Korean Journal of Polar Research
Vol. 4. No. 1. p.25~37 June 1993

Paleoceanographic Evolution of Subantarctic South Atlantic

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南大西洋 亞南極지역의 古海洋學的 硏究

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ABSTRACT : Paleoenvironmental study of the high-latitude South Atlantic has been documented based on the occurrence of radiolarians collected on Ocean Drilling Program (ODP) Leg 114. The thick and relatively complete Paleogene sequences (65-24 Myr) from ODP Leg 114 cores provide an unparalleled opportunity to describe a Paleogene oceanographic evolution for the high-latitude Southern Ocean. Based on radiolarian investigations of the Paleogene sections from Leg 114, three major periods of climatic and paleoceanographic evolution are recognized. They are: 1) Early/Middle Eocene boundary, 2) Eocene/Oligocene boundary, and 3) late Early Oligocene. These major changes can be recognized world-wide, however specific first and last fossil occurrences on which they are based may be diachronous.

KEY WORD : ODP, South Atlantic, radiolarian

요 약: 남극 주변지역에서 채취된 ODP Leg 114의 시료에 다량 포함되어 있는 방산충의 산출상태를 근거로 고위도 남대서양 해역에 대한 고해양학적 연구를 수행하였다. 특히 ODP Leg 114의 퇴적물 시료들은 현재까지 연구가 미흡했던 고제3기층에 대한 고해양환경 연구에 중요한 자료를 제공하였다. 본 연구에서는 방산충 군집의 변이를 이용, 고제3기 지질시대에서 일어난 세번의 해양학적 중요 변천과정을 인지하였다.

주요어 : ODP, 방산충, 남대서양

Introduction

Previous drilling in the Antarctic and Subantarctic areas (DSDP Legs 28, 29, 35, 36 and 71) has provided a framework for our current understanding of Cenozoic paleoceanographic history in the high-latitude Southern Ocean. From those works we know some of the major paleoceanographic changes during the Neogene, but our understanding of earlier stages of ocean cooling and development has been limited by insufficient numbers of stratigraphically continuous, well-preserved, and well-dated biogenic records. Most holes of these legs were rotary drilled, resulting in drilling disturbance and poor core recovery; other holes were sparsely cored, with long washed intervals, in order to reach basement objectives.

Recently, recognizing the need and importance of additional high-latitude samples, the Ocean Drilling Program (ODP) Leg 114 drilled seven sites along a west-east transect from the Northeast

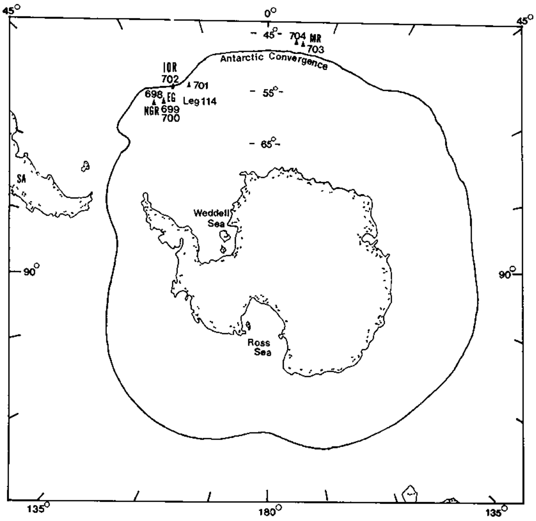


Fig. 1. Location map of Leg 114 sites in the South Atlantic sector of the Southern Ocean.
IOR : Islas Orcada Rise EG : East Georgia
SA : South America MR : Meteor Rise
NGR : Northeast Georgia Rise

Georgia Rise to the Meteor Rise, in water depths from 1,807 to 4,632 m(Fig. 1).

One of the major successes of Leg 114 was the recovery of a virtually complete Late Cretaceous through the Cenozoic sequence with rich assemblages of calcareous and siliceous microfossils. Particularly well-preserved radiolarian assemblages occur in the Middle to Late Paleocene, Middle to Late Eocene, and Oligocene sediments. Thus, radiolarians are an excellent tool for paleoceanographic studies of high-latitude deposits. Distinctive changes in the rediolarian faunas over certain time intervals indicate significant temperature variation and changes in ocean circulation. In this study, indications of faunal change at certain intervals may testify to critical paleoceanographic variations during Paleogene time. The results from radiolarian investigations documented here have also been compared with other microfossil data to more completely understand global paleoceanographic and paleoclimatic conditions for the high-latitude Southern Ocean.

Paleoceanographic Systems

The evolution of paleoceanographic systems in the Southern Ocean has been controlled by two factors; plate tectonic events and Antarctic glacial history. Continental configuration in the Subantarctic region during the Cretaceous and Paleogene profoundly restricted deep and intermediate water-mass connections between the Weddell Basin in the south and the Atlantic Basin to the north. The increase of thermal gradients in the Southern Ocean has been linked to the development of the Antarctic Circumpolar Current (ACC) system (Kennett, 1978, 1982), first by the onset of deep water flow through the Tasman Seaway between Australia and Antarctic during the Late Eocene (Weissel and Hayes, 1972), and second by opening of the Drake Passage between South America and West Antarctica during the Oligocene (Barker and Burrell, 1977 ; LaBrecque and Hayes, 1979 ; Ciesielski et. al., 1988). The result was a fully developed ACC in the Late Oligocene that strongly influenced Cenozoic climate because it allowed thermal isolation of the Antarctic. Because of its nearly homogeneous water, produced by vertical instability, the wind-driven ACC is a deep current in contrasts in lower latitudes. The ACC also effectively separated high- and low-latitude planktonic assemblages as well (Kennett, 1978 ; Haq and Milliman, 1984).

Paleoenvironmental Interpretation

In the broad outline, the climatic evolution deduced from paleontological records from different DSDP sites displays a world-wide conformity. During the Paleogene, climatic evolution shows important cooling events in the mid- and high-latitudes of the Atlantic and Pacific Oceans, which occurred in a step-like manner than continuously (Savin et al., 1975 : Shackleton and Kennett, 1975 ; Keigwin and Keller, 1984 ; Miller and Thomas, 1985 ; Oberhansli and Toumarkine, 1985 ; Kennett and Stott, 1990).

Radiolarians are useful paleoceanographic indicators and were abundant in the Subantarctic South Atlantic sediment during the paleogene. Based on radiolarian investigations of the Paleogene section from Leg 114, three threshold events in the climatic and paleoceanographic evolution are recognized. They are: 1) Middle/Late Eocene, 2) Eocene/Oligocene, and 3) Early/Late Oligocene boundaries.

Table 1. Summary of the occurrences, preservation, and diversity of Paleogene radiolarian assemblages for holes of ODP Leg 114.

Epoch		Holes	Radiolarian		
			Diversity	Preservation	Occurrences
Oligocene	L	699B 701C 699B 704B	Lowest	Moderate	Few to Common
	E	699A 701C 703A	Low	Moderate to Good	Common
Eocene	L	701C 702C 702B 703B	Moderate	Moderate to Good	Common to Abundant
	M	702B	High	Good	Abundant
	E	698A 702B	Highest	Good	Abundant
Paleocene	L	698A 702B 700B	High	Moderate to Good	Common to Abundant
	E	700B	Low	Moderate	Common

Paleocene Oceanorgraphic Evolution: Gradual Warming

The Paleocene sediments were recovered from three holes during Leg 114. The radiolarians were observed at Sites 698 and 702 present only a small part of the Late Paleocene, mainly as a result of incomplete recovery and the presence of hiatuses (Kim, 1992). A nearly continuous radiolarian section through the uppermost Early Paleocene is available from Site 700. It appears that the evolution of paleoceanographic systems have major effects upon radiolarian distribution, productivity, and diversity (Table 1). In the Middle to Late Paleocene, radiolarian assemblage contains some warm-water and cosmopolitan species such as *Buryella tetradica*, *Buryella pentadica*, *Stylosphaera goruna and Lithomespilus mendosa* (Kim, 1992). Those species were also reported from the Paleocene sediment of DSDP Leg 10 in the Gulf of Mexico (Sanfilippo and Riedel, 1973). Calcareous nannofossils also include a low-diversity but abundant group of discoasters. Abundant discoasters are reliable indicators of warm surface waters (Crux, 1991), and the occurrence of low-latitude radiolarians in combination with abundant discoasters in the Subantarctic Altantic suggests warm temperature to cool subtropical conditions during the Late Paleocene.

Although the overall diversity among radiolarians increased, differences among radiolarian assemblages from the Subantarctic regions become more pronounced than those from lower latitudes; *Buryella tetradica*, already rare in the Late Paleocene, and missing at the uppermost Late Paleocene which while consistently present from the Early Eocene samples of Hole 94, DSDP Leg 10 in the Gulf of Mexico (Foreman, 1973) and Hole 603B, DSDP Leg 90 in the North Atlantic (Nishimura, 1987). In the low-latitude, the only recognized Paleocene rediolarian *Bekoma bidartensis* zone extends downward to the Late Paleocene samples of Hole 94, DSDP Leg 10 in the Gulf of Mexico (Sanfilippo and Riedel, 1973 ; Foreman, 1973). However, the occurrence of *Bekoma bidartensis* was not observed at Subantarctic South Atlantic, suggesting the presence of latitudinal temperature gradient during Late Paleocene.

During the Late Paleocene to Middle Eocene, sedimentation in the vicinity of Sites 699 and 700 was remarkably continuous, even though the Georgia Basin should have been an avenue for deep-water exchange from the Antarctic to the South Atlantic prior to the Eocene opening of the Islas Ordadas Rise - Meteor Rise gateway (Ciesielski et al., 1988). Therefore, if the East Georgia Basin as an Early Paleogene deep-water passage, thermocline circulation was too weak to cause significant erosion.

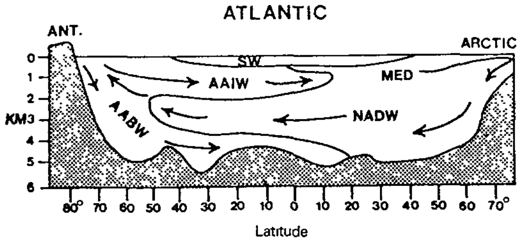
Eocene Oceanorgraphic Evolution

Early Eocene: Warmest interval of Cenozoic

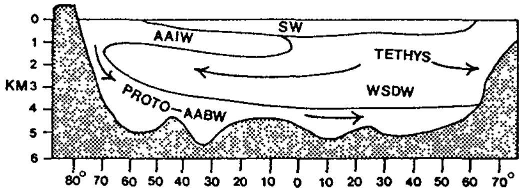
Although no radiolarians were observed from earliest Eocene sections from Leg 114, calcareous microfossil data indicate that this is perhaps the warmest interval of the entire Cenozoic. A peak in discoaster diversity and adundance also coincides with the Paleocene/Eocene transition (Crux, 1991).

One of the current paleoceanographic questions is to explain this exceptional Cenozoic warmth and the subsequent transition to colder climates. Modern deep ocean circulation is primarily driven by the process of deep and intermediate water formation at high latitudes. The formation of cold deep waters in the Antarctic is the direct result of freezing condition at these latitude. In the Paleogene, when global climate was distinctly warmer than today, the production of deep waters may have occurred through a different variety of processes and at various locations. In the absence of very cold polar regions covered with extensive ice sheets, deep and intermediate waters might still have formed by cooling at high latitudes (Schnitker, 1980 ; Barrera et al., 1987 ; Katz and Miller, 1991). An alternative interpretation of the source of deep-water is given by Barron et al. (1981), Hay (1988), and Kennett and Stott (1990). These authors suggested that the dense, warm, and salty deep waters were formed at low-latitude as a result of excess evaporation. These warm, salty deep waters would have been depleted in dissolved oxygen at their formation because of the lower solubility of that gas at higher temperatures, and they could have been close to saturation with $CaCO_3$ because this salt is less soluble at higher temperatures. Thus they would have been different from the present deep waters, which are cold, rich in dissolved oxygen, and strongly undersaturated in $CaCO_3$ at their formation. According to Kennett and Stott (1990), the ocean at times during the Eocene, and perhaps the Late Paleocene is inferred to have been two-layered, consisting of warm, saline deep water at low latitudes and overlain by cooler waters formed at high-latitude (Fig. 2). Under such conditions, production of cool intermediate water at high southern latitudes may have been turned off briefly at the Paleocene/Eocene boundary as a result of extreme warmth and an infusion of warm waters from low latitudes.

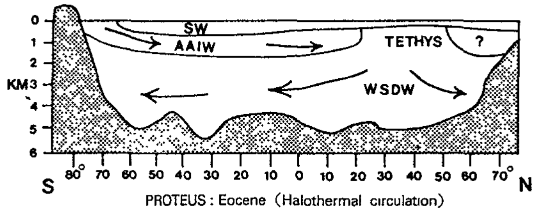
During the Eocene, the Antarctic ice sheet did not exist and the surface water in the Southern Ocean was warmer (Shackleton and Kennett, 1975 ; Murphy and Kennett, 1986 ; Kennett and Stott, 1990). The combined effects of the absence of ACC and high surface water temperature could



OCEANS: Modern, psychrospheric (Thermohaline circulation)



PROTO-OCEANUS : Oligocene
(Mixed halothermal & thermohaline circulation)



PROTEUS : Eocene (Halothermal circulation)

Fig. 2. Evolution of deep, and intermediate-water circulation during the Cenozoic. Proteus, the ocean of the Eocene, was dominated by halothermal circulation; Proto-Oceanus, the ocean of the Oligocene, exhibited mixed halothermal and thermohaline circulation; whereas the modern ocean, Oceanus, is a psychrospheric ocean dominated by thermohaline circulation.

AABW : Antarctic Bottom Water
AAIW : Antarctic Intermediate Water
NADW : North Atlantic Deep Water
WSDW : Warm Saline Deep Water
MED : Mediterranean
(From Kennett and Stott, 1990)

have led to the prevalence of low-latitude faunas around Antarctic. It follows that the Middle Eocene radiolarian assemblages at Sites 698 and 702 consist essentially of low diverse low-latitude radiolarians such as *Lithomitra docilis*, *Lychnocanoma amphitrite*, *Lophocyrtis biaurita*, and *Eusyringium fistuligerum* (Kim, 1992). Those species were earlier reported from the Gulf of Mexico of the DSDP Leg 10 (Foreman, 1973) and siliceous Eocene deposits in central California (Blueford, 1988). This warming trend did not end until the upper part of Middle Eocene when radiolarians changed to lower diversity and less abundance than in the Early Eocene.

Middle/Late Eocene boundary:Beginning of climatic cooling

The end of the Middle Eocene is marked worldwide by the extinction of some of the planktonic microfossils (Berggren et al., 1985 ; Premoli-Silva and Boersma, 1988).

The Middle Eocene was a transitional period leading to cooler surface waters during the Oligocene. The diversity of radiolarians steadily declined from Middle Eocene to Late Eocene. However, the abundance of radiolarian assemblages declined sharply near the Middle / Late Eocene boundary. Evidence for this cooling includes the disappearances of Early to Middle Eocene radiolarians such as *Lychnocanoma amphitrite*, *Lophoconus titanothericeraos*, *Eusyringium fistuligerum*, and *Lophocyrtis biaurita* (Kim, 1992).

At Hole 702B, the increase of oxygen isotope value occurs between 114-702B-8X-3 and 114-702B-6X-2, 110−104cm (66.8~46.8 mbsf). Katz and Miller (1991) estimate that the increase occured in the upper Middle Eocene (42-41 Ma), although the chronology of this part of the Hole 702B section is unclear. The increase begins within chron C18N (42.73~41.29 Ma). This increase is not restricted to the Subantarctic Atlantic. Similar oxygen isotope changes are known from the western South Atlantic, eastern

South Atlantic (Oberhansli and Tourmarkine, 1985), Pacific (Shackleton and Kennett, 1975), as well as Weddell Sea of the Antarctic Ocean (Kennett and Stott, 1990).

Paleontological studies also reveal drastic changes from the Middle to Late Eocene in surface and bottom water. The geographical distribution patterns of calcareous nannofossils and planktonic foraminifer assemblages from the North Atlantic indicate an environmental change within Zone NP16 (Haq et al., 1977), which may be due to a cooling of high-latitude surface water. Possible causes for such a widespread and extensive oxygen isotope changes have generally been ascribed to deep-water cooling (Savin et al., 1975 ; Shackleton and Kennett, 1975), or a change in the evaporation/precipitation pattern in several main source areas of surface and bottom water masses (Oberhansli and Tourmarkine, 1985), or ice formation prior to the Oligocene (Barron et al., 1981).

The Late Eocene rediolarian assemblages are represented by cold-water forms, such as *Calocyclas semipolita* and *Eucyrtidium* sp.A, which were reported earlier in the Early Oligocene sediments from the high- and mid-latitude Southern Ocean (Chen, 1975 ; Petrushevskaya, 1975 ; Weaver, 1983). Recently, Kennett and Stott (1990), reported that average sea surface temperature in the Weddell sea continued to decrease during the Late Eocene, and also suggested a mild increase in upwelling rates at this time, perhaps resulting from increases vigor of atmospheric circulation and leading to higher biosiliceous productivity at Antarctic region. Evidently, cool waters continued to expand toward the north, as reflected by the presence of cooler calcareous nannofossil assemblages on the Falkland Plateau area (Wise et al., 1985) and Subantarctic Atlantic (Crux, 1991). These changes clearly record the transition from relatively warmer conditions of the Eocene to distinctly cooler conditions of the Oligocene.

Eocene/Oligocene boundary:Gradual climatic deterioration

An almost continuous sequence of Late Eocene to Early Oligocene sediments were recovered at Sites 699, 701, and 703. There the Eocene/Oligocene boundary was picked on the extinction of *Hontkenina* (Nocchi et al., 1991) and of Discoaster *Saipanensis* (Wise et al., 1985). However, the Eocene/Oligocene boundary could not be placed by calcareous microfossils at the three studied sites because of drilling disturbances, incomplete recovery at Site 703, and the strong dissolution of calcareous microfossils in the Late Eocene and Early Oligocene at Sites 699 and 701 (Nocchi et al., 1991). Although the Eocene/Oligocene boundary could not be placed by calcareous microfossils, radiolarians were generally well-preserved and common throughout the Late Eocene to Early Oligocene sediment at Sites 701 and 703. This provided the opportunity to examine the Eocene/Oligocene boundary events from Leg 114.

The Eocene/Oligocene boundary appeared as one of the most important break within the Cenozoic. Dramatic changes in deep water circulation conditions near the Eocene/Oligocene boundary are inferred from a variety of paleontological and isotopic data. The most widely accepted interpretation of this major cooling event is the thermal isolation of Antarctica, the initiation and growth the Antarctic ice sheets, and the formation of cold bottom water circulation (Shackleton and Kennett, 1975 ; Benson et al., 1984).

The deep circulation event at the Eocene/Oligocene boundary was suggested to have been one component of a series of bottom water changes occurring in the Middle to Late Eocene. Recent isotopic studies have corroborated this interpretation by showing that bottom water coolings in the deep ocean occurred at different times during the Eocene (Keigwin and Keller, 1984 ; Obwerhansli and Toumarkine, 1985 ; Kennett and Stott, 1990). Surface circulation changed markedly near Eocene/Oligocene boundary as well. Biogeographic patterns of calcareous and siliceous microfossils assemblages changes across this boundary which were interpreted as reflecting a cooling of surface water (Haq and Lohmann, 1976 ; Haq et al., 1977 ; Weaver, 1983 ; Wise et al., 1985). According to Leg 36 data the number of radiolarians rapidly declined and preservation and diversity deteriorated sharply throughout the Late Eocene and Early Oligocene at DSDP site 328, near the northwest margin of Northeast Georgia Rise. DSDP Leg 71 (Weaver, 1983 ; Wise et al., 1985) data also indicated that the surface water productivities were high, and temperatures were relatively warm at Hole 511 on the Falkland Plateau during the Middle to Late Eocene, but surface and bottom waters cooled markedly during Oligocene time.

Evidence from benthic foraminifera, according to Thomas (1990), and from stable isotopes indicates that Weddell Sea may have been source of warmer deep saline waters during part of the Eocene. These waters are believed to have their origin in lower latitude. Kennett and Stott (1990) stated that the cooling near the Eocene/Oligocene boundary was responsible for the gradual displacement of these warmer waters (see Fig. 2).

Although the Eocene/Oligocene boundary is considered as a major evolutionary break within the Cenozoic, the interpretation of the increase in isotope values at this boundary is still controversial. A high-latitude cooling or a build-up of the continental ice-sheets could account for this increase. However, the controversy over the relative importance of ice buildup versus temperature decrease at the Eocene/Oligocene boundary continues despite new data and information from high-latitude drill sites. Shackleton and Kennett (1975) believed that the abrupt Early Oligocene temperature drop as representative of the formation of sea ice around the Antarctic continent and the initiation of the formation of bottom waters close to freezing. Their assumption, however, that no significant continental ice was present on Antarctica and that the enrichment in their oxygen isotope values was purely a function of temperature, has recently been reported by number of workers (Miller and Fairbanks, 1985 ; Keigwin and Keller, 1984).

As noted previously, Shackleton and Kennett (1975) interpreted the dramatic cooling in the vicinity of the Eocene/Oligocene boundary as a critical stage in the development of the psychrosphere. Their pioneering study was done on DSDP site 277 on the Campbell Plateau. Shackleton and Kennett (1975) dated the cooling event as having occurred during the Early Oligocene. However, in a more detailed study of the same section, Keigwin and Keller (1984) dated this event as having occurred across the Eocene/Oligocene boundary. As far as the question of worldwide synchroneity of this event is concerned, studies of the late 1970s have been rather ambiguous, mainly because of the sparsity of data points in rotary cored sections which, by their nature, are not ideal for making such a determination. More recent isotope studies, however, seem to support an Early Oligocene timing for the event (Oberhansli and Toumarkine, 1985 ; Miller and Fairbanks, 1985 ; Murphy and Kennett, 1986 ; Kennett and Stott, 1990).

The dominance of Late Eocene radiolarian assemblages by *Lophocyrtis* (*Cyclamoterium*) sp., *Calocyclas semipolita*, *Calocyclas* sp. A, *Eucyrtidium* sp. A and *Heliodiscus linckiaformis* is characteristics of Eocene/Oligocene boundary (Kim, 1992). This trend did not end until the Early Oligocene when radiolarians changed to lower diversity and less abundance that the Late Eocene. Thus radiolarian results from Leg 114 support the Early Oligocene data for the cooling event as suggested by Shackleton and Kennett (1975).

Oligocene Oceanographic Evolution

A wide range of parameters indicates that climate remained cool throughout the Oligocene and at no time returned to the warmer conditions that marked the Early to Middle Eocene (Kennett, 1977 ; Kennett and Stott, 1990).

A relatively well-preserved and abundant Oligocene radiolarians were observed from Sites 699,. 701, 703, and 704 (Kim, 1992). The sedimentary record of Site 701, the only Leg 114 site under the influence of Antarctic Bottom Water (AABW), differs significantly from the sites, all of which are under the influence of Circumpolar Deep Water (CPDW)(Fig. 3). Prior to formation of the gateway between the Islas Orcadas Rise and the Meteor Rise, a major impediment to bottom, deep, and intermediate water-masses exchange existed between the Antarctic and South Atlantic basins (Ciesielski et al., 1988). During the Late Cretaceous, Paleocene and Early Eocene, a system of linked bathymetric highs extended from South America to Africa and interfered with oceanic exchange. The Falkland-Agulhas ridge system remained relatively shallow through much of the Paleogene, restricting meridional deep-water exchange in a manner analogous to the Iceland-Greenland-Faeroe Ridge in the North Atlantic. During the Eocene, a breach began forming in the Falkland-Agulhas Ridge system as the Islas Orcadas Rise and Meteor Rise began rifting apart; this formed a 4,000 m deep gap by the Early Oligocene (Ciesielski et al., 1988). A thick sequence of biosiliceous muds and clays overlies the attenuated uppermost Late Eocene - Early Oligocene sequence. A significant increase in sedimentation rate during the Late Oligocene at Sites 699 and 701 is attributed partially to higher terrigenous supply by CPDW and AABW.

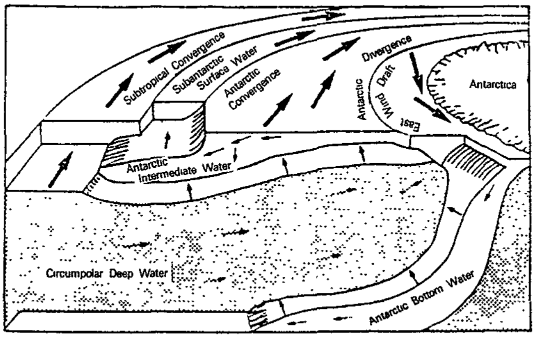


Fig. 3. Schematic cross section of major surface and subsurface water masses of the Southern Ocean (from Gordon, 1971).

Paleogene sedimentation contrasts greatly with that of Neogene in the region of the Leg 114 sites. Sedimentation was more continuous during the Paleogene, with the accumulation of calcareous nonnofossil ooze above the CCD. Below the CCD (Site 701), biosiliceous sedimentation prevailed, with only significant change in sedimentation being an increase in terrigenous clay deposition during the Middle Oligocene. Site 704 is within a zone that experienced mixed biosiliceous and calcareous productivity throughout the Oligocene, with very little influx of terrigenous sediment by currents or ice rafting (Ciesielski et al., 1988). The Meteor Rise and Islas Orcadas Rise show an apparent difference in the thickness of the Oligocene biogenic sedimentation, with a thinner sequence on the Meteor Rise. This may indicate either that the investigated part of the Meteor Rise is a slighty younger feature or that the Early Paleogene paleoceanographic regime separated the two rises into areas of different productivity.

Early/Late Oligocene boundary: Further cooling

Additional episodes of pronounced surface-water cooling occurred at or near the Early/Late Oligocene boundary, and were accompanied by the successive disappearance of Late Eocene and Early Oligocene radiolarian assemblages by *Heliodiscus linckiaformis*, *Lophocyrtis* (*Cyclampterium*) sp., and *Calocyclas semipolita* (Kim, 1992). During the Late Oligocene, the abundance of radiolarians dropped, and the diversity of the assemblages decreased (see Table 1). At Site 699, some warm-water and cosmopolitan diatom species persisted into the Early Oligocene, but they also disappeared by the Late Oligocene (Ciesielski et al., 1988). The lack of development of radiolarian diversity at this time reflects the change in climate and supports a cooling trend of the surface water.

Decrease in diversity of planktonic foraminiferal (Nocchi et al., 1991) and calcareous nannofossil assemblages (Crux, 1991) mark the early Oligocene relative to the Late Eocene. The presence of the warm-water discoaster in the Paleocene and Eocene and the subsequent absence of this form in the Oligocene also indicate a cooling trend.

The reversed oxygen isotopic gradient in the Early Oligocene interpreted by many workers to reflect the initiation of significant sea-ice formation and the beginning of thermohaline driven circulation in the ocean (Shackleton and Kennett, 1975; Miller and Fairbanks, 1985). However, the magnitude of any such ice accumulations, and hence the effect upon oceanic oxygen isotopic composition is not well known. Kennett and Stott (1990) suggested that the inferred warm, saline deep-water mass was progressively displaced upward to water depths. This could have resulted from enhanced production of cold, dense Antarctic bottom waters sinking beneath the warmer, saline water mass (see Fig. 3). Thus, the suggestion of Kennett and Stott (1960) that by the time AABW developed, or became established, may be meaningful.

Late Oligocene: Coldest interval of the Cenozoic

Siliceous biogenic sediments began to dominate, starting from the Late Oligocene, and reflect further developments of Antarctic surface waters. This change marks a further step in the long-term trend toward increasing biosiliceous sedimentation during the Neogene. Site 699 is located near the present-day Antarctic Covergence Zone (ACZ), and its sedimentary history is linked to the development of the polar front during the Cenozoic. At this site, a sharp change in sedimentation occurs just above the Oligocene/ Miocene boundary, and marks a shift from dominantly siliceous sedimentation.

The Oligocene radiolarian assemblages are of a lower-diversity and cosmopolitan distribution was replaced in the Late Oligocene by distinct belts of radiolarian assemblages arranged latitudinally. The separation of high- and low-latitude radiolarian assemblages was almost certainly caused by the development of Antarctic Circumpolar Current in the Late Oligocene.

Conclusions

The major results of this examination of the Paleogene radiolarians in Leg 114 samples are:

1) Paleoenvironmental analysis of Paleogene radiolarians has been carried out on material collected on Leg 114. The radiolarian events thus recognized during this study from the Subantarctic South Atlantic have been compared with previously reported occurrences from mid- to high-latitudes in the Southern Ocean.

2) Three major periods of paleoceanographic evolution were recognized from Paleogene sections on Leg 114. They are: a) Early/Middle Eocene boundary, b) Eocene/Oligocene boundary, and c) Late Early Oligocene. The results presented here are also compared with other microfossils data to better understand global paleoceanographic and paleoclimatic conditions during Paleogene time.

3) Relatively abundant and well-preserved radiolarians occur in Leg 114 samples for the early Late Paleocene. They contain some warm-water and cosmopolitan species. Although the overall diversity among radiolarians increased, differences among radiolarian assemblages from the Subantarctic region become more pronounced than those from lower latitudes, suggesting the presence of a latitudinal temperature gradient during the Late Paleocene.

4) Early to Middle Eocene radiolarians (Holes 698A and 702B) show high diversity and also contain some of low-latitude radiolarians, suggesting warm-water conditions in the high-latitude Southern Oceans during this interval. This warming trends persisted until the late Middle Eocene, when radiolarian diversity and abundance declined as compared to the Early Eocene.

5) The diversity and abundance of radiolarians steadily declined from late Middle Eocene to Late Eocene but remained relatively high during most of the Middle Eocene. The abundance of radiolarians declined drastically near the Middle/Late Eocene boundary.

6) Late Eocene radiolarian assemblages from Leg 114 are represented by cold-water species, and clearly record the transition from relatively warmer conditions of the Eocene to distinctly cooler conditions of the Oligocene.

7) Additional faunal changes of radiolarian assemblages occurred in the late Early Oligocene. These faunal changes are either result of a hiatus or cooling event in this interval.

8) This study suggests that the two layer (Eocene) model of Kennett and Stott (1990) either needs to be extended for the Early Oligocene to account for widespread distribution of radiolarian assemblages or, conversely, a new mechanisms should be derived to explain fossil abundances other than by land-proximal upwellings.

Acknowledgements

I would like to express my sincere appreciation to Dr. Robert M. Goll who read the manuscript and made helpful suggestion. A special thanks are extended to Dr. Bong Kyun Kim for his helpful discussion and critical review of the manuscript. I also wish to thank Dr. Hsin Yi Ling for providing sample materials on which the present investigation was carried out.

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