Late Oligocene–early Miocene glacial record of the Ross Sea, Antarctica: Evidence from DSDP Site 270

R. Mark Leckie
Department of Geological Sciences, University of Colorado, Boulder, Colorado 80309
Peter-Noel Webb
Department of Geology and Mineralogy and Institute of Polar Studies, Ohio State University, Columbus, Ohio 43210

ABSTRACT

Foraminifera from Deep Sea Drilling Project Site 270, Ross Sea, Antarctica, are used to trace an early phase of glaciation during the late Oligocene–early Miocene. The central Ross Sea underwent significant bathymetric and oceanographic evolution with the inception of glaciomarine sedimentation, resulting in the sequential development of four contrasting foraminiferal populations (assemblage zones). Gradual climatic change in the Ross Sector during latest Paleogene–early Neogene time culminated in major ice build-up by the late early Miocene. Conclusions derived from our microfaunal studies reaffirm climatic and oceanographic trends interpreted from oxygen-isotope data for sub-Antarctic deep sea sites north of the Ross Sea. Intensification of glaciation within the Ross Sea area may be responsible for the increase in production of Antarctic Bottom Water and associated development of widespread early Neogene deep-sea hiatuses reported from lower latitude regions.

INTRODUCTION

We present here the results of an investigation on the foraminifera of late Oligocene–early Miocene sediments at Deep Sea Drilling Project (DSDP) Site 270. This site is located on the flank of a broad, deep Cenozoic sedimentary basin within the eastern Ross Sea continental shelf (Fig. 1). The importance of this stratigraphic succession stems from the fact that it provides the southernmost Paleogene to Neogene transition known at this time. It also presents an opportunity to monitor faunal trends and climatic deterioration in the Ross Sector of Antarctica and to compare this record with events documented at deep-sea sites in sub-Antarctic areas of the Southern Ocean.

During the Eocene, Australia started moving northward away from Antarctica (Weissel, et al., 1977). There was no important circum-Antarctic circulation at this time, but by the late Eocene some shallow-water interchange had developed between the south Indian and Pacific Oceans (Kennett, 1978, 1980). At about 38 m.y. (Eocene-Oligocene boundary), oceanic flow south of Australia contributed to the progressive cooling on Antarctica and the adjacent oceanic water masses. This cooling trend continued during the Oligocene as deep-water circum-Antarctic flow developed. Cool-temperate currents flowed southward into the Transantarctic Strait during the middle to late Paleogene (Webb, 1978, 1979, 1981). Complete circum-Antarctic circulation was accomplished at about 22 m.y. ago with the opening of the Drake Passage (Barker and Burrell, 1977). It was not until about 25 m.y. ago (late Oligocene) that ice-rafted debris was deposited in the central Ross Sea, indicating the calving of glaciers at the coastline of the Transantarctic Strait and development of major iceberg transport (Hayes et al., 1975). More geographically restricted alpine and coastal glaciation had developed close to the emergent Transantarctic Mountains earlier in the Oligocene and Eocene (Webb et al., 1982). Growth of terrestrial ice masses and glaciomarine sedimentation continued through the early Miocene (Stump et al., 1980; Webb, 1981). By the middle Miocene, the East Antarctic Ice Sheet had undergone significant development, and the peripheral marine polar front had expanded toward sub-Antarctic latitudes (Hayes et al., 1975; Kennett, 1978, 1980; Woodruff et al., 1981).

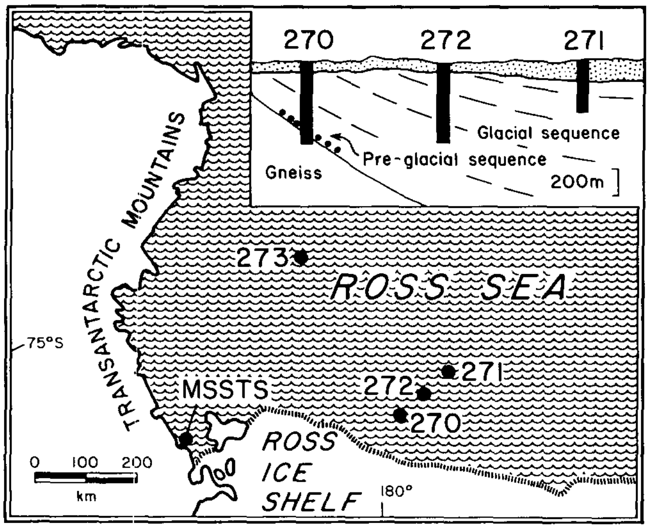

Figure 1. Map of Ross Sea region showing location of McMurdo Sound Sediment and Tectonic Studies (MSSTS) and DSDP drill sites. Inset shows stratigraphic and structural relationships of Sites 270–272 series of drillholes.

Paleontologic, magnetostratigraphic, and isotope dating suggest that the late Oligocene–early Miocene marine phase of sedimentation at Site 270 spans a 9 m.y. interval, between 26 and 17 m.y. ago (Allis et al., 1975; Webb, 1981). A sedimentary succession of 412 m overlies a metasedimentary basement complex (marble and calc-silicate gneiss) that is tentatively correlated with the early Paleozoic Koettlitz Marble of the Transantarctic Mountains (Ford and Barrett, 1975) (Fig. 2). The lowermost sedimentary unit, unit 5, rests unconformably on the basement and is a subaerial breccia of supposed Tertiary age. Two thin, shallow marine sandstones of late Oligocene age—a carbonaceous quartz sand (unit 4) and a glauconitic greensand (unit 3)—overlie this breccia. These sands may represent the thin marginal facies of an extensive late Mesozoic–early Cenozoic preglacial basin (Fig. 1). Above the sandstone units lie the thick (363 m) late Oligocene–early Miocene glaciomarine sediments of unit 2, composed of silty claystones with granules and pebbles distributed throughout. Unit 2 is divided into ten subunits, each delineated by subtle bedding features and clast abundance (Barrett, 1975). Unit 1, also of glaciomarine origin, caps the sequence at Site 270. An early Miocene–Pliocene-Pleistocene angular unconformity separates unit 2 from unit 1 above (Fig. 1).

METHODS

One hundred and ten samples from units 2–4 were examined for foraminifera. Because of the paucity of foraminifera in these late Oligocene–early Miocene glaciomarine sediments, the 26 samples[1] containing the greatest number of specimens are used to delineate the four assemblage zones (Fig. 3) and are believed to portray more realistic biocoenoses. Throughout unit 2 there are numerous intervals that contain deformed soft-sediment clasts suggesting bottom-current scour or slump of semilithified claystone (see Discussion below). Twenty-five of the 26 representative samples, however, are not from such intervals and therefore should consist of truly autochthonous faunas.

FORAMINIFERAL TRENDS OF SITE 270

Glaciation on land provoked widespread effects in the bordering marine water masses, directly influencing both benthic and pelagic marine ecosystems. Benthic and planktonic foraminifera from the sediments of Site 270 have been used to infer changes in the bathymetry and hydrology of this part of the Ross Sea. Four benthic foraminiferal assemblage zones are recognized in units 2–4 (Fig. 2) (Leckie and Webb, 1980a, 1980b). These are based on generic abundance, species diversity, and the composition of individual assemblages (Figs. 3, 4) (Leckie and Webb, in prep.).

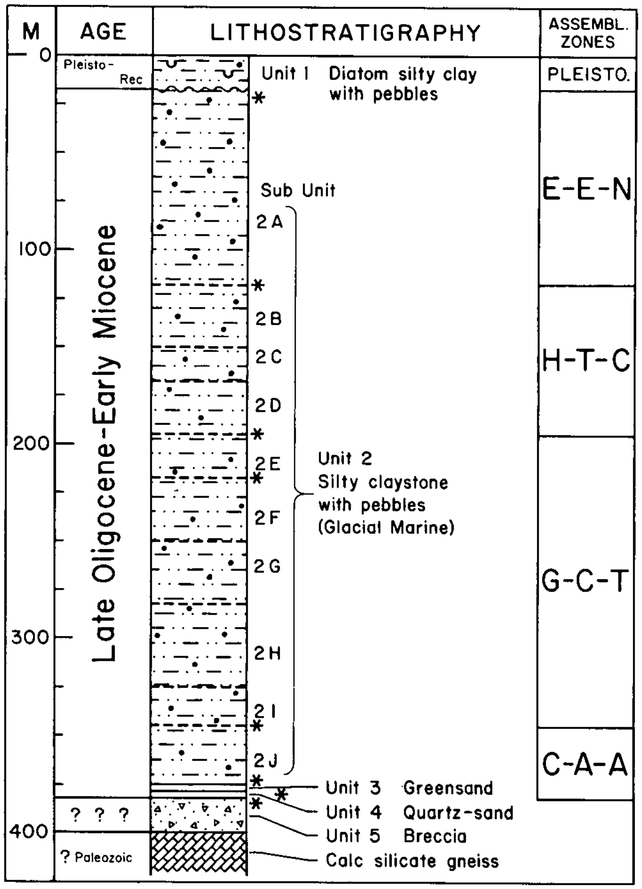

Figure 2. Stratigraphic column at Site 270 with proposed foraminiferal assemblage zones and subdivision of late Oligocene–early Miocene sediments. Asterisks mark positions of suspected diastems or minor hiatuses as discussed in text.

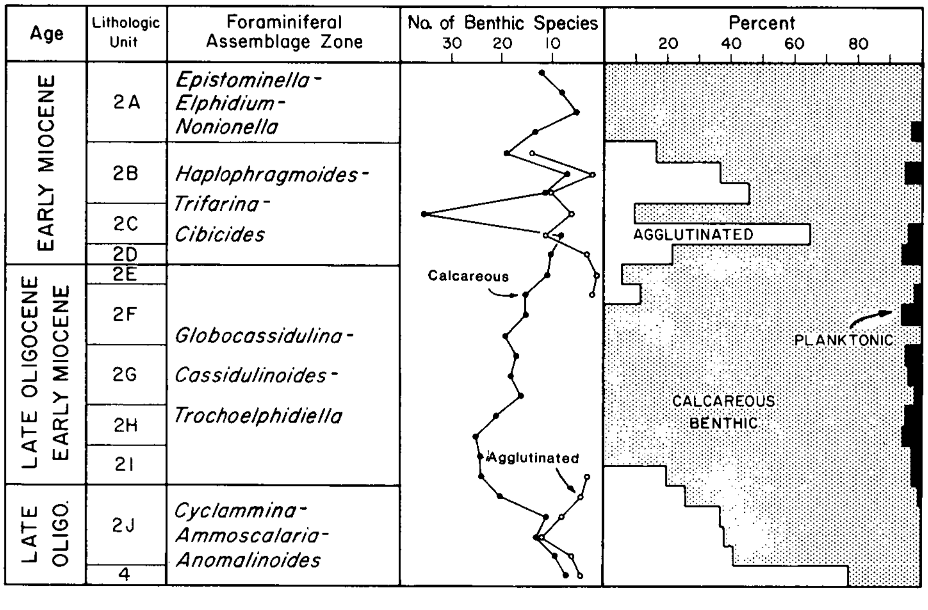

Figure 3. Diversity trends of agglutinated and calcareous benthic species and proportions of agglutinated, calcareous benthic and planktonic taxa expressed as percentages. Based on 26 of 110 samples investigated in units 2–4 at Site 270. Selection determined by size of population and stratigraphic distribution. Thin (1 m) glauconitic sand of unit 3 is apparently devoid of foraminifera.

Cyclammina-Ammoscalaria-Anomalinoides (C-A-A) Assemblage Zone (Unit 4, Subunit 2J)

Sedimentary textural characteristics of unit 4 (carbonaceous sandstone) suggest a protected, shallow marine environment of deposition, probably an estuarine or littoral setting (Barrett, 1975). The dominantly agglutinated foraminiferal populations of *Cyclammina* spp., *Ammoscalaria pseudospiralis*, and *Ammobaculites* sp., among others, plus lack of any planktonics provide support for this environmental interpretation (Fig. 3). Although apparently devoid of foraminifera, the

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[1] Appendix 1: Sample Intervals Plotted in Figure 3 is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. Ask for Supplementary Material 83-18.

glauconitic sands of unit 3 also indicate shallow marine conditions. In subunit 2J, the observed increase in abundance and diversity of calcareous benthic taxa at the expense of agglutinated forms and the appearance of planktonic foraminifers in the upper part of this subunit (Fig. 3) clearly indicate a deepening water column, but probably one not exceeding 100 m deep (inner shelf). A transgressive trend from the subaerial breccia of unit 5 to the continental shelf sediments of subunit 2J is interpreted on lithologic and foraminiferal evidence. The C-A-A Assemblage Zone ranges through a complex of shallow-water lithofacies, is associated with a subsiding basin, and is probably diachronous in the Ross Sea shelf area. The faunas exhibit some affinities to temperate New Zealand mid-Tertiary shallow-water assemblages (Fig. 4).

Globocassidulina-Cassidulinoides-Trochoelphidiella **(G-C-T) Assemblage Zone (Subunits 2I–2E)**

A significant change in benthic foraminiferal faunas is observed across the lithologic break between subunits 2J and 2I. The G-C-T Assemblage Zone is dominated by calcareous benthics such as *Globocassidulina subglobosa* and *Cassidulinoides* spp., and it also marks the first appearance of important members of the Elphidiidae: *E. magellanicum* and the endemic *Trochoelphidiella* species complex (Fig. 3). This change suggests the presence of a minor hiatus and reflects further basin subsidence from shallow inner shelf to depths more typical of an outer shelf or upper slope environment (150–300 m)—calcareous benthics dominate in this environment in today's ocean margins (Douglas, 1979). Gradual subsidence is believed to have continued throughout unit 2, possibly reaching depths of 500 m in subunit 2A.

A gradual decline in benthic diversity (number of taxa per sample) occurs in the populations of the G-C-T Assemblage Zone (Fig. 3). Although there is some indication of dissolution, the gross aspect of change in diversity appears to reflect the biotic environment rather than the preservational environment. It is suspected that environmental conditions became less stable and more rigorous throughout this zone. Considering the glaciomarine environment of the Ross Sea in the latest Paleogene–early Neogene, it is possible that gradual changes in the physical and chemical hydrology of the Ross Sea may have been caused by ice-sheet growth on land and/or increased ice-shelf development at the coastal margins of the Transantarctic Strait.

Haplophragmoides-Trifarina-Cibicides **(H-T-C) Assemblage Zone (Subunits 2D–2B)**

The transition from the G-C-T Assemblage Zone to the H-T-C Assemblage Zone appears to have been gradual, as indicated by the increased abundance of agglutinated species through uppermost subunit 2F and subunit 2E (Fig. 3). Although 64% of the calcareous benthic taxa of the H-T-C Assemblage Zone also occur in the G-C-T Assemblage Zone below, the most common and characteristic forms of that lower zone (*Globocassidulina subglobosa* and *Cassidulinoides* spp.) are not associated with the arenaceous faunas of the H-T-C Assemblage Zone. This fact may suggest a diastem between subunits 2E and 2D, or it could represent either environmental exclusion or taphonomic dissolution.

As the Ross Sea cooled further, bottom waters became colder, more saline, and richer in dissolved carbon dioxide. These conditions increase the solubility of calcium carbonate and therefore are more favorable for the preservation of agglutinated rather than calcareous benthic faunas. Calcareous benthics show a greater degree of dissolution in the H-T-C Assemblage Zone than in underlying zones. The presence of solution pits near the umbones of bivalves (Dell and Fleming, 1975) recovered from this interval provides additional support for the argument in favor of more pronounced carbonate dissolution during this part of the early Miocene. Kennett (1968) has noted that calcareous benthic species associated with agglutinated faunas at depths between 430 and 650 m in the Ross Sea today show partial dissolution effects; this is related to the shallow calcite compensation depth (CCD) of the Ross Sea. The observed diversity patterns of the H-T-C Assemblage Zone (Fig. 3) are most likely the artifacts of differential preservation in a harsh benthic environment combined with the effects of reworked penecontemporaneous assemblages. Regardless of these diversity fluctuations, taphonomic uncertainties, or possibilities of faunal recycling, the gradual reappearance of agglutinated taxa in the foraminiferal assemblages of subunits 2E through 2B indicates changing benthic conditions, here considered to be in response to bottom water becoming increasingly carbonate depleted.

Epistominella-Elphidium-Nonionella **(E-E-N) Assemblage Zone (Subunit 2A)**

A sudden change in the composition of benthic foraminiferal assemblages occurs at the boundary between subunits 2A and 2B. This faunal change is the most abrupt and obvious of those previously discussed and probably represents a minor hiatus in the sedimentary record. The low-diversity calcareous benthic taxa that characterize the E-E-N Assemblage Zone (*Epistominella vitrea, Elphidium magellanicum, Nonionella iridea, Cibicides* spp., and *Melonis* spp.) may be resistant to dissolution. In the

Figure 4. Diversity totals for agglutinated and calcareous benthic and planktonic foraminifera in each assemblage zone. Except for one new taxon (Leckie and Webb, in prep.), all planktonic species are represented by single specimens. Based on study of 110 samples: C-A-A (34 samples), G-T-C (48 samples), H-T-C (10 samples), E-E-N (18 samples). There is a decrease in proportion of benthic species in each zone with New Zealand–Australian affinities, whereas there is a clear increase in proportion of benthic species that characterize Antarctic Neogene faunas; this is in response to gradually deteriorating climatic conditions resulting in increasing contrast with faunas beyond Antarctica and development of endemic polar fauna.

Assemblage Zone	Number of Agglutinated Species	Number of Calcareous Benthic Species	Number of Planktonic Species	Total No. of Species Reported in Zone	No. Benthic Spp. w/ New Zealand-Australian Affinities	No. Benthic Spp. Previously Reported from Antarctica
Epistominella-Elphidium-Nonionella	0	28	1	29	2:28 (7%)	19:28 (68%)
Haplophragmoides-Trifarina-Cibicides	25	56	2	83	12:81 (15%)	41:81 (51%)
Globocassidulina-Cassidulinoides-Trochoelphidiella	13	68	7	88	9:81 (11%)	37:81 (46%)
Cyclammina-Ammoscalaria-Anomalinoides	33	43	2	78	15:76 (20%)	26:76 (34%)

Ross Sea today, an analogous suite of calcareous benthics is thought to be more resistant to the corrosive effects of carbonate-depleted waters than other species (Kennett, 1968). Similarly, Anderson (1975) interpreted a low-diversity assemblage of solution-resistant calcareous forms of the Weddell Sea (Antarctica) to indicate severe environmental conditions. The absence of agglutinated taxa may possibly be related to a lowered CCD surface as controlled by increased primary productivity and/or production and mixing of different water masses (see Osterman and Kellogg, 1979). The significant increase in diatoms in subunits 2A, 2B, and 2C (Hayes, et al., 1975, p. 216) and virtually monospecific populations of planktonic foraminifera indicate truly polar marine conditions in the Ross Sea in early Miocene time.

The E-E-N Assemblage Zone represents a culmination of marine events inferred from the underlying sequence that reflect gradual deterioration of climatic conditions in the Ross Sector during the early Miocene. This is believed to represent a phase of major ice build-up near sea level in the form of fringing ice shelves, expanded outlet glaciers and/or vast seasonal ice formation. Intensification of glaciation had profound effects on the physical and chemical hydrology of the Ross Sea, resulting in the sequential development of paleoenvironmentally controlled benthic foraminiferal assemblages. The oxygen-isotope record from sub-Antarctic deep-sea sites north of the Ross Sea shows a significant enrichment in $\delta^{18}O$ in the latter part of the early Miocene that can be interpreted as a cooling trend or increased ice volume in Antarctica (Shackleton and Kennett, 1975) and also supports the thesis of climatic deterioration presented here.

DISCUSSION

Site 270 is located near the southern extremity of a crystalline basement high or ridge that is aligned north-south along meridian 180° and extends south to a point just north of the present Ross Ice Shelf front. It is suggested that prior to its submergence in the late Paleogene, at least part of this feature formed an island and submarine bank near the center of the Transantarctic Strait (Webb, 1981). If units 4/3 to subunits 2A (Fig. 2) span a period of 9 m.y. and if units 4/3 and subunit 2A represent depositional depths of 10–50 m and 300–500 m, respectively, plus the sedimentary thickness of 365 m, then an average rate of subsidence amounting to 68–95 m/m.y. is apparent.

The transition from nonglacial (units 4 and 3) to glacial (unit 2) sedimentation is marked by abrupt changes of lithology. Minor hiatuses are suspected between each of these distinct lithologic units. All the foraminifera of unit 4, however, pass up into subunit 2J, although more diverse faunas are present in the slightly deeper water part of subunit 2J (Fig. 3) (Leckie and Webb, 1980b). Small clasts of reworked sediments and recycled Late Cretaceous and Paleogene foraminifera do occur sporadically in the lower two-thirds of unit 2, but it seems unwarranted to propose large-scale stripping of the nonglacial sequence, or the presence of a major disconformity between the nonglacial and glacial sediments. We propose for this part of the Ross Sea, then, a gradual transition toward increased marine glaciation at about 26–24 m.y. ago (latest Oligocene).

In unit 2, the occurrences of soft-sediment clasts, intervals of inclined bedding, and minor amounts of stratification produced by low-intensity traction or bottom currents (Barrett, 1975) all indicate a somewhat unstable shelf. However, the lack of abrupt changes in benthic foraminiferal assemblages adjacent to these sedimentological features suggests gradual rather than abrupt basin subsidence.

A nearly constant sedimentation rate of 41 m/m.y. was proposed by Allis et al. (1975) for unit 2 (glaciomarine) on the basis of their magnetostratigraphic studies. The notion of a constant sedimentation rate is not supported here. One has only to look at a plot of ice-rafted pebbles per metre (Fig. 9 of Barrett, 1975) to see that there are significant fluctuations, the most notable of which distinguishes subunits 2B–2E as having a persistent 75% fewer pebbles per metre than the subunits below and subunit 2A above. The boundaries between subunits 2E–2F and 2A–2B could be associated with missing record—particularly the subunit 2A–2B contact, where the most abrupt faunal change also occurs. The presence of such diastems or minor hiatuses in the glaciomarine section of Site 270 has the effect of increasing the apparent sedimentation rates. Recently, Savage and Ciesielski (1983) have interpreted ice-rafted sediment accumulation rates of > 150 m/m.y. for the early and middle Miocene suprajacent sequences of DSDP Sites 272 and 273 in the Ross Sea. Likewise, we believe that sedimentation rates varied and were most likely greater than 41 m/m.y., although lack of refined biostratigraphic control prohibits any quantitative estimates.

As previously discussed, there are numerous levels in units 2–4 of Site 270 where suspected diastems or minor hiatuses occur, but there is no evidence, foraminiferal nor sedimentological, to distinguish unique sedimentary sequences bounded by major hiatuses as recognized in the McMurdo Sound Sediment and Tectonic Studies drill hole adjacent to the Transantarctic Mountains (Webb et al., 1982). It is suspected that the central Ross Sea was not only deep enough by the early Miocene but also received high enough rates of ice-rafted sedimentation to effectively mask bottom-current erosion-dissolution induced by changing eustacy and/or intensification of glaciation as observed in shallower continental-margin settings (Loutit and Kennett, 1981) or in the deep sea (Moore et al., 1978; Barron and Keller, 1982).

Cool-temperate waters flowed southward from the Southern Ocean during the late Oligocene (C-A-A Assemblage Zone) and only sporadically in the latest Oligocene–earliest Miocene (G-C-T Assemblage Zone). These currents sustained benthic and planktonic foraminifera with marked Australasian affinities (Fig. 4). Cold water advanced northward, at first flowing beneath this temperate water mass, but later displacing it north of Site 270. Sporadic occurrences of temperate planktonic foraminifera along with calcareous nannoplankton were replaced by monospecific polar planktonic foraminiferal populations and more abundant diatom assemblages (H-T-C and E-E-N Assemblage Zones). The moderately diverse benthic foraminiferal populations of unit 2 include some polar endemic taxa. Dissolution effects in benthic populations from early Miocene glaciomarine sediments point to the accelerated evolution of terrestrial ice masses and associated carbonate-depleted marine waters close to Antarctica.

Late Oligocene–early Miocene glaciomarine sedimentation at Site 270 originated largely from iceberg-related processes. The seas in the vicinity of Site 270 were free of permanent ice (such as the present Ross Ice Shelf) and supported active photic zone productivity, although growth or expansion of semipermanent marine ice was most likely occurring elsewhere in the Transantarctic Strait. Although Balshaw (1981) found that several intervals of unit 2 met the textural criteria to be classified as basal till, these did not meet the mineralogical criteria of Anderson et al. (1980) (J. B. Anderson, personal commun.). There is no convincing evidence for grounded shelf ice at or near Site 270 during the late Oligocene–early Miocene.

An increase in hiatus abundance through

the early Miocene of the Southern Ocean and southwest Pacific was identified by Moore et al. (1978), whereas Barron and Keller (1982) described their NH1 hiatus (20.0 to 18.0 m.y. ago) as the most widespread of the eight intervals of major hiatuses they recognize in the world ocean during the late Oligocene and Miocene. Both studies attribute the hiatuses to erosion and dissolution of deep-sea sediments during times of intensified glaciation in Antarctica. The data we present here represent direct evidence from Antarctica in support of glacial intensification during the latest Paleogene and early Neogene. The gradual build-up of ice probably initiated an increase in Antarctic Bottom Water production which, as we have speculated, may have been a principal cause of the widespread hiatuses.

SUMMARY

The central Ross Sea gradually subsided from just above sea level to 300–500 m (outer shelf–upper bathyal depths) during the late Oligocene–early Miocene. This is recorded in units 5–2 of DSDP Site 270. Glaciomarine sedimentation in the central Ross Sea (mainly iceberg transport) commenced in the latest Oligocene (26–24 m.y. ago). This is recorded in unit 2 of DSDP Site 270. Deteriorating climatic conditions around Antarctica had a direct influence on marine ecosystems. Bathymetric and oceanographic changes resulted in the sequential development of paleoenvironmentally controlled benthic foraminiferal assemblages. Four assemblage zones are recognized. Major sea ice build-up in the Ross Sector late in the early Miocene is inferred from foraminiferal and sedimentary evidence and parallels oxygen-isotope paleotemperature curves from the sub-Antarctic. This is believed to be in the form of fringing ice shelves, expanded outlet glaciers and/or vast seasonal ice formation. Widespread deep-sea hiatuses (erosion-dissolution) recognized in the late early Miocene of the world's oceans, particularly in the Pacific, may have been caused by an increase in the production of Antarctic Bottom Water as glaciation around Antarctica intensified during latest Paleogene and early Neogene time.

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