0.002; 6865 ± 957 ^{14}C yr BP (uncorrected radiocarbon years before present) barnacles and molluscs had D/L ratios of 0.016 ± 0.006; and 35 025 ± 704 ^{14}C yr BP molluscs had D/L ratios of 0.048 ± 0.035. In other analyses, however, Antarctic mollusc shells with ages of 30 600 and 32 160 ^{14}C yr BP have been measured with D/L ratios ranging from 0.113 to 0.169 that indicate they were at least 120 000 yrs old (Clapperton & Sugden 1982). These data indicate that Late Pleistocene radiocarbon ages for Antarctic marine fossils should be considered as minimum ages and that their true ages may be much older.

Beyond the technical considerations, radiocarbon ages of Antarctic marine species are strongly influenced by the local seawater reservoir age. In the Southern Ocean, the radiocarbon reservoir is dominated by the upwelling of deep water at the Antarctic Divergence and produces apparent radiocarbon ages of marine species that exceed 1000 years (Broecker 1963, Stuiver *et al.* 1983, Gordon & Harkness 1992, Berkman & Forman 1996). The radiocarbon reservoir in the Southern Ocean also has been affected by natural changes in the production of atmospheric radiocarbon (Bard *et al.* 1990, Stuiver & Braziunas 1993). Additionally, spatial variability in the Antarctic marine radiocarbon reservoir (Omoto 1983, Gordon & Harkness 1992) may be influenced by glacial meltwater (Domack *et al.* 1989, Melles *et al.* 1994) or regional differences in upwelling around the continent.

Aside from natural impacts, human activities also have dramatically altered the Southern Ocean radiocarbon reservoir. During the 20th century, "old" radiocarbon from fossil fuel combustion (Suess 1955, Stuiver & Quay 1981) and "new" radiocarbon from nuclear explosions (Broecker & Walton 1959) have been added to the global atmosphere. The 53‰ difference between the mean Δ^{14}C values of the pre-bomb and post-bomb biogenic carbonates (Berkman & Forman 1996) is in close agreement with the *c.* 50‰ offset which has been described for surface seawater south of 50°S (Broecker *et al.* 1985). Moreover, the bomb signal is evident in long-lived brachiopods which were collected alive near Signy Island (Peck & Brey 1996). Together, these radiocarbon data indicate that the surface seawater age of the Antarctic marine radiocarbon reservoir has been altered by more than 500 years during the 20th century due to nuclear explosions and fossil fuel combustion. More importantly, prior to 1950 the radiocarbon content of surface waters around Antarctica was nearly equivalent to the 1300-yr age of the deep waters which are upwelling around Antarctica today (Michel & Druffel 1983, Stuiver *et al.* 1983). These geochemical data indicate that, as a first approximation, the general radiocarbon reservoir correction for the circum-Antarctic marine ecosystem is 1300 years (Berkman & Forman 1996).

In addition to the marine reservoir effects, radiocarbon ages of Southern Ocean species are influenced by 'vital effects' associated with their ecology and composition. For example, based on published data (Gordon & Harkness 1992, Berkman & Forman 1996), there are significant differences in the "pre-bomb" radiocarbon ages of living calcareous invertebrates (1346 ± 104 yrs), penguins (1130 ± 134 yrs) and seals (1424 ± 200 yrs). Radiocarbon ages of these taxa were similarly offset after the Earth's atmosphere was contaminated by bomb-produced radiocarbon: calcareous invertebrates (901 ± 227 yrs), penguins (606 ± 388 yrs) and seals (778 ± 412 yrs). Inherent differences between Antarctic marine taxa also are reflected by their $\delta^{13}C$ values (Harkness 1979, Gordon & Harkness 1992) relative to seawater which is around 0‰: carbonate species (1.6 ± 0.6‰), algae (-18.7 ± 6.2‰), seals and whales (-19.3 ± 2.4‰), penguins (-20.0 ± 3.1‰) as well as krill and fish (-26.3 ± 4.8‰).

Marine sediments present additional problems for interpreting radiocarbon ages because of mixtures of organic constituents that may differ in age by as much as 10 000 yrs (Eglinton *et al.* 1997). In the Southern Ocean, radiocarbon-dated sedimentary organic matter and calcite are offset in age on the order of 700 to 3000 yrs (Domack *et al.* 1995). In East Antarctica, this radiocarbon dating problem with bulk sediments (which may range up to 7000 yrs between samples) has been attributed to contamination from Jurassic pollen, spores and other materials which have been eroded and incorporated into Holocene diatom oozes (Harris *et al.* 1996). Moreover, because of varying degrees of meltwater dilution over time, radiocarbon ages of bulk organic carbon are irregularly distributed in emerged marine sedimentary sequences (Melles *et al.* 1994, 1997).

The above data indicate that geochemical, glaciological and ecological as well as technical considerations are necessary for interpreting radiocarbon ages within the global climate system (Stuiver & Reimer 1993, Stuiver & Braziunas 1993, Hughen *et al.* 1998). For Antarctic marine fossils, these diverse considerations have confused the situation with more than 25 proposed radiocarbon reservoir corrections which range from 750 to 5500 yrs (Table IV). Because accepted species-specific and region-specific corrections have not yet been developed, the general pre-bomb marine reservoir correction of 1300 years will be applied to the radiocarbon ages of emerged Antarctic marine fossils discussed in this paper.

The composite radiocarbon age profile of emerged Late Quaternary fossils in the circum-Antarctic coastal zone (Fig. 5), shows a bimodal distribution (Kellogg *et al.* 1990, Igarashi *et al.* 1995). The same bimodal age distribution has also been observed from marine-lacustrine sedimentary sequences cored in the Bunger Hills in East Antarctica (Melles *et al.* 1997). Clearly, there was a distinct environmental phase during the Holocene when diverse species assemblages (ranging from calcareous marine taxa to birds, seals and whales) were occupying the circumpolar coastal zone. There also appears to have been an earlier phase of coastal occupation by calcareous marine species and birds which occurred between at least 35 000 and 20 000 yr BP. These emerged marine deposits provide a circumpolar framework for interpreting environmental shifts in Antarctic coastal regions in relation to global climate changes during the Late Quaternary.

Circum-Antarctic emerged marine chronologies for the Late Quaternary

Antarctic ice margin evolution during the Late Pleistocene

The data in Fig. 2 show that calcareous marine fossils with continuous radiocarbon-age distributions between at least 35 000 and 20 000 yr BP also have been found along the Syowa coast (Yoshida 1983, Hayashi & Yoshida 1994, Igarashi *et al.* 1995) as well as on the McMurdo Ice Shelf (Kellogg *et al.* 1990). Isolated deposits of reworked biogenic carbonates with radiocarbon ages from this period also have been found along the coasts of east and west McMurdo Sound (Hendy *et al.* 1969, Hall 1997), the Antarctic Peninsula (Sugden & Clapperton 1980, Ingólfsson *et al.* 1992) and Wilkes Land (Zhang & Peterson 1985). In some cases, radiocarbon ages from these isolated deposits greatly underestimate the actual fossil ages, as shown by Clapperton & Sugden (1982), and by Pickard (1986) who noted that Pliocene molluscs from Marine Plain were being misinterpreted as Late Pleistocene in age. Nonetheless, the complete absence of any carbonate fossils in Antarctic coastal areas from roughly 20 000 to 8500 yr BP (Fig. 5), which is well with the resolution of radiocarbon dating, indicates that calcareous species were not inhabiting nearshore marine environments around the continent during much of the LGM and for several thousand years afterwards.

Aside from the fact that some of the Late Pleistocene radiocarbon ages of calcareous marine macrofossils in Fig. 2 may be much older, the presence of marine species in Antarctic coastal areas between at least 35 000 and 20 000 yr BP is consistent with the relatively warm climate conditions of Marine Isotope Stage 3 (MIS3), approximately 61 000 to 29 000 yr BP, which has been identified in marine sediment cores from the southern Indian Ocean (Hays *et al.* 1976) as well as in ice cores from Antarctica, Greenland and the Tibetan Plateau (Jouzel *et al.* 1987, 1989, Thompson *et al.* 1997).

Based on marine sediment core data from the Southern Ocean, it has been shown that there was a 'melt-water lid' covering the ocean south of the Antarctic Convergence from 35 000 to 17 000 yr BP (Labeyrie *et al.* 1986). This marked

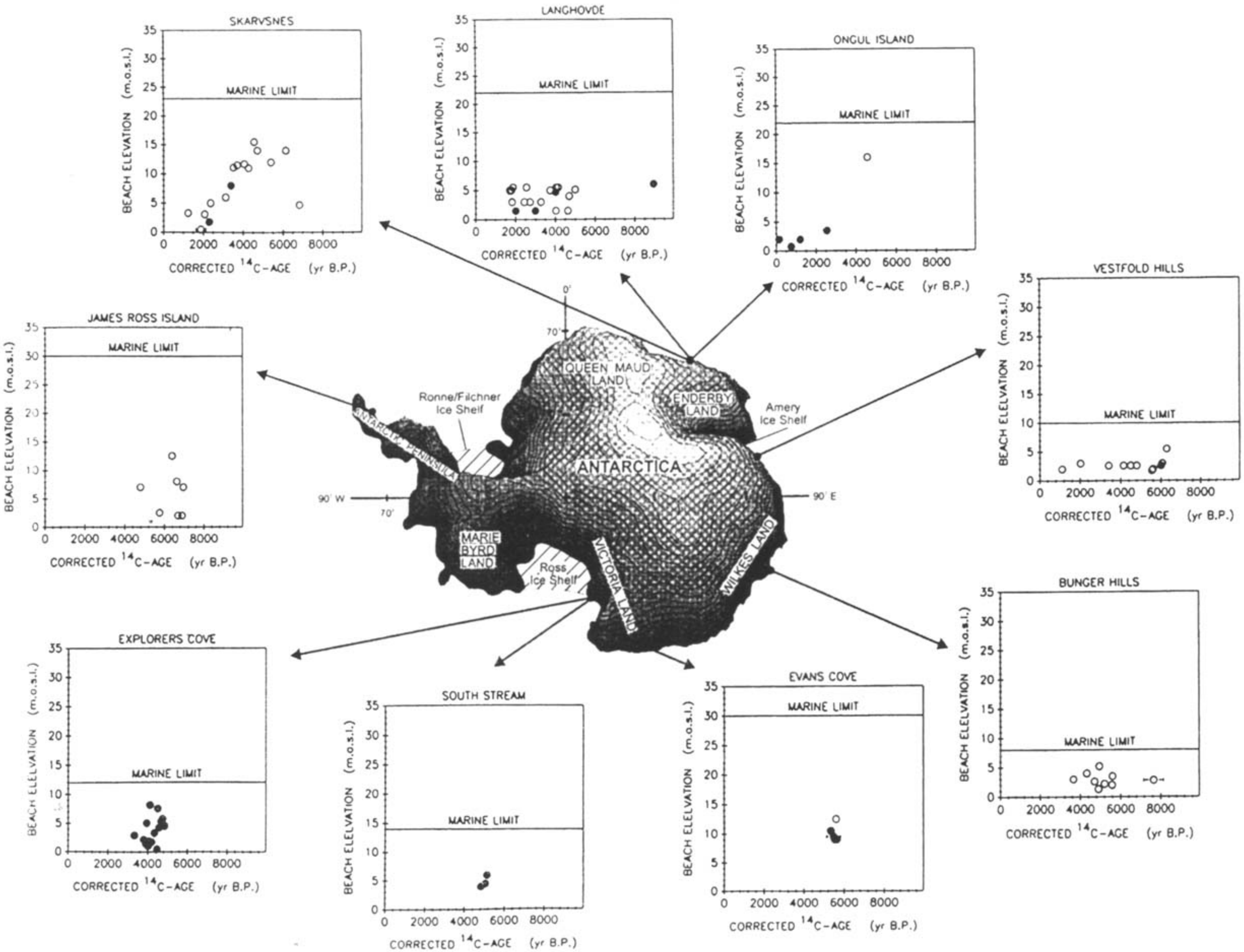

Fig. 6. Elevation-age relationships relative to the marine limits for raised beaches in East and West Antarctica based on deposits of the circumpolar scallop (*Adamussium colbecki*: ●), and clam (*Laternula elliptica*: ○). Radiocarbon ages of these calcareous benthic macroinvertebrates have been corrected by subtracting the 1300-yr age of Southern Ocean seawater (see text). Data were compiled from: Explorers Cove (Stuiver *et al.* 1981); South Stream (Stuiver *et al.* 1981); Terra Nova Bay (Baroni & Orombelli 1991); Bunger Hills (Adamson & Colhoun 1992); Vestfold Hills (Adamson & Pickard 1986); Skarvsnes, Langhovde and Ongul Island along the coast near Syowa Station (Hayashi & Yoshida 1994); and James Ross Island (Hjort *et al.* 1997). Three-dimensional illustration of Antarctica based on data from Drewry (1983).

change in the hydrology of the Southern Ocean, which was caused by abundant melting icebergs calved from surging glaciers and ice shelves around Antarctica (Labeyrie *et al.* 1986), led to surface-water stratification and subsequent reduction in atmospheric CO_2 concentrations during the last glacial period (Francois *et al.* 1997). The Dome C, Vostok and Byrd ice-core records further reveal that the Last Glacial Maximum (LGM) occurred around Antarctica from 25 000 to 15 000 yr BP (Jouzel *et al.* 1989).

The transition from interstadial to glacial conditions is reflected in Antarctic coastal areas. Radiocarbon-dated marine sediments from the western Ross Sea (*c.* 165–175°E) indicate that there was open water on the outer continental shelf near north Victoria Land from 32 685 to 18 200 ^{14}C yr BP, followed by a hiatus of 6000 years when the basin was covered by an extended ice shelf (Licht *et al.* 1996). Geological data from the Dry Valleys in southern Victoria Land also suggest that ice streams from West Antarctica extended across McMurdo Sound from 23 800 to 13 800 ^{14}C yr BP (Stuiver *et al.* 1981, Denton *et al.* 1989, Hall 1997). Similarly, radiocarbon dating of lacustrine sediments from the Bunger Hills in East Antarctica show MIS3 ages ranging from 35 700 to 24 140 ^{14}C yr BP which were followed by a hiatus in deposition until 14 320 ^{14}C yr BP (Melles *et al.* 1997). Additional geomorphological evidence from the Windmill Islands (*c.* 110°E), Bunger Hills (*c.* 101°E) and Vestfold Hills (*c.* 78°E) suggests that the East Antarctic Ice Sheet only expanded to a limited extent across the coast of Wilkes Land during the LGM (Colhoun *et al.* 1992, Goodwin 1993, Colhoun 1997).

In contrast, evidence from moss deposits suggests that the Larsemann Hills (76°E) were deglaciated by 24 950 ^{14}C yr BP (Burgess *et al.* 1994). Geomorphological evidence also suggests that the Syowa coast (*c.* 39°E) remained unglaciated throughout this period (Omoto 1977, Hayashi & Yoshida 1994). In addition, stomach oil deposits from breeding colonies of petrel species in the Untersee Oasis (13°E) have radiocarbon ages that are continuously distributed from 33 900 ^{14}C yr BP to the present, suggesting that this region of East Antarctica has been continuously ice free since MIS3 (Hiller *et al.* 1988).

Based on glacial drift and emerged beach deposits, Late-Pleistocene/Holocene deglaciation in the Ross Sea region of Antarctica is thought to have begun around 13 000 yr BP and continued until the mid-Holocene (Denton *et al.* 1989). Recent radiocarbon ages of algae in kenyte deposits from the McMurdo Dry Valleys (Hall 1997) and cosmogenic exposure ages of subglacial erratics from the Vestfold Hills (Fabel *et al.* 1997) support this timing of deglacial onset. The timing of Antarctic deglaciation also has been deduced from geophysical models of ice-sheet topographic changes (Clark & Lingle 1979, Nakada & Lambeck 1988, Peltier 1994), which have been constructed to explain the history of sea-level rise since the LGM (Fairbanks 1989). The magnitude of the Antarctic contribution to sea-level rise after the retreat of the northern hemisphere ice sheets, however, is unresolved (Colhoun *et al.* 1992).

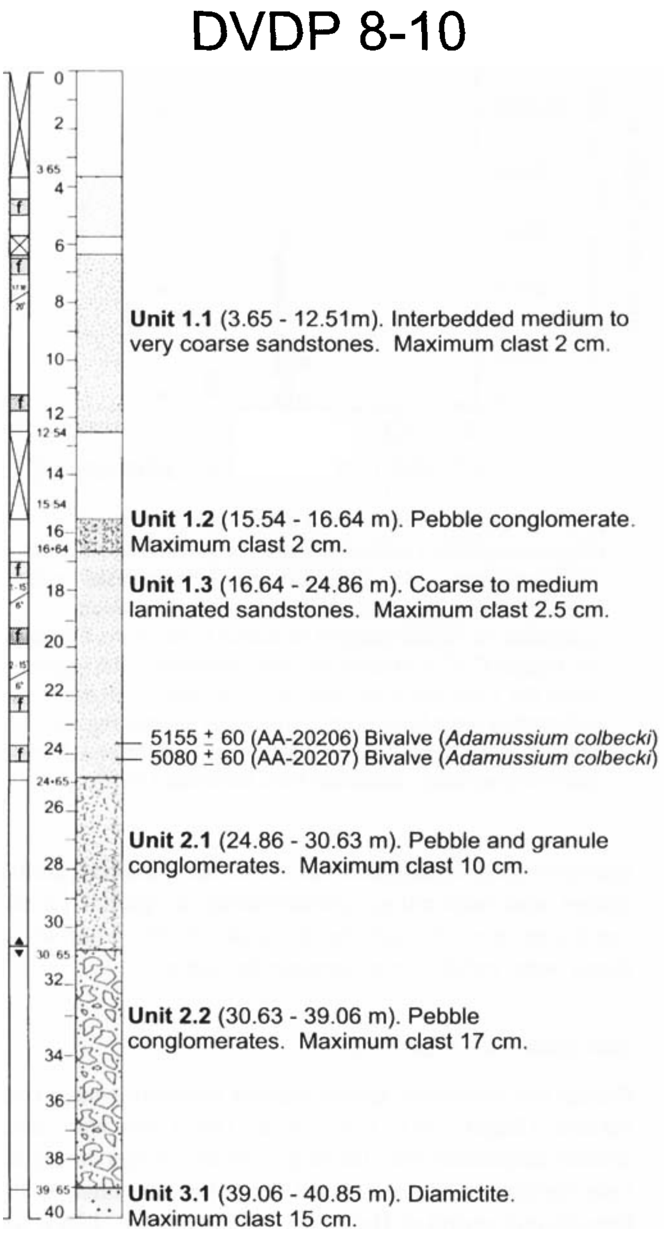

Fig. 7. Stratigraphy of the core DVDP 8-10 in Explorers Cove (Fig. 3a) based on the profile by McKelvey (1981). New radiocarbon ages (with associated laboratory numbers from the University of Arizona) are shown for calcareous macrofossils from the core. An earlier radiocarbon date at a core depth of 23 to 24 m was 6670 ± 200 ^{14}C yr BP (Stuiver *et al.* 1976).

Together, these diverse datasets indicate that the cycle of colonization, absence and recolonization by nearshore marine species around Antarctica (Fig. 5) coincided with global climate changes during Marine Isotope Stage 3, the Last Glacial Maximum and the subsequent Holocene interglacial period. Moreover, the uniform absence of calcareous marine macrofossils around Antarctica, from roughly 20 000 to

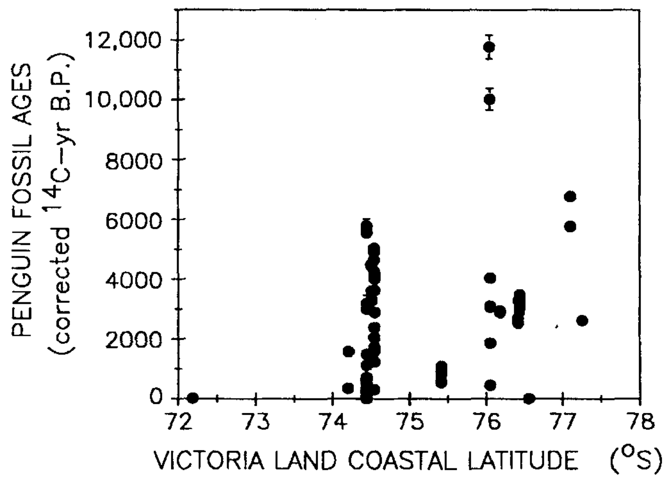

Fig. 8. Locations of radiocarbon-dated Adélie penguin (*Pygoscelis adelie*) rookeries along the Victoria Land coast which have been redrawn in relation to latitude based on data from Baroni & Orombelli (1994a). Note the continuous occupation of Adélie penguin rookeries north of the Drygalski Ice Tongue (75°24'S) since the mid-Holocene in the region where the Terra Nova Bay polyna exists today. All of the radiocarbon dates have been corrected by subtracting the 1300-yr age of the pre-bomb Antarctic marine radiocarbon reservoir (see text). Modified from Berkman (1997).

8500 yr BP (Fig. 5), suggests that the circum-Antarctic coastal system was responding synchronously to glacial climate conditions, even though the dynamics of the adjacent ice sheets were variable in a circumpolar context.

Mid-Holocene climate shift

During the Holocene, global climate conditions have been variable (Beget 1983, Alley *et al.* 1997), but with much smaller amplitudes than the huge climate swings during the Late Pleistocene (Taylor *et al.* 1993, Behl & Kennett 1996). One distinct period of Holocene climate change, which was sustained for more than three millennia, occurred during the mid-Holocene when global average temperatures were at their maximum (Folland *et al.* 1990, Pielou 1991). Antarctic ice-core records indicate, however, that this Holocene 'climate optimum' occurred earlier in the Southern Hemisphere than in the Northern Hemisphere and that a significant cooling period occurred around Antarctica from 8000 to 4000 yr BP (Lorius *et al.* 1979, Cias *et al.* 1992). These data suggest that hemispheric temperatures were not in phase on a global scale during the early-mid Holocene. However, if the mid-Holocene 'climate optimum' represents a global change, then there should have been an Antarctic response, although perhaps not in terms of temperature. Cryospheric changes in the circum-Antarctic coastal zone provide a framework for assessing climate feedbacks associated with the global hydrological cycle (Chahine 1992, Jacobs 1992) during the Holocene.

In contrast to the fragments of calcareous marine macrofossils from MIS3 (Fig. 5), Holocene macrofossils have been found intact and in growth positions within emerged beaches around Antarctica (Berkman 1992, 1994a). These macrofossil deposits have been used primarily for dating the emergence of Antarctic coastal areas to generate relative sea-level curves (Adamson & Pickard 1986, Baroni & Orombelli 1991, Colhoun *et al.* 1992, Zwartz *et al.* 1997, Pallàs *et al.* 1997). All of the emerged beaches around Antarctica have Holocene marine limits which are less than 35 m above sea level (Fig. 6), in contrast to the marine limits across the Arctic which range in elevation by hundreds of metres (Andrews 1970, Forman *et al.* 1997). These emerged beaches reflect minimal isostatic uplift around Antarctica during this period (Colhoun et al. 1992) when the rates of relative sea-level rise were markedly decelerating (Chappell 1983, Fairbanks 1989, Pirazzoli 1996).

The principal species that have been used for dating Antarctic beaches have been bivalve molluscs (Fig. 6), especially *Laternula elliptica* and *Adamussium colbecki* (Fig. 4a & b). These species thrive in protected low-energy nearshore habitats rather than exposed high-energy environments where their wafer-thin shells would be crushed. *Adamussium*, because it lives on the sediment surface (unlike *Laternula* which lives in the sediments), is particularly vulnerable to wave action (Berkman 1994b, Berkman & Prentice 1996). Nearshore habitat conditions which are suitable for *Adamussium* colonization are reflected in sediments cored in West McMurdo Sound from the Dry Valley Drilling Project (McGinnis 1981).

DVDP 8-10 (Fig. 7), which was collected from a prograding delta that formed in association with glacial meltwater stream runoff from Taylor Valley (Fig. 3a), reveals that *Adamussium* continuously colonized sandy sediments in this area after 3900 yr BP. This corrected radiocarbon-age was derived from AMS-radiocarbon analyses and is 1400 yrs younger than previously determined from conventional radiocarbon analyses of an *Adamussium* fragment from the same core depth (Stuiver *et al.* 1976, McKelvey 1981 Elston & Bressler 1981). Prior to this mid-Holocene period, which also is reflected by the ages of molluscan fossils from adjacent emerged beaches (Fig. 6), *Adamussium* was absent while pebble and granule conglomerates were being deposited under high-energy coastal conditions (Fig. 7). The underlying diamictite from DVDP 8-10 is assumed to have been associated with suspension current sedimentation and profuse glacial ice-rafting (McKelvey 1981). These sedimentary data along with general ecological requirements of *Adamussium* (Berkman 1994b), suggest that its occurrence in emerged beaches around Antarctica (Fig. 6) was influenced by relative sea-level changes as well as the expansion of sea ice and the creation of low-energy nearshore marine habitats after the mid-Holocene.

Around the East Antarctic margin, offshore sediments indicate that open-water conditions existed from 10 700 to 7300 yr BP (Domack *et al.* 1991). Petrel stomach oil deposits also suggest that the Bunger Hills area was deglaciated by 10 000 yr BP with increased access to open water from 8000 to 6000 yr BP (Verkulich & Hiller 1994). Between 11 770 and 10 325 yr BP, Adélie penguin rookeries existed at Cape Hickey (76° 05'S) along the Victoria Land coast (Baroni & Orombelli 1994a), which indicates that there was open water in the Ross Sea in the early Holocene. However, it has only been since 6000 yr BP when Adélie penguins began continuously to occupy rookeries north of the Drygalski Ice Tongue (75°24'S) in the Terra Nova Bay region (Fig. 8). Marine sedimentary deposits with terrigenous and biogenous components support the notion that the Drygalski Ice Tongue has been present since the mid-Holocene (Krissek 1988), several thousand years after the Terra Nova Drift retreated from this region of the Ross Sea (Denton *et al.* 1989, Licht *et al.* 1996).

Given that the Drygalski Ice Tongue is a primary forcing factor for the Terra Nova Bay polynya (Kurtz & Bromwich 1985) and that Adélie penguins require access to open water (Fraser *et al.* 1992), it is suggested that that polynya has been present in the western Ross Sea since the mid-Holocene (Berkman 1997). As the Terra Nova Bay polynya may stimulate up to 20% of the sea-ice production in the Ross Sea (Gallée 1997), the data indicate that there has been substantially more sea ice in the Ross Sea since the mid-Holocene. This inference is supported by higher abundances of sea-ice diatoms (*Fragilariopis curta*) in Ross Sea bottom sediments since the mid-Holocene (Cunningham 1997). Lower phytoplankton productivity in Lallemand Fjord, Antarctic Peninsula, also has been attributed to extensive sea ice coverage from 6700 to 4700 yr BP (Shevenell *et al.* 1996). This increased sea-ice production in the Ross Sea, Antarctic Peninsula and from elsewhere around the continent would have contributed to the abrupt change in the deuterium and methanesulfonic acid concentrations which has been identified in the Taylor Dome ice core from Victoria Land after 6000 yr BP (Steig *et al.* in press).

In addition to increased sea-ice extent, across East Antarctica there was an expansion of outlet glaciers through ice shelves and ice tongues during the mid-Holocene (Domack *et al.* 1991). Subsequent glacial advances along East Antarctica during the mid-Holocene are reflected further by moraines which formed in the Bunger Hills after 6200 yr BP (Adamson & Colhoun 1992) and in the Windmill Islands after 5500 yr BP (Goodwin 1996). In the Antarctic Peninsula region, emerged marine deposits suggest that there were re-advances of the George VI Ice Shelf after 6500 yr BP (Sugden & Clapperton 1980) as well as glacial re-advances on James Ross Island from around 7000 to 5000 yr BP (Ingólfsson *et al.* 1992, Björck *et al.* 1996) and the South Shetland Islands after 6800 yr BP (Clapperton 1990). In the Ross Sea, there were glacial advances in the Terra Nova Bay area after 5000 yr BP (Baroni & Orombelli 1994b).

Significant changes in the hydrological cycle following the mid-Holocene also have been identified elsewhere on Earth. For example, by 6000 yr BP most of the deglacial impacts on global sea level had been completed (Chappell 1983, Fairbanks 1989, Pirazzoli 1996). There is geoarchaeological evidence from the Peruvian coast that the El Niño/Southern Oscillation originated between 6000 and 5000 yr BP (Sandweiss *et al.* 1996). Climate and cultural changes of that period also have been recognized in the Atacama desert in southern Chile (Grosjean *et al.* 1997). Glaciers also began fluctuating in tempo across the Andes after 5000 yr BP (Clapperton & Sugden 1988), suggesting that there has been a synchronous climate response by Antarctic and other Southern Hemisphere glacial systems since the mid-Holocene (Clapperton 1990). Significant glacier advances during the early–middle Holocene have been identified in cold and dry regions of the Arctic which are thought to be more sensitive to precipitation than to air temperature changes (Miller & De Vernal 1992). Environmental conditions on the Tibetan plateau, which is important in influencing atmospheric circulation in the Northern Hemisphere were warmer and wetter during the early to mid-Holocene. Across the latitudinal belt 8.9–26.6°N, lake levels during the Holocene have been uniformly low since 5000 yr BP (Kutzbach & Street-Perrott 1985). These hydrolgic changes are further reflected by decreased atmospheric methane concentrations (Blunier *et al.* 1995) and abrupt changes in atmospheric circulation which have been recorded from the equator to the poles (Stager & Mayewski 1997) during the early to mid-Holocene.

Climate models suggest that the seasonal insolation cycle in the Northern Hemisphere between 12 000 and 6000 yr BP could have increased summer sea surface temperatures in the tropical Atlantic, enhanced the northern African summer monsoon and modified the global hydrological cycle (COHMAP 1988, Kutzbach & Liu 1997). Coral geochemistry from the Great Barrier Reef indicates that increased temperatures during the mid-Holocene also led to enhanced evaporation in the tropical western Pacific around 5350 yr BP (Gagan *et al.* 1998). Extratropical transport of atmospheric moisture from these source areas may have influenced the sea-ice and glacial changes around Antarctica during the mid-Holocene. This Antarctic environmental feedback with the hydrological cycle is consistent with polar-tropical atmospheric linkages that have been observed during the last two decades (Gloersen 1995) as well as inferred during the mid-Holocene (Stager & Mayewski 1997) and the last 124 000 yrs (Thompson *et al.* 1997).

Widespread changes in terrestrial (outlet glaciers), marine (sea ice) and atmospheric (moisture transport) phenomena in the Antarctic coastal zone indicate that there was circumpolar environmental transition which originated between 8500 and 4500 yr BP. Along with the synchronous environmental changes associated with the hydrological cycle in other regions of the Earth, the composite datasets from the Antarctic coastal zone suggest that there was a global climate shift during the mid-Holocene.

Conclusions

Emerged marine deposits in Antarctic coastal areas provide an accessible circumpolar framework for assessing environmental changes on a continental scale during the Late Quaternary. Together, emerged marine fossils and sediments indicate that the configuration of the Antarctic ice margins has oscillated approximately in phase with the interstadial, glacial and Holocene climate conditions that have occurred around the Earth. Moreover, synchronous environmental changes in the coastal zone surrounding Antarctica reveal the imprint of a mid-Holocene climate shifts connected with the hydrological cycle. Innovative interdisciplinary research strategies, coordinated among nations and scientific programs on a continental scale (Weller & Lorius 1989, Goodwin 1997), are needed to investigate further these environmental connections and feedbacks between the circum-Antarctic coastal system and the Earth's climate.

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