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# The Sedimentary Record of Antarctic Climate Change

Peter F. Barker

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# The sedimentary record of Antarctic climate change

PETER F. BARKER

*British Antarctic Survey, Natural Environment Research Council, Madingley Road, Cambridge CB3 0ET, U.K.*

## SUMMARY

Circum-Antarctic marine sediments contain a record of past climate and Southern Ocean circulation that both complements and considerably extends the record in the continental ice. Variations in primary biological production, reflecting changes in sea-ice cover and sea surface temperature, in bottom current strength and the size of the grounded continental ice sheet, all contribute to changes in sediment characteristics, in a record extending back many million years. It is possible to assess both the value of the proxy record in Antarctic sediments, and the validity of the analogue approach to understanding climate change, by focusing on the last glacial cycle and, for comparison, on earlier periods that were significantly different: the Pliocene before 3 Ma ago that could provide an analogue for global warming, and the Oligocene before there was an Antarctic Circumpolar Current.

## 1. INTRODUCTION

The value of the proxy record of past climate change, in understanding future change, is based on two inescapable facts: the limited time span and geographic extent of the direct observational record of climate, and the potential importance of components of the global climate engine that vary over longer periods. The proxy record shows that global climate has been very different in the past, and the earth system has used different modes of response to external stimuli from those operating today. Global change models should include these alternative modes, with realistic thresholds, to be robust.

The proxy record is especially valuable for Antarctica and its surrounding ocean, large parts of which are known only through the satellite observations of the last ten years. The Antarctic ice sheet and the oceans, important components of the global engine, are ponderous in some aspects of their response, but capable of rapid change in others. Ice sheet behaviour and climate record, and model studies of modern Southern Ocean circulation are discussed elsewhere in this symposium (Lorius, Morris & Drewry, Killworth). Here I assess the achievements and potential of the sedimentary record, that both complements the ice sheet record and extends it back in time.

Palaeoclimate studies using sediments try to establish firmly the relation between sedimentation and aspects of modern circulation or climate, and then use changing sediment parameters to infer how those aspects have varied in the past. Times are reached when circulation or climate was so different from today's that basic sedimentary parameters were influenced by totally different factors. Such times are less useful for global change studies, but retain considerable broader interest.

The main influences on sedimentation, described below, persisted through the last glacial–interglacial cycle. I discuss this cycle first, for its high energy and proximity, then the period 4.8–3 Ma in the Pliocene when conditions were significantly warmer, and the Oligocene before Antarctica was ringed by a complete deep-water pathway. This allows some consideration of the stability of today's influences on sedimentation, and what might have preceded them.

## 2. BACKGROUND: MODERN SEDIMENTARY RÉGIME

### (*a*) *Continental ice sheet*

The grounded ice sheet deforms or erodes its base (e.g. Drewry 1986). Material eroded at the ice sheet base is transported to the edge, mostly within a thin sheared layer of till beneath fast-moving ice streams (Alley *et al.* 1989). Sediment transport remote from ice streams is much less. The transported material is poorly sorted, and most is released and deposited close to the grounding line. A little is carried north by icebergs, and a fine fraction entrained in currents close to the grounding line, to be deposited farther offshore (e.g. Dunbar *et al.* 1985). Essentially however, little terrigenous sediment reaches the continental shelf edge during interglacials. Till and till-derived sediment distribution therefore measures the past extent of the continental ice sheets (subject to sediment preservation through subsequent advances).

### (*b*) *Sea-ice and primary production*

Sea-ice cover inhibits biogenic production but an admixture of siliceous (diatomaceous) skeletal debris typifies modern shelf sediments (e.g. Dunbar *et al.* 1985). In open water, the relatively protected environments of the continental shelf and marginal ice

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zone enhance production (El Sayed *et al.* 1983; Smith & Nelson 1986). Most Southern Ocean waters are undersaturated with respect to calcite, so that calcareous skeletal debris is rarely preserved below 500 m (Echols & Kennett 1973; but see Grobe *et al.* 1990). Sea-floor cover south of the Polar Front ranges from siliceous ooze through biosiliceous muds to barren tills and terrigenous turbidites. Distribution of such facies therefore indicates the past extent of sea-ice and the ice sheet, and the position of the Polar Front.

### (*c*) *Bottom currents*

The world oceans' densest waters are created in the Weddell Sea and, progressively modified by mixing, form the basal layer over much of the deep sea floor (Mantyla & Reid 1983). High-latitude sinking of dense water created close to the sea surface also ventilates the deep ocean, providing oxygen for deep-water and benthic respiration, and thus influencing the oceanic carbon cycle. The fine fraction of sediment flowing down the Antarctic margin in turbidity currents is entrained by western boundary undercurrents, including Weddell Sea Bottom Water (WSBW), as a nepheloid layer, and redeposited as currents slacken: the grain-size distribution of hemipelagic sediment becomes a measure of bottom current strength (Pudsey *et al.* 1988; Pudsey 1992). WSBW flow is slow, but the Antarctic Circumpolar Current (ACC), the other prominent component of Southern Ocean circulation, extends to the seabed with sufficient vigour in some areas to resuspend sediment. For this reason and because the ACC axis, apparently associated with the Polar Front, migrates latitudinally through eddy activity, the sedimentary record towards the Polar Front is often incomplete (Kennett & Watkins 1976).

## 3. GLACIAL–INTERGLACIAL VARIATION

### (*a*) *Continental margin sediments and ice sheet history*

The continental shelf of Antarctica (and to a lesser extent those of high northern latitudes) is unusually deep, and typically slopes inward towards the continent. Opposite large ice streams or where high snowfall and high relief promote erosion and glacier flow, the outer shelf and slope comprise a thick wedge of prograded glacial sediments (Haugland *et al.* 1985; Larter & Barker 1989; Cooper & Webb 1990; Wannesson 1991). These are effects of ice sheets grounded to the continental shelf edge during glacial maxima (Stuiver *et al.* 1981). The shelf is striated, and in shallow water ploughed by iceberg keels (Barnes 1987): glacial sediments are overlain by a Holocene hemipelagic biogenic veneer (Anderson *et al.* 1980). The continental slope is dissected where the prograded wedge is narrow or absent, smooth and steep where it is better-developed (cf. Chase *et al.* 1987; Larter & Barker 1989; Fuetterer *et al.* 1990).

A conceptual model for prograded margin sedimentation through a glacial cycle (Larter & Barker 1989, 1991) involves (i) transport of unsorted material to the uppermost slope, in the sheared base of an ice sheet grounded to the shelf break during glacial maximum. With subsequent warming; (ii) sea-level rises, the ice sheet thins and eventually floats and retreats. Initially, glacial till is deposited on the shelf beneath and in front of the thinning and retreating ice sheet, and its top ploughed by the keels of calved icebergs. A hemipelagic and biogenic sediment veneer is deposited on shelf and slope as the ice shelf front recedes, but sediment supply to the slope is much reduced. After the interglacial (iii) the thickening and advancing grounded ice sheet once more smooths the shelf, consolidates, deforms and erodes shelf sediments and redeposits them on the slope.

The continental shelf edge in these depositional areas is straight or gently curved: the ice sheets approximate a line source of sediment to the upper slope (Bartek *et al.* 1991; Larter & Cunningham 1992), presumably because the widespread till layer on the outer shelf allows narrow ice streams, topographically confined inland, to spread and even coalesce before the shelf edge is reached. Slopes are steep, with gravity slumping and gullying, feeding a dendritic channel pattern on lower slope and rise (Tomlinson *et al.* 1992).

The shelf sedimentary record is therefore intermittent: in the absence of overall shelf subsidence, successive sinusoidal glacial cycles might remain virtually unrecorded, because of regular re-erosion. On the slope, the record is much more complete (despite slumping), but highly cyclic; thick, rapidly-deposited diamictons alternate with thin biogenic/hemipelagic sediments.

The respective contributions of ice sheet erosion and isostatic depression to the inverse shelf profile are uncertain (e.g. Ten Brink & Cooper 1992). However, the inversion exists along the Antarctic Peninsula margin, where ice load is limited by the negligibly wide 'interior', and a low-profile, low-load ice sheet is induced by widespread till on the outer shelf. This argues against a major contribution from isostatic depression; the shelf then approximates an equilibrium grounding profile of a low-profile ice sheet shortly after glacial maximum.

The Holocene record, after the ice sheet grounding line had retreated past the site, occurs in the hemipelagic biogenic sediment of the middle and inner shelf, particularly in topographic troughs (Domack 1988, 1990; Domack *et al.* 1989). The main influences on this record are usually intensely local, but high productivity, leading to high accumulation, provides an expanded section that preserves much detail. Ice sheet retreat may be described on a regional basis, using piston core samples from around its present margin.

An unknown but significant part of the sediment transported to the uppermost slope by grounded ice sheets becomes involved in gravity-driven flow, and is transported by turbidity current or nepheloid layer to the lower slope and over vast areas of the continental rise. The palaeoclimatic potential of 'glacial' turbidites is unknown, and perhaps highly valuable.

An important direct benefit of shelf sediment studies, on a glacial–interglacial scale, would be more-precise numerical models of the grounded ice sheet at glacial maximum, the size of which has long been disputed. If ice-sheet grounding to the shelf edge around most of Antarctica is accepted, a map of till distribution on the shelf will define boundary conditions at the ice sheet base, and thence constrain flow régime and thickness.

By eroding and redepositing, ice sheets modify their own base in a way that is irreversible and in the longer term significant. In general they: (i) erode the continental interior, a planing down only partly compensated isostatically, thereby reducing elevation and changing the climatic conditions necessary for future ice sheet development; (ii) erode also the inner shelf, making re-grounding more difficult and lift-off easier; and (iii) create broad outer shelves that increase the lateral extent of grounding but only of low-profile ice, because of the low-friction till base. On balance, ice sheets act so as to make their future re-growth less likely, but maximum volume greater. Thus, past Antarctic ice sheets were more limited in maximum extent but could grow in warmer conditions than today's.

### (*b*) *Sea-ice and primary production*

Glacial–interglacial variation in sea-ice cover and primary biogenic production is not considered in detail, being discussed by Bathmann *et al.* (this symposium). Essentially however, studies of microfossil abundance and assemblage composition in sediments (Hays *et al.* 1976; Defelice & Wise 1981; Burckle 1984; Shemesh *et al.* 1989; Pudsey 1992) have shown that the mean annual positions of both pack ice edge and Polar Front lay farther north during glacials. Indirect evidence from planktonic $^{13}$C comparison (Charles & Fairbanks 1990) suggests reduced primary production south of the Polar Front during glacials. This belies speculation that enhanced glacial production (possibly mediated by Fe abundance; Martin *et al.* 1990) increased $CO_2$ drawdown in the Southern Ocean, contributing to a biogenic greenhouse amplifier. However, the careful assay and analysis of glacial-age biogenic production in the Southern Ocean remains to be done.

### (*c*) *Bottom currents*

Weddell Sea Bottom Water (WSBW) is produced in the southern and western Weddell Sea by modification of the ambient Warm Deep Water by some combination of surface cooling, increased salinity from extraction of fresh sea ice (Gill 1973), and 'supercooling' on the continental shelf beneath a floating ice shelf (Foldvik & Gammelsrod 1988; Nicholls *et al.* 1991). Newly-formed WSBW becomes a dense basal addition to the clockwise Weddell gyre, mixing with and renewing the overlying Antarctic Bottom Water (AABW). AABW exits the Weddell basin along deep pathways into the South Atlantic, Indian and South-east Pacific oceans, beneath the Circumpolar Deep Water of the ACC.

The Weddell gyre hugs the Antarctic margin from its eastward extremity at about 30°E to the northeast Antarctic Peninsula margin at 50°W, and is topographically constrained to some extent to at least 20°W on its return path. The margin is a source of sediment resuspended by turbidity currents and other means, and incorporated in a nepheloid layer near the gyre margin. Deposition from that layer depends on current speed so that, sufficiently far from the closest source, sea-bed sediment grain size distribution is a measure of bottom current speed. Study of a transect of sediment cores and current meter moorings in the northern Weddell Sea near 40°W (Pudsey *et al.* 1988; Pudsey 1992) demonstrates the connection between modern circulation and sedimentation, and infers a significant reduction in WSBW and AABW flow during glacial periods. Concordant variation in sediment diatom abundance shows pack ice cover during glacials to have been greater than today. Work continues toward semi-quantitative estimates of water mass transport at glacial maximum and through earlier cycles, by more-detailed comparison with modern physical oceanographic data.

The grain-size data are compatible with expected changes in WSBW production: during glacials, ice sheets around the Weddell Sea were most probably grounded to the continental shelf edge, preventing access to their cold underside and use of the inward-sloping shelf as a reservoir where water might grow more dense. Strictly, the proportion of newly formed bottom water to re-circulating older water in the reduced glacial-age flow is uncertain: palaeo-oceanography has no suitable measure of water mass properties. The nature of coupling between WSBW and AABW, that might answer this question, or of coupling between AABW and ACC, is unknown. Model studies might resolve this, but existing fine-resolution models (Webb *et al.* 1991; Killworth, this symposium) lack explicit parameterisation of sea-ice cover and bottom water production.

Oxygen dissolved in the surface component of WSBW and North Atlantic Deep Water serves to ventilate the deep ocean (Broecker & Peng 1982). Reduced glacial-age NADW production has long been known (Streeter & Shackleton 1979) but most workers investigating carbon isotope partition (e.g. Duplessy *et al.* 1988) and inferring glacial-age biogenic production and $CO_2$ drawdown (e.g. Keir 1990) have not anticipated a similar reduction in WSBW/AABW production and flow.

## 4. LONGER-TERM CHANGE

### (*a*) *Isotopes and sea-level through time*

I summarize Antarctic Cenozoic climate development here, so that limits to simple extrapolation of modern features can be set, and the potential of Antarctic sediments more easily assessed.

Oxygen isotopic estimates of ocean palaeotemperature (figure 1*a*) confirm and partially quantify a host

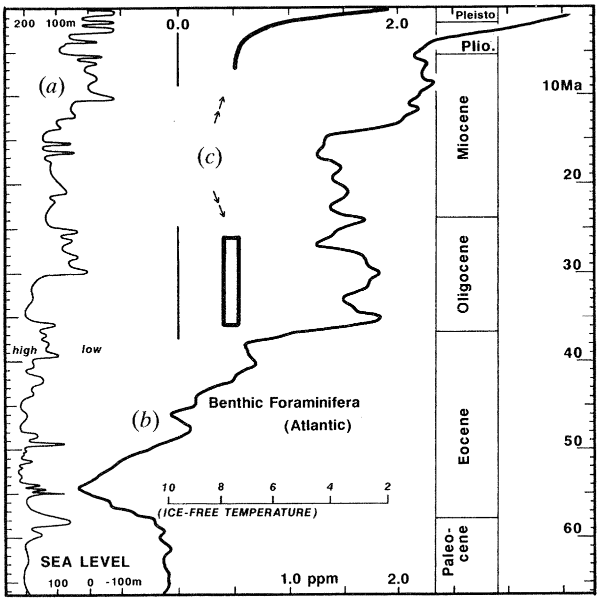

Figure 1. Cenozoic variations in (*a*) sea level (Haq *et al.* 1987) and (*b*) oxygen isotopic ratio for Atlantic benthic foraminifera (Miller *et al.* 1987). Calcite dissolution below 600 m water depth south of the Polar Front over the past 30 Ma precludes direct isotopic measurement on most Antarctic sediments. However, intermediate and deep waters are assumed to retain their high-latitude formation temperatures, so benthic foraminiferal tests from lower latitudes record the sum of high-latitude temperature and ice volume effects. The inset ice-free temperature scale suggests the limit of credible options within the temperature–ice volume ambiguity. As grounded ice is the generally agreed principal source of global eustatic sea-level change, curves (*a*) and (*b*) should be similar, but are not. Amplitude of glacial–interglacial benthic isotopic variation (Hodell & Kennett 1986; Kennett & Stott 1990; Shackleton *et al.* 1990; Hodell & Warnke 1991) is shown separately (*c*), since (*a*) and (*b*) are insensitive at short periods. The validity of the sea-level curve is not universally accepted (Pitman 1978; Watts 1982; Sahagian & Watts 1991).

of other proxy indicators of stepwise global cooling through the Cenozoic. The main causes are generally considered to include: increasing mean ocean-floor age, hence ocean depth, continental freeboard and area, thence earth albedo; changing distributions of continents and oceans, that changed albedo distribution and pathways available for ocean circulation; consequent growth of ice sheets and sea-ice cover, also affecting albedo, and invigorating ocean circulation; changing land elevation, affecting atmospheric circulation.

Many of these factors interact, and some are irreversible (which limits the validity of analogue models of climate change).

Major cooling episodes occurred at about 37 Ma, 15–13 Ma and 2.5 Ma, with more stable periods, including minor warming, between. Opinions differ on the history of continental ice sheet growth (Miller *et al.* 1987; Shackleton 1987; Prentice & Matthews 1988). Oxygen isotope variations reflect both palaeotemperature and changes in mean oceanic isotopic composition, from light-isotope fractionation into the ice sheet: the present ice sheet is equivalent to 0.9 p.p.m. (about 4°C temperature drop). Ice sheet volume is variously considered to have grown mainly well before 37 Ma, at 37 Ma, or 15–13 Ma. Moderate glacial recession may have characterized the late Oligocene and early Miocene, and early Pliocene. Controversy involves disagreement over the significance of ice-rafted debris distribution, the isotopic composition of a large 'temperate' ice sheet, and the necessity for close coupling between ice sheet volume and global climate. It is fuelled by discrepancies between the isotopically derived history and the history of global eustatic sea-level change (for which grounded ice is an acknowledged principal cause) derived from low-latitude shelf sediments (figure 1*b* and Haq *et al.* 1987).

The prograded sediment wedge at the Antarctic margin could help resolve these discrepancies. It contains a long-term record of major Antarctic glaciation, preserved in detail in slope foreset deposits, more crudely in subsided outer shelf topset beds. That record is accessible to scientific drilling: the SCAR-supported ANTOSTRAT programme (Cooper & Webb 1990) aims to synthesize Antarctic margin seismic reflection data to produce a coordinated, optimal drilling proposal. These sediments are an important intermediate data source, linked directly to grounded ice but analysed by the same techniques as the low-latitude sediments that provide the sea-level curve.

The orbitally induced (glacial–interglacial) oxygen isotopic variation (figure 1*c*) that dominates recent times is more difficult to interpret farther back in the record, but its amplitude is potentially useful in considering ice volume changes. Over the past 0.8 Ma the isotopic variation has been greater than previously (e.g. Shackleton *et al.* 1990). Approximately 1.6 p.p.m. of the ca. 1.9 p.p.m. isotopic change over the last cycle is accounted for by ice volume changes (Broecker & Peng 1982).

Those values match glacial–interglacial surface temperature change estimates from species composition within core samples (CLIMAP 1981), which reach 10°C in places, but average only 1.5°C. The greatest temperature changes are associated with sea-ice cover and with passage of fronts through sites; elsewhere, changes are small. To some extent, oceanic water masses respond to climate change by preserving water mass temperatures but changing volumes. Similar local distortion in the past complicates the interpretation of isotopic variation.

There have been few specific attempts to investigate past amplitudes of the orbitally induced variation, but at several drill sites, isotopic measurements are sufficiently numerous to give an indication. The amplitude declines back through the Pleistocene and late Pliocene (Shackleton *et al.* 1990), reaching about 1.0 p.p.m. (benthics) by 2.6 Ma. It declines further through the Pliocene, to 0.4–0.6 p.p.m. for most of the period 7.0 to 3.0 Ma (Hodell & Kennett 1986; Hodell & Warnke 1991). This has implications for Antarctic continental ice volume: an imperfect appreciation of the nature of glacial–interglacial change may be at the root of some of the controversy over Pliocene palaeoclimate.

### (*b*) *The Pliocene record*

The Pliocene may be an analogue for global warming. The global climate record shows a warmer early and middle Pliocene (about 4.8 to 3.0 Ma), with higher sea levels (Haq *et al.* 1987), than either latest Miocene or the last 3 Ma, and suggests that the greatest differences from today occurred at high latitudes. The southern high latitude record itself is sparse, however, and indirect.

Warmer conditions, with a smaller ice sheet and higher sea level, are suggested by Pliocene diatomite exposed onshore at Vestfold Hills (Pickard *et al.* 1988), and occurrences of Pliocene diatom clasts in tills (the Sirius Group) exposed onshore around the Ross Sea. These imply marine incursions of warm water (+2 to +6°C, Harwood 1986; Webb & Harwood 1991; but 0 to +2°C, Burckle & Pokras 1991) into interior basins of East Antarctica. Complementing this is the oxygen isotopic record of a warmer sub-Antarctic South Atlantic (Hodell & Warnke 1991), and high siliceous productivity, with incursions of lower latitude flora south of the Polar Front (Abelmann *et al.* 1990). Conditions cooled gradually during the Pliocene until about 2.5 Ma, and then more rapidly as northern hemisphere glaciation developed.

A perspective on Pliocene Antarctica is important. For example, there was no renewed deposition of calcareous biogenic sediments, as might happen if water mass structure changed considerably. However, ACC flow may have been low, as a consequence of reduced meridional temperature gradients, to permit the southward incursion of lower-latitude siliceous flora. This notion is testable through study of piston core samples.

Estimates of minimum early Pliocene grounded ice volume range down to one-third (Webb & Harwood 1991) of today's volume. Oxygen isotope measurements record a mixture of ice volume and temperature changes: if the sea-level estimates of ice volume change are accepted, then deep-sea temperatures (e.g. Hodell & Warnke 1991) were little warmer than today's. The early Pliocene short-term isotopic variability (figure 1*c*) limits glacial–interglacial ice volume change to about 60% of today's volume. Thus, in this upper limit, ice volume during Pliocene glacial maxima would not be much less than at present. It may therefore be reasonable to compare a global warming model with retreat from an early or mid-Pliocene glacial maximum.

What of terrigenous sediments of the shelf and slope, and the hemipelagic record of bottom water, during the Pliocene? At Prydz Bay where the Lambert Glacier, draining one-seventh of East Antarctica, reaches the coast, ODP drilling sampled Pliocene shelf sediments poorly, recovering one thin diatomite containing dropstones. This suggests open water on the present outer shelf, consistent with other evidence but not extending it (Hambrey *et al.* 1991). The Prydz Bay glacial record is intermittent: better conditions for sampling the Pliocene section occur along the Ross Sea outer shelf and off the Antarctic Peninsula, where seismic profiles indicate more continuous deposition, preserved by subsidence (Hinz & Block 1983; Barrett 1989; Larter & Barker 1989, 1991; Bartek & Anderson 1990).

The hemipelagic record of slope and rise is more informative. In the eastern Weddell Sea, ODP Site 693 (Barker *et al.* 1988) shows continuous diatomaceous mud deposition through late Miocene, Pliocene and Pleistocene. The period 4.8–3.0 Ma saw faster biogenic and terrigenous deposition than before or since, which is difficult to reconcile with an East Antarctic deglaciation sufficiently severe to starve a glacial margin. In the western Weddell Sea also, in Jane Basin (Site 697), hemipelagic deposition was continuous through the Pliocene, and faster than in the Pleistocene. Grain-size measurements (Pudsey 1990) imply bottom currents through most of the Pliocene at least as strong as today, but with rather less variability (that might reflect Milankovich cyclicity) and few excursions before about 2.0 Ma towards the low values of late Pleistocene glacial maxima.

Thus, there is every indication that the Weddell gyre was active through this time, with bottom water being produced in the southern Weddell Sea. In some regions at least, sea-ice was being formed, ice shelves were moderately extensive and ice sheets were grounded occasionally to the continental shelf edge.

In this context we need to reconsider today's deep, inward-sloping Antarctic continental shelf. Interglacial sedimentation fills only a fraction of this shelf basin, and only suspended fines, biogenic and ice-rafted detritus reach the upper slope before the next glacial maximum. Sediment provision to the western boundary undercurrent nepheloid layer, that feeds hemipelagic deposition, nevertheless continues through interglacials because slope instability created by deposition during glacials takes time to dissipate. However, how was hemipelagic sediment supply sustained during a prolonged warm Pliocene?

The unique 90 m-thick turbidite sand deposited in the central Weddell Sea (Site 694, Barker *et al.* 1988) is considered the result of massive erosion of a preglacial West Antarctic shelf during a latest Miocene glacial maximum. Probably therefore, a deepened reverse shelf profile of some kind was in place at the start of the Pliocene warm period, in both West and East Antarctica (the latter has always been the more deeply glaciated: Kennett & Barker 1990). If that period was prolonged, one might expect reduced supply to the nepheloid layer, until the shelf basin had been filled. This did not happen and, paradoxically, as a more modern glacial-interglacial cycle developed, starting at 2.4 Ma, hemipelagic sedimentation actually slowed.

The simplest explanation is that neither Weddell Sea margin had a wide prograded shelf, the eastern because it was a mature starved margin cut by canyons that by-pass the slope except for suspended hemipelagic sediment (Barker *et al.* 1988; Fuetterer *et al.* 1990), the western (Antarctic Peninsula) because its ice-sheet phase had only just begun. During Pliocene deglaciation, these coasts retained local glaciers and ice streams that could cross a shelf lacking a broad prograded wedge, maintaining sediment supply to the nepheloid layer. Also, a warmer Pliocene might have seen higher precipitation and ice stream flow around the Weddell Sea than today.

### (*c*) *The Oligocene record*

The value of examining the Oligocene lies in the irreversible difference of certain of its boundary conditions for circulation and climate, from today's. Principally, Drake Passage had not opened to complete a deep-water circumpolar pathway (Barker & Burrell 1977, 1982). Modelling (Gill & Bryan 1971) suggests that a Polar Front without the ACC would be less effective in isolating Antarctica from warm low-latitude circulation.

Yet the rapid global cooling through mid- and late Eocene, culminating in a sharp drop at 37 Ma (Shackleton & Kennett 1975; Miller *et al.* 1987; Kennett & Stott 1990; figure 1*a*) had produced grounded ice in places at the Antarctic margin by the early Oligocene, from the evidence of prograded sediment wedges (Barrett *et al.* 1987; Barrett 1989; Barron, Larsen *et al.* 1989). Ice rafted material in the Weddell Sea and Indian Ocean (Barker, Kennett *et al.* 1988; Barron, Larsen *et al.* 1989), significant cooling of bottom waters (e.g. Benson 1975) and widespread deep-sea hiatuses reflecting greatly strengthened thermohaline circulation (Moore *et al.* 1978; Johnson 1985), provide supporting evidence.

The Oligocene equivalent of modern shelf–slope–rise sedimentation was sampled at Prydz Bay and in the Ross Sea (Barrett 1989; Hambrey *et al.* 1991). The Oligocene hemipelagic bottom-current régime is unsampled. To understand early Cenozoic regional palaeo-oceanographic and climatic evolution, additional Antarctic margin and gyre margin drilling sites are needed.

Recent drilling on Maud Rise throws additional light on Oligocene palaeo-oceanography in the Weddell Sea region (Kennett & Barker 1990). Foraminiferal and nannoplankton assemblages became much less diverse than before 37 Ma and, through the early Oligocene, calcareous dissolution increased and siliceous microfossils became more abundant. Interestingly, calcareous assemblages at Maud Rise (64.5°S) and the Falkland Plateau were similar (Wei & Wise 1990), indicating the northward extent of cooler water and absence of an intervening oceanic front. In contrast, Maud Rise assemblages differed markedly from those farther south and west in the Weddell Sea, where Oligocene sediments were biosiliceous. This strongly suggests a clockwise gyre like today's, and cooling along the continental margin. Glacial–interglacial isotopic variation appears to have been small (less than 0.5 p.p.m.): Oligocene Maud Rise sediment sample spacing was too great to describe the cyclicity completely, but even an aliased record provides some estimate of amplitude. The subdued variation limits the fluctuation in ice sheet cover.

Much of the Oligocene (36–28 Ma) at Maud Rise saw a persistent temperature inversion at intermediate depth (2500–1650 m), of at least 2°C (Kennett & Stott 1990), showing southward intrusion of warm water into a region that was generating cool water at the surface and deep sea floor. This inversion is seen also in Eocene samples, and supports the idea that there was no Polar Front north of Maud Rise. Additionally, it might explain the considerable extent of Eocene–Oligocene hiatuses in deep-sea sediment deposition, unmatched within the Neogene. During the Oligocene, there was no ACC, thus no cold-water (Circumpolar Deep Water) reservoir, Water mass modification at the Antarctic margin may thus have been more episodic, but could also have been much more extreme. The agent of erosion, and subsequent non-deposition, may have been a series of episodes of strong flow of greatly modified bottom water, through the Oligocene.

The irreversible differences between Oligocene times and today severely limit the value of the period as an analogue for modern climate change.

## 5. CONCLUSIONS

### (*a*) *Ice volume and the continental shelves*

Through the past 37 Ma, continental ice sheets grounded to the continental shelf edge have eroded the interior and deposited sediments that have built out the shelf, and contain a record of glaciation. By planing down the interior, deepening the inner shelf and broadening the outer shelf, ice sheets have acted so as to make their future re-growth more difficult, but their maximum potential extent greater. Conversely, past ice sheets were more limited, but could grow in warmer conditions than today's. The sedimentary record of the margins would allow a reasonably precise reconstruction of ice sheet history, taking these changes into account.

### (*b*) *Bottom Water production*

Modern bottom water production at the Antarctic margin involves (i) concentration on continental shelves of brine created as sea-ice forms and (ii) 'supercooling' beneath floating ice shelves, modifying the ambient Circumpolar Deep Water that forms a large, cool reservoir, constrained by the ACC. That process could have continued since the early Miocene when the ACC began, with minor cyclic changes in the ambient water mass and in rates of production. During the Oligocene, however, there was no reservoir, so water mass modification was probably more episodic, but more extreme. Episodes of northward flow of an extremely dense water mass (comparatively) may explain the energy and extent of the deep-sea erosional 'event' commonly associated with the onset of cold high-latitude bottom water formation 37 Ma ago.

### (*c*) *The Pliocene Antarctic*

The early and middle Pliocene probably involved: (i) a smaller glacial–interglacial variation, that may have alternated between 30–50% and 80–100% of present grounded ice volume; (ii) warmer Antarctic surface waters than today, with more restricted sea-ice cover and greater biosiliceous productivity, during interglacials; (iii) floating ice shelves in the Weddell Sea, and occasional ice sheet grounding to the continental shelf edge during glacials; and (iv) WSBW flow slightly more vigorous than today, but ACC flow somewhat weaker.

Retreat from Pliocene glacial maximum may be an analogue for global warming.

### (*d*) *The Oligocene Antarctic*

The Oligocene saw the development of several features of the present circulation and climate: (i) ice sheets grounded in places to the continental shelf edge of East Antarctica, depositing sediments like those on the modern glacially-prograded outer shelf; (ii) cold deep and bottom water produced at the Antarctic margin; (iii) the siliceous biofacies of modern Antarctic sediments, via progressive restriction and dissolution of calcareous microfossils; and (iv) an orbitally-induced variability in ice volume about half as great as the present-day ice volume, at most.

Nevertheless, early Miocene creation of the ACC modified conditions significantly, and prevents use of the Oligocene as an analogue for a partly deglaciated modern world.

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