Paleogene Paleoceanography Workshop Report

Lowell D. Stott
and

James P. Zachos

Organizers and Convenors

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Workshop Attendees

Dr. Lowell D. Stott - Convenor
Dept. Geological Sciences
Univ. of Southern California
Los Angeles, CA 90089-0740

Dr. James Zachos - Convenor
Dept. of Geological Sciences
University of Michigan
1006 C.C. Little Bldg.
Ann Arbor, MI 48109-1063

Dr. Marie-P. Aubry
Woods Hole Oceanographic Inst.
Woods Hole, MA 02543

Dr. Enriqueta Barrera
Dept. Geological Sciences
1006 C.C. Little Bldg.
Ann Arbor, MI 48109-1063

Dr. Eric Barron
Dept. Geosciences
Pennsylvania State University
University Park, PA 16802

Dr. John Barron
U.S. Geological Survey
Menlo Park, CA 94025

Dr. Louis R. Bartek
Wiess Sch. of Nat. Sciences
Rice Univ., P. O. Box 1892
Houston, TX 77251-1892

Dr. Jack Bauldauf
ODP
1000 Discovery Dr.
College Station, TX 77845-9547

Dr. William Berggren
Woods Hole Oceanography Inst.
Woods Hole, MA 02543

Dr. Joyce R. Blueford
Math/Science Nucleus
3710 Yale Way
Fremont, CA 94538

Dr. Anne Boersma
Microclimates
Route 1, Box 405
Stoney Point, N.Y. 10980

Dr. Garrett Brass
Div. of Mar. Geology & Geophysics
University of Miami
Miami, FL 33149

Dr. Richard Corfield
Dept. Earth Sciences
University of Oxford
Parks Road, Oxford, OX1 3PR
England

Dr. Richard H. Fluegeman, Jr.
Dept. of Geology
Ball State University
Muncie, IN 47306

Dr. William W. Hay
CIRES
University of Colorado
Boulder, CO 80309-0216

Dr. Timothy Herbert
Scripps Inst. of Oceanography
La Jolla, CA 92093

Dr. Brian Huber
Dept. Paleobiology
Smithsonian Institution
Washington, D.C. 20560

Dr. Michael Kaminski
GEOMAR
Christian-Albrechts-Univer zu Kiel
West Germany

Dr. Michael Kaminski
Dept. of Geology
Dalhousie University
Halifax, NS B3H 3J5 Canada

Dr. Gerta Keller
Dept. of Geological & Geophys
Princeton University
Princeton, N.J. 08544

Dr. James P. Kennett
Marine Science Institute
University of California
Santa Barbara, CA 93106

Dr. Hsin Y Ling
Dept. of Geology
Northern Illinois Univ.
DeKalb, IL 60115-2854

Dr. Mitch Lyle
Lamont Doherty
Geological Observatory
Palisades, N.Y. 10964

Mr. Greg Mead
Dept. Geology
University of Florida
Gainesville, FL 32611

Dr. Philip A. Meyers
Dept. Geological Sciences
University of Michigan
Ann Arbor, MI 48109-1063

Dr. Kenneth Miller
Dept. Geological Sciences
Rutgers, The State Univ. of N.J
New Brunswick, M.J. 08903

Dr. Greg Mountain
Lamont Doherty
Geological Observatory
Palisades, N.Y. 10964

Dr. Catherine Nigrini
510 Papyrus Drive
La Habra Heights, CA 90631

Dr. Susan O'Connell
Dept. Earth & Envir. Sc
Wesleyan University
Middletown, CT 06457

Dr. Robert Owen
Dept. Geological Sciences
1006 C.C. Little Bldg.
Ann Arbor, MI 48109-1063

Ms. Dorothy Pak
Lamont Doherty
Geological Observatory
Palisades, N.Y. 10964

Dr. David Rea
Dept. Geological Sciences
1006 C.C. Little Bldg.
Ann Arbor, MI 48109-1063

Dr. Annika San Fillippe
Scripps Inst. Oceanography
La Holla, CA 92093-0220

Dr. Nicholas Shacketon
University of CambridgeGodwin Lab.
for Quaternay Res.
Free School Lane
Cambridge CB2 3RS England

Dr. Isabella Premoli Silva
Dipartimento de Scienze dela Terra
Universita di Milano
vis Mangiagalli 34
20133 Milano Italy

Dr. Lisa Sloan
Dept. Geological Sciences
Univ. Michigan
1006 C.C. Little Bldg.
Ann Arbor, MI 48109-1063

Dr. Ellen Thomas
Dept. of Geology & Geophysics
Kline Geology Laboratory
P. O. Box 6666
New Haven, CT 06511-8130

Ms. Carol Tang
Dept. Geological Sciences
Univ. of Southern California
Los Angeles, CA 90089-0740

Dr. Sherwood Wise
Dept. of Geology
Florida State University
Tallahassee, FL 32306

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Rationale

The recovery of high-quality Paleogene sequences by the Ocean Drilling Program over the past several years has lead to an increased interest in Paleogene Paleoceanography. This increased interest results from the intriguing, and often enigmatic, nature of data collected from Paleogene sections. The contrasts between the Paleogene and the modern climate/ocean systems are profound and limit the extent to which the Present can be viewed as a key to the Past. However, the Past may provide some key to the Future. The climate transitions that occurred during the Paleogene, and the biotic and oceanographic changes coupled with them, provide an accessible record of the environmental consequences of global warming. To access and understand that record, however, requires a coordinated interdisciplinary scientific plan. Such a plan was initiated at the Lake Arrowhead workshop in January 1991. The workshop was sponsored by JOI-USSAC.

The workshop was attended by an international contingent of scientists from varied disciplines. Most participants were currently, or had in the past, worked on some aspect of Paleogene paleoceanography and were familiar with the Deep Sea Drilling Program (DSDP) and the Ocean Drilling Program (ODP). During the three day workshop participants from a variety of disciplines were asked to summarize current data on Paleogene paleoceanography. These discussions were used to identify primary paleoceanographic questions that would form the foundation of future drilling and research proposals. Discussions centered on regions to be drilled and the types of material that should be recovered. Considerable attention was given to lessons learned by previous drilling and approaches that should be employed in the future. This included, for example, the need to multiple-core Paleogene sections in order to recover complete sections and provide enough material for high resolution sampling. The workshop participants emphasized the need to make recovery of well-preserved Paleogene sections a top priority. This involved discussions of technology requirements. These centered on the need for ODP to continue efforts to overcome the problems associated with recovery at hard-soft sediment transitions, a major problem in Paleogene paleoceangraphy. On the final day we organized the participants into subgroups to synthesize discussions and ideas into pre-proposals and specific recommendations. The following sections summarize the primary issues in Paleogene paleoceanography and present a set of site proposals and specific recommendations.

Paleogene Paleoceanographic Problems

This section summarizes the major paleoceanographic problems of the Paleogene as recognized by the 1991 Paleogene Paleoceanography workshop. Many of the problems discussed fell under one or more of the following four major categories.

I. **The Nature of the Early Eocene Warm Interval**
II. **The Nature and Timing of the Cenozoic Transition from a Greenhouse to an Ice-house World**
III. **The Global Biogeochemical Systems of the Paleogene - The Ocean/Atmosphere/Terrestrial Link**
IV. **The Nature and History of Ocean/Atmospheric Circulation Changes including its Impact on Biological Evolution**

I. Nature of the Early Eocene Warm Interval

The early Eocene represents one of the warmest periods of the last 100 m.y (e.g., Barron and Peterson, 1991). This warm interval actually consists of at least two distinct, but overlapping events which occurred on very different time scales, a long term warm episode spanning the late Paleocene to early Eocene (Shackleton and Kennett, 1975; Savin, 1977; Miller et al., 1987) and abrupt short-term event(s) (Kennett and Stott, 1991). The long-term warming initiated in the early late Paleocene, peaked in the early Eocene, and ended by early middle Eocene time, lasting 3-4 m.y . Oxygen isotopic records for this interval reveal that high latitude marine regions were substantially warmer than present day, with mean annual sea surface temperatures (SST) in excess of 15 to 17°C **(Fig. 1)** and deep ocean temperatures as high as 12°C (Stott et al., 1990; Kennett and Stott, 1990; Barrera & Huber, 1991; Wise et al., 1991; Zachos et al., 1992a) and only small temperature increase near the equator (Shackleton et al., 1984; Miller et al., 1987a).

Terrestrial fossil records also suggest warm early Eocene polar climates; high latitude biota of both hemispheres were characterized by temperate to sub-tropical fauna and flora (Wolfe, 1978; Estes and Hutchison, 1980; Axelrod, 1984; Wing et al., 1991). The distribution of clays suggest the climate in mid to high latitudes was not only warmer but also more humid (Robert, 1991). There is also evidence that atmospheric circulation was significantly weaker during the early Eocene than today (Rae et al., 1990; Hovan and Rea, 1992).

The shorter-term (~10-100ky) warm climate excursion(s) were superimposed upon the long term trend. One of these coincided with a major benthic foraminiferal extinction 'event' just before the Paleocene-Eocene boundary (Tjalsma and Lohmann, 1983; Miller et al., 1987; Thomas, 1990a, b; Kennett and Stott, 1991; Stott, in press). This short-term event was extreme in terms of global warming. Oxygen isotopic records indicate temperatures in the high latitudes and deep ocean exceeded 22° and 17°C respectively at the peak of this event **(Fig.2)** (Stott and Kennett, 1990; Kennett and Stott, 1991; Stott, in press). The temperature excursion was associated with an abrupt increase in the ^{13}C composition of marine organic matter and an elimination of vertical $\delta^{13}C$ gradients in the polar ocean (Stott, in press). This has been interpreted to reflect a drop in productivity, possibly caused by reduced upwelling and nutrient cycling in the surface ocean (Stott, in press). This warm interval has also been precisely correlated to terrestrial sequences and appears to coincide with a major evolutionary event in land mammals (Rea et al., 1990; Koch et al., in press). The origin of both the long and short-term excursions remain unknown. Several unique hypotheses have been proposed to explain the long-term warming, from increased mantle degassing related to plate reorganization (Owen and Rea, 1985) to changes in nutrient availability and oceanic productivity (Shackleton, 1986; Corfield and Shackleton, 1988; Boersma and P.-Silva, 1991). These and other hypotheses need to be more rigorously tested.

Major Questions Concerning the Early Eocene Warm Interval

(1) The early Eocene warm interval was a fundamentally different climatic regime than that of the post-Eocene world. It was a time of maximum Cenozoic warmth, the opposite climatic end member to the current ice-age. Planetary temperature gradients were significantly reduced (e.g. Shackleton and Boersma, 1981; Shackleton and Boersma, 1984; Zachos et al., in prep.), polar regions were warm (Stott et al., 1990; Barrera and Huber, 1991), atmospheric and sea-surface circulation was more sluggish (e.g. Rea et al., 1990; Hovan and Rea, 1992), and bottom water may have formed at low latitudes (e.g. Brass et al, 1982 ; Kennett and Stott, 1990). Benthic foraminiferal assemblage data suggest relatively low deep water oxygen contents (Thomas, 1990b). Quantification of these general observations into a form that can be integrated into global geochemical ocean models and Global General Circulation Models is a primary objective for future Paleogene Paleoceanographic research.

(2) The cause of the early Eocene warming is not known. General circulation models point to the importance of paleogeography on global climate patterns (Barron,

1987). Many workers have suggested that enhanced levels of pCO_2 characterized that time period (e.g., Popp et al., 1989; Berner, 1990). The abrupt short-term excursion may represent a transient response to the long term warming.

(3) Substantial debate characterizes the interpretation of Paleogene sea surface temperatures within the low latitudes. Matthews and Poore (1980) argued for stable tropical temperatures during earth history, largely based upon the idea that strong influence of temperature on evaporation rate limits changes in tropical temperature (essentially an increase in temperature would largely be compensated for by evaporative cooling). Conversely, oxygen isotopic paleotemperature data (e.g. Shackleton and Boersma, 1981) indicate substantially lower tropical temperatures in the Eocene compared with the present day. This data is not supported, however, by paleontologic evidence (e.g. Adams et al., 1990). A variety of comprehensive climate modeling studies (e.g. Barron and Washington, 1985) suggest that, although polar regions are more sensitive to climate change in external forcing factors, the low latitude SSTs can also be changed if internal processes such as oceanic heat transport are involved. Verification and quantification of low latitude sea surface temperatures and the factors that control them in the Paleogene is of primary importance.

(4) The abrupt Paleocene/Eocene boundary warming was accompanied by the largest, global, benthic extinction event of the Cenozoic, the most important benthic foraminiferal event since the Cenomanian/Turonian boundary 90 m.y. ago **(Fig.3)**. As a result, the Paleocene/Eocene boundary differs fundamentally from the Cretaceous/Tertiary Boundary, when planktonic foraminiferal groups suffered much more than the benthics. Subsequent to the extinction event at the Paleocene/Eocene boundary, the repopulation of the abyss provides the most accessible record of these evolutionary phenomena (Thomas, 1991). Significant biotic changes occurred on land, especially among the mammals which radiated at the beginning of the Eocene. Conversely, neither the benthic foraminifera nor the mammals were much affected by events of the Cretaceous/Tertiary boundary. An important evolutionary question, therefore, is why, if both benthic and terrestrial organisms undergo important events at the Paleocene/Eocene boundary, planktonic forms seem to be much less affected?

(5) The Paleocene/Eocene transition is marked by the single largest shift in oceanic carbon isotopes in the entire Cenozoic, a rapid decrease of about 2.5‰ **(Fig. 4)** (Shackleton et al., 1984; Miller et al., 1987; Stott et al., 1990; Stott, in press), an order of

magnitude increase in the flux of hydrothermal materials to the sea floor, and a significant reduction in the intensity of atmospheric circulation **(Fig. 5)** (Owen and Rea, 1985; Olivarez and Owen, 1989). These events suggest major changes in the physical/chemical state of the ocean and atmosphere that may provide clues for unraveling the cause(s) of this fundamental change in global climate.

1. Scientific Justification

The early Eocene warmth, and the possibility that it was related to greenhouse warming, provides an attractive means of validating the predictions of coupled ocean-atmosphere general circulation models that try to quantify the effects of increased oceanic heat transport or enhanced atmospheric carbon dioxide on the global climatic regime. Initial climate experiments using atmospheric circulation models (GCM) with fixed Eocene SSTs predicted high seasonality in continental interiors **(Fig. 6)**, a prediction that was in conflict with paleobotanical proxies of continental temperatures (Sloan & Barron, 1990). Such paleoclimatic tests with different sets of boundary conditions help to identify weaknesses in climate models. The tropics are the primary energy source for the ocean-atmosphere heat engine, and the nature of the tropical climate is a governing factor in the atmospheric moisture budget. The importance of the tropics in defining the behavior of the ocean-atmosphere system is clear, yet there are substantial questions as to the stability of tropical climates (Walker and Sloan, 1992). The response of the tropics to a change in climatic forcing factors, such as atmospheric carbon dioxide levels, orbital variations or changes in paleogeography, is uncertain. The climate history of low latitude oceans and their response to external perturbations pose critical questions for deciphering past climates and for predictions of future global climate change. Moreover, the Eocene oceans might have played a larger role in redistributing heat from low to high latitudes than present day oceans. Modeling studies have suggested that even small changes in oceanic heat transport might have noticeable effects on high latitude climates (Covey and Barron, 1988; Covey and Thompson, 1989). Finally, study of the early Eocene will provide insight into the relative importance of the various biogeochemical processes that control the long term chemical and climate evolution of the ocean/atmosphere system. Both observations and model studies suggest that the Paleogene provides a unique opportunity for the study of these important problems.

2. Drilling Strategy

One of the most critical issues for understanding oceanic processes during the Eocene is to establish what the meridional sea surface temperature gradients were during very different climatic conditions. For example, one unique but enigmatic finding of the first generation Eocene climate reconstructions was the oxygen isotope estimates for cooler tropical sea-surface temperatures than exist today **(Fig. 7)** (Shackleton and Boersma, 1981; Zachos et al., 1992). Warm high-latitude temperatures coupled with lower tropical temperatures can be accommodated in climate model simulations without invoking greenhouse processes by increasing meridional heat transport via the ocean/atmosphere. Thus, it will be important to determine if earlier estimates of tropical SST were accurate. The SST for high southern latitudes are currently being established through studies of samples from Legs 113, 114, 119, and 120. At present, there are no reliable data for high northern latitudes. The most promising locations for recovery of well-preserved Paleogene sediment in the northern hemisphere are in the Bering Sea and Arctic. Drilling at low latitudes must include at least two paleolatitudinal transects from the equator to 30 degrees of latitude. Multiple, double-cored sites along the transects are essential in order to define the difference between modern and Paleogene sea surface temperatures and to track changes in tropical temperatures. Single sites near the Paleogene equator will be inadequate, since the equatorial oceans probably had a substantial longitudinal temperature structure, in part reflecting tropical upwelling. At a single site isotopic temperature changes could reflect either changing proximity to tropical upwelling, changes in vapor transport, or real tropical temperature change in response to changes in the Paleogene climate. At least two transects are required if the importance of major low latitude salinity differences are to be addressed. For example, ocean model simulations indicate a major salinity difference between the Pacific and Atlantic-Tethyan areas of the Paleogene tropics (Barron and Peterson, 1991); and such predictions could be tested with the appropriate set of cores from these regions (see later section for location of sites).

The sites that would be drilled in the transects described above would also provide the necessary sequences for high resolution paleontologic, geochemical, and sedimentologic studies needed to address questions 1-5 above.

II. Nature and Timing of the Transition to an Ice-house World.

A. Late Eocene to Oligocene Climate Changes

Although the pre-Neogene history of Antarctic glaciation is still poorly understood, several lines of evidence strongly suggest that the transition from warm conditions to more glacial conditions occurred sometime in the late Paleogene. Deposits of ice-rafted debris (IRD) and diamictites have been observed in shelf and deep sea sediments as old as upper Eocene from several localities near Antarctica (see ODP volumes 119 and 120). Also, the benthic foraminifera oxygen isotope record exhibit several ubiquitous positive excursions in the late middle Eocene to earliest Oligocene, suggesting substantial increases in global continental ice-volume and global cooling **(Fig. 8)** (Shackleton and Kennett, 1975; Miller et al., 1987; Matthews and Poore, 1980). The largest of these increases occurred in the early Oligocene. In the Indian Ocean sector of the southern ocean, this oxygen isotope increase was found to correspond with an episode of ice-rafted debris deposition, indicating large scale glacial activity on the Antarctic continent **(Fig. 9)** (Zachos et al., 1992).

The relative timing of this isotopic event raises several questions concerning the transition between a non-glaciated and glaciated world. Was the event abrupt and were the ice-sheets permanent? Were the first ice-sheets wet or dry based, temperate or polar, continental or alpine? Does the early Oligocene increase in ice-volume represent some type of threshold event, in the transition from one climatic state to another? If so, what were the specific climatic conditions that triggered the change; how cold were sea surface temperatures? Did ocean circulation respond to this climatic event and if so did it provide any feedbacks? At least one high resolution oxygen isotope record reveals the presence of a distinct, but brief peak, indicating that the ice-sheet may have initially overshot its equilibrium size (Zachos et al., in press). Geochemical evidence, and stable carbon isotope ratios, indicate a substantial perturbation in the carbon cycle during the initial oxygen isotope increase. Was this a response to changes in climate and ocean circulation, and if so, was there a feed back to the carbon cycle and climate?

1. Scientific Justification

Establishing the timing and magnitude of the first large, continental ice-sheets is a high priority. Inferred sea level curves indicate that rates of Paleogene eustatic rise and fall similar to those in the Neogene, which imply a ice-volume connection. Establishing the history of Paleogene ice-sheets is thus important to understanding the nature of the sea level coastal onlap and offlap record. Recognition of the prevailing "boundary" conditions under which ice-sheets formed and/or decayed may provide a better understanding of the future stability of present day ice-sheets in the face of global warming. Although it is generally assumed that tectonics played an important role in the thermal isolation from the global ocean, and hence cooling of Antarctica (e.g. Shackleton and Kennett, 1976), it is unknown whether this mechanism alone is primarily responsible for the initiation of ice-sheet growth. The role of other climatic parameters such as atmospheric CO_2 and vapor transport by the atmosphere are not known at this time and should be examined as well. Investigation may also provide insight into the nature of abrupt climatic transitions.

2. Drilling Strategy

Drilling targets should be identified that would provide a record of ice rafted debris and glacial sedimentation. The limited number of sites in which such materials have been recovered are insufficient to determine the scale of ice sheet growth during the Paleogene. The continental margin and associated basins of Antarctic are priorty regions. Although some drilling has been conducted on the Antarctic margin (e.g. Ross Sea Drilling) the Paleogene is poorly documented.

High resolution geochemical (e.g., stable isotopic and trace element), sedimentologic, microfossil studies needed from each of the ocean basins with particular emphasis on the high latitudes. The available data is low resolution and was largely conducted on older DSDP sequences. Isotopic records are needed on single faunal species (size-specific). The benthic foraminiferal record is poorly documented across this interval and needs to be resolved to at least 25 ky to 50 ky. Trace element studies similar to that applied to Pleistocene sequences should be explored for Paleogene sequences. The use of stable isotopic and trace element techniques are currently the best approach to deciphering deep water pathways. Determination of carbonate accumulation rates is a critial component of research that addresses carbon cycling, sea level, and climate history. Stable isotopic studies of organic compounds currently afford the best opportunity to study [CO_{2aq}] in the ocean. However, this approach has not been applied at high enough resolution to the Paleogene. Application of this type of study to deep sea carbonate sequences needs to be thoroughly assessed. This is a high priority for Paleogene paleoceanography.

A coordinated project should be organized to address these issues using core material currently available and that which would be recovered from critical regions. between geochemists, stratigraphers and paleontologist .

B. <u>High frequency Variability - Milankovitch in the Paleogene</u>

Nearly every measure in pelagic sediments-calcium carbonate content (Arrhenius, 1952; Hays et al., 1969), oxygen and carbon isotopic composition of foraminifera (e.g., Raymo et al., 1990), planktonic foraminiferal species composition (McIntyre et al., 1989), eolian grain size (Janecek and Rea, 1984), and detrital chemistry (Boyle, 1983) seems to have varied at discrete frequencies during the late Pleistocene. The periodicities are statistically significant (Imbrie et al., 1984), and are closely matched to those of the major perturbations in the earth's orbit due to eccentricity (short cycle of circa 100 ky), obliquity (circa 41 ky) and precession of the equinoxes (23 and 19 ky). Much of Pleistocene climate variance on these time scales is thus somehow forced by these slight changes in insolation known collectively as "Milankovitch cycles". This finding has revolutionized Pleistocene paleoclimatology for two reasons. First, it has highlighted the need to understand feedback mechanisms to the known forcing of the insolation cycles. Second, the maxima and minima of orbital forcing recorded in sediments mark off approximately equal units of time. The periodic structure of sedimentary records thus facilitates the construction of high resolution time scales and sediment accumulation rates, as well as high precision correlation between coring locations (e.g. Martinson et al., 1987).

While there has been little attempt to document similar variations in Paleogene sediments, there is reason to believe that they may occur, and that cyclic sedimentation may have recorded the pulse of Paleogene climate in a manner similar to the Pleistocene. The last statement does not imply that the response to Milankovitch forcing is constant, after all, it seems unlikely that substantial ice sheet fluctuations occurred prior to the Oligocene. However, there are indications that carbonate sedimentation continued to oscillate at orbital frequencies in pre-Pleistocene times. Estimates of periodicities in sedimentation have been obtained in sequences with good magnetochronologic control. Precessional variations have been found in lowermost Pliocene sediments of Southern Italy and Sicily (Hiligern and Langeresis, 1988), and precessional and obliquity cycles have been documented in the Oligocene of the South Atlantic (Mead et al., 1986). Herbert and D'Hondt (1990) and Huang et al. (in press) have found precessional cycles in carbonate sedimentation in Campanian through Danian pelagic sections recovered by DSDP and ODP. Although no statistical work has been done, Paleocene to Eocene sediments drilled during Leg 113 of ODP contain striking alternations in carbonate content.

1. Scientific Justification

What can be learned from the study of high frequency oscillations in the Paleogene, and how can we record and interpret climatic changes in the Milankovitch band in such old strata? First, paleoclimatic studies should document the spectral evolution of climate at key localities (equatorial, gyres, high latitudes). Transitions in sensitivity to different components of orbital forcing may coincide with other indicators of paleoclimate , in a similar manner to the Matuyama/Brunhes shift from dominant 41 ky to 100 ky cyclicity documented by Ruddiman et al. (1986). A first order prediction is that warm climates should be dominated by low-latitude (precessional and eccentricity) forcing, while climatic cooling and the formation of ice sheets might enhance the power of the 41 ky obliquity signal. In addition, regional variations in the relative amplitude of different orbital signals might give an indication of the climatic coupling of Paleogene oceans. It seems likely that the chronostratigraphic capabilities of orbital signals can improve time-resolution at individual sites, and correlation between drilling locations. This obviously requires calibration of cyclicity within the standard magnetostratigraphic and biostratigraphic framework before the cycles can be used to answer high-resolution correlation questions. Improved chronometry should be particularly helpful in resolving time within magnetochrons. Such an approach has recently been shown to yield consistent estimates of time across the K/T boundary in magnetostratigraphically constrained DSDP sites (Herbert and D'Hondt, 1990). Core-log calibrations are necessary to help decipher stratigraphic discontinuities, particularly when core recovery is poor.

2. Drilling Strategy

(1) Paleoclimatologists and paleobiologists need to coordinate their investigations at the right scale to resolve orbital cycles. To date, stable isotope variations, color variations, fossil floral changes, and carbonate variations have been used to decipher cyclicity in older strata. It is not clear to what degree these oscillations record changes in productivity, in dissolution, or in dilution by terrigenous material. In any case, substantial climate variability during warm geologic intervals is implied. The inclusion of other aspects (quantitative measures of fossil preservation, organic matter characterization, isotopic data, grain size, and non-carbonate mineralogy/elemental chemistry) will help to shed much more light on exactly how climate responded to orbital perturbations in the Paleogene.

(2) Drilling targets should include consideration of the potential for capturing "Milankovitch" cycles in key intervals. Sites should have reasonably high (~2 cm/ky) sedimentation rates in order to capture high-frequency signals. It is important, however, to keep in mind that preservation should not always be sacrificed for high sedimentation rates. Sediments from locations with high sedimentation rates often suffer from poor preservation due to greater burial and lithification. An alternative approach is to at least triple core sites with low sedimentation rates, but good preservation, recovering separate cores for high resolution studies. Double coring is needed to insure overlap between cores. This approach is commonly used in the drilling of Neogene sequences but is seldom applied in drilling the Paleogene.

Lithologic sensitivity to climate change will be maximized by location-selective coring. Sites on the boundaries of major climatic belts, and where there is a significant source of non-carbonate material will be preferable, since high carbonate sediments are not very sensitive to changes in carbonate input or preservation (c.f., Pisias and Prell, 1985). Track records of locations with reliable magnetic stratigraphies should also be considered, and susceptibility studies of previous boreholes and piston cores of Paleogene subcrops from the region should be conducted.

III. Global Biogeochemical Systems of the Paleogene - The Terrestrial/Ocean/Atmosphere Link

An important scientific objective is to better understand the role of the ocean and its chemistry in climate change (COSOD II). The Paleogene is marked by substantial shifts in ocean chemistry as evidenced by changes in the long term records of sea water strontium isotopic (Burke et al., 1982; Hess et al., 1986; Francois and Walker, 1992; Berner and Reye, 1992), and stable carbon isotopic compositions (e.g., Shackleton, 1986), Sr/Ca ratios, (Graham et al., 1982), Li/Ca ratios (Delaney and Boyle, 1986), the level of the calcite compensation depth (CCD) (Van Andel, 1975), loci of Si deposition, and oceanic pCO_2 levels (Popp et al., 1989). Many of the large-scale marine chemical events coincide with long or short term climatic or evolutionary transitions implying some type of cause and effect relationship. Thus, given the extreme climatic states, the Paleogene may be ideal for improving our understanding of the role of biogeochemical cycles in climate change.

One important component of the earth climate system in terms of energy balance is carbon dioxide. Modeling experiments and empirical records both indicate that variations in pCO_2 may have been responsible for both long and short term climatic changes in Earth history. The levels of atmospheric CO_2 as well as other greenhouse gases (i.e., methane) are controlled by a number of factors, exchange with the ocean reservoir appear to be most influential on short time scales, while exchange with sedimentary and crustal reservoirs become important on longer time scales. Thus, to better understand the origin of paleoclimatic variability in the Paleogene it is important to 1) develop a detailed proxy record of pCO_2 and other greenhouse gases, and 2) identify the processes that changed the concentration of these gases within the ocean/atmosphere system on both short and long time scales.

A. Crustal, Ocean, and Atmospheric Interaction

Weathering of rocks on land and in the sea, and hydrothermal cycling at plate boundaries are important processes in the maintenance of ocean chemistry on long time scales (Li, 1972; Holland, 1978; Edmond et al., 1979; Delaney and Boyle, 1988). As such, these processes must be considered in the long term maintenance of ocean/atmosphere chemistry and climate.

In the past only changes in the rate of sea floor spreading were thought to effect hydrothermal circulation rates. More recently, however, plate collisions, and ridgetransform reorganizations have also been recognized as major tectonic events capable of producing changes in crustal/fluid interaction. Thus, there is a need to reevaluate their effects on hydrothermal circulation and ocean chemistry. Several prominent plate reorganizations occurred during the Paleogene. For example, data from recent ODP drilling in the Indian Ocean indicates that the greater India and Asia were already colliding by the Cretaceous/Tertiary boundary interval (Klootwijk et al., 1991). Northward movement of India continued at a rate of 18-19.5 cm/year until 55 Ma at which point the movement slowed to 4.5 cm/yr. Tectonic events throughout the Paleocene and that near the Paleocene/Eocene boundary (Chron 24) (Rona and Richardson, 1978) coeval with the period of climatic warming. Geochemical evidence of enhanced hydrothermal activity has been recorded in deep sea sections over this interval, implying a possible cause and effect relationship **(Fig. 5**). It was suggested that such activity might have resulted in increased atmospheric pCO_2 through increased mantle degassing or chemical exchange (Owen and Rea, 1985). This hypothesis and similar others can be tested by quantifying changes in ocean geochemistry (pCO2, mantle derived trace elements and isotopes) over this critical interval. Establishing a mantle-CO_2-climate link would have significant implications for interpretations of earlier warm climates (e.g. late Cretaceous super plumes) as well as reinforce certain expectations for future climate change.

Tectonic processes have an additional influence on climate by altering continental geography, by affecting planetary albedo and the locations of oceanic gateways (Frakes and Kemp, 1973; Berggren and Hollister, 1974; Barron et al., 1981; Barron, 1985). The long-term climate of the Paleogene might have been most profoundly affected by changes in plate geography and associated effects on ocean circulation and heat transport. Northward migration of Australia and South America during the Eocene and Oligocene increased the oceanic isolation of Antarctica as circumpolar circulation developed (Kennett and Shackleton, 1976), while movement of India and Africa resulted in the gradual closing of the Tethyan sea way. These continental rearrangements significantly altered pathways for surface and deep ocean circulation during the Paleogene. The climatic response to these rearrangements may have been gradual (for example cooling of the high southern latitudes), or more abrupt as critical thresholds were surpassed (formation of continental ice-sheets) (Kennett, 1977; Crowley et al., 1986). An important objective is to determine the nature of the climatic response to these gradual changes in paleogeography. The geochemical record of the ocean is also strongly influenced by the products of continental weathering (Li, 1972; Holland, 1978; Robert and Kennett, 1992). Riverine input represents the largest source of most major and minor elements found in the ocean. The rate of continental weathering is not constant; it has varied through time as a function of changes in 1) area of of changes in 1) area of continents exposed to weathering, 2) relative percentage of exposed rock types, 2) climate and rates of runoff, 3) atmospheric CO_2 levels (Berner, 1990), and 4) tectonic uplift. For example, during the late Paleogene the rate and character of continental weathering at high latitudes dramatically changed from predominantly chemical to a mixture of physical and chemical as the global climate shifted from wet and warm, to dry and cold, and as the rate of continental uplift intensified **(Fig. 10)** (e.g., Robert and Maillot, 1991; Robert and Kennett, 1992). This shift in weathering patterns might have significantly altered the overall flux of chemicals into the ocean. One strong indicator of continental weathering fluxes to the ocean, the record of seawater $^{87}Sr/^{86}Sr$ ratios, shows a significant change during the late Paleogene **(Fig. 11)** (e.g., Hess et al., 1986; Miller et al., 1991; Burke et al., 1982; Elderfield, 1986). In addition, the level of the CCD shows a dramatic drop at this time, although this record remains poorly constrained **(Fig. 12)** (Van Andel, 1975). Both these changes occurred roughly near the time that large continental ice-sheets first appear on Antarctica (Miller et al., 1987; Zachos et al., 1992).

B. Biogeochemical Cycles of the Ocean

On short time scales (10^3 yr) , the distribution of carbon on the earths surface is controlled largely by the exchange of carbon between terrestrial and marine biospheres and the ocean/atmosphere and sedimentary reservoirs. The flux of carbon between these reservoirs is controlled mainly by rates of primary production, respiration, and C-org burial. These are in turn controlled mainly by nutrient levels, sedimentation rates, dissolved oxygen concentrations and carbonate equilibria (i.e., alkalinity). Because the rate of exchange between the biosphere, ocean and atmosphere system is relatively, large and rapid changes in plant (terrestrial and marine) productivity has the capacity to affect global pCO_2.

Quantifying marine and terrestrial plant paleoproductivity, especially for the Paleogene is not a trivial task. It requires the integration of several sedimentological and geochemical proxies of production and nutrient distributions. The fluxes of carbon in paleoceans can be determined directly by measuring accumulation rates of carbon bearing components of the sediments. For carbonate this can only be achieved if the depth to which calcite is preserved in the ocean, the calcite compensation depth (CCD), is well constrained. This method of reconstructing productivity, however, is limited because it requires many measurements in both space and time to characterize changes on a global scale adequately, a nearly impossible task for Paleogene oceans for which the number of cores will always be limited. Fortunately, this method can be supplemented with other methods which attempt to balance inputs with outputs by measuring and modeling geochemical tracers and isotopes of the carbon cycle and nutrients (e.g., Shackleton, 1987; Delaney and Boyle, 1987; Lea and Boyle, 1990). For example, the carbon isotope distributions are strongly affected by the fluxes of C_{org} between the ocean and sedimentary reservoirs (Kroopnick, 1985; Miller and Fairbanks, 1985; Shackleton, 1986). For any given period of time, reconstruction of vertical and lateral carbon isotope distributions in several key locations can provide reasonable constraints on the overall rate of C_{org} production, and fluxes between surface and deep ocean reservoirs. Temporal changes in the mean isotopic composition of the ocean may reflect changes in the balance of organic carbon production and burial. With the aid of geochemical models, the various proxies of productivity can be used to examine the potential effects of paleoproductivity changes on ocean/atmosphere CO_2 levels.

Several distinct excursions are recorded in the carbon isotope record of the Paleogene (**Fig.4**), each of which occurred near or coeval with major climatic events and/or biotic turnover events such as the Paleocene/Eocene boundary. Major changes in productivity are thought to have occurred at several of these times. The largest, long-term carbon isotope excursion of the Cenozoic occurred from the mid Paleocene to early Eocene (Shackleton, 1986). Carbon isotope ratios of calcareous microfossils decreased from values of between 3 to 5°/oo in the mid to late Paleocene to values of between 0 to 1°/oo in the early Eocene. The end of this long-term isotopic change was associated with significant climate warming at high latitudes (Stott et al., 1990). Superimposed on this long-term change was the abrupt warming event near the Paleocene/Eocene boundary that was associated with a dramatic negative carbon isotopic excursion and the extinction of approximately 50% of all deep-sea benthic foraminifera (see discussion above). The close correlation between isotopic, climate, and evolutionary events suggest some type of cause and effect relationship. For example, marine productivity changes have been cited as one possible source of the long-term carbon excursion (Shackleton, 1986; Corfield and Shackleton, 1988). A reduction of productivity due to the absence of nutrients may have resulted in increased levels of pCO_2. Alternatively, enhanced hydrothermal activity associated with plate reorganization has also been cited as a potential mechanism for increasing pCO_2 (Owen and Rea, 1985; Rea et al., 1990).

Another important transition in global productivity may have occurred in the early Oligocene. The first appearance of large ice-sheets on Antarctica is marked by an abrupt increase in the mean carbon isotope composition of the ocean (Miller and Fairbanks, 1985; Zachos et al., 1992) and by a sudden increase in the accumulation rates of biogenic silica in some southern ocean locations (Barron, Larsen et al., 1991; Wise, Schlich, et al., 1992; Diester-Haass, 1991). Both changes are consistent with a rapid, but brief intensification of global oceanic productivity. The cause of this high productivity episode is uncertain; it may be related to changes in oceanic and atmospheric circulation that resulted from the sudden cooling and appearance of large ice-sheets on Antarctica (Miller and Fairbanks, 1985; Zachos et al., 1992b). At least one important question arises from this and similar problems; what effects did such an abrupt and intense episode of productivity have on oceanic and atmospheric CO_2 levels and climate?

C. The enigma of Eocene siliceous deposits and Oligocene monospecific chalks

The Paleogene is marked by brief episodes (10^3 to 10^4 yr) of widespread deposition of lower and middle Eocene siliceous deposits and monospecific chalks in the Oligocene. Although several hypotheses have been provided (e.g., McGrowan, 1991), it is still unclear what triggers these "events" and what effects, if any, the events had on the ocean biogeochemical system.

Explaining the distribution of Eocene siliceous deposits has been a matter of controversy since Leg 2 of the Deep Sea Drilling Project. At that time it was discovered that the prominent seismic reflector (Horizon A) in the North Atlantic was not the Cretaceous/Tertiary boundary as had been suggested, but was either middle Eocene chert in a siliceous sequence rich in radiolarians and diatoms, or a hiatus at which much of the Eocene was missing. The hiatus was later found to characterize the North American margin while the chert and associated siliceous deposits have been found to occur as a widespread deposit throughout the central North Atlantic and in the Caribbean. Although there are siliceous deposits in other parts of the world, a major output appears to have been in the North Atlantic. Better understanding of the spatial and temporal distribution of these deposits that will result from further calibration of seismics by additional sites penetrating Paleogene strata in the North Atlantic should allow us to discriminate between these different possible causes.

Within the deep-sea sediment record there are horizons composed of the remains of single fossil species. The most notable of these are the layers composed entirely of pentaliths of the nannofossil *Braarudosphaera rosa* that have been found in the Oligocene of the South Atlantic. These layers are a few centimeters thick, and are distributed from the Walvis Ridge to the Rio Grande Rise. Because *Braarudosphaera* occurs presently in abundance only where conditions are unsuitable for other calcareous nannoplankton, their occurrence in monospecific layers has been attributed to either unusually high or low salinity conditions, or in regions of unusually high or low productivity. Clearly, they represent an unusual condition for the open ocean, but the nature of that condition remains uncertain. The chalks were recovered mostly during the early phases of the Deep Sea Drilling Project (Leg 3), and core disturbance and incompleteness has prevented investigation of this intriguing phenomenon. Cores through the Oligocene in the central South Atlantic should provide the material required to investigate these layers and determine their origin.

1. Scientific Justification

An important objective is to understand the nature of biogeochemical cycles and their relationship to climate change. The Paleogene provides an ideal opportunity to investigate the importance of various long and short-term controls on the ocean biogeochemical system. First, the period is marked by a major a plate reorganization in the Paleocene, which may have resulted in several fold increase in hydrothermal cycling rates as evidenced by metals accumulations. Also the character and rates of weathering changed dramatically during the Eocene, from predominantly chemical to a mixture of physical and chemical, as the climate cooled and dried and the first ice-sheets appeared on Antarctica. Indirect evidence also indicates that the pCO_2 declined during the Paleogene. Moreover, several large scale changes in oceanic productivity occurred during the Paleogene, beginning with the K/T boundary extinctions, the subsequent long-term recovery during the early Paleocene, an abrupt drop in productivity near the P/E boundary, and the initial development of the highly productive regions of the Southern Ocean during the Oligocene. Characterizing the effects of these large scale biogeochemical changes during the Paleogene on ocean chemistry and global climate will require development of more quantitative records of Paleogene weathering rates, hydrothermal cycling, and productivity.

2. Drilling Strategies

Understanding the relationship between biogeochemical changes in the ocean and climate will require integration of empirical data with geochemical models (e.g. Delaney and Boyle, 1988). Before this can be achieved, however, the biogeochemical data bases upon which the chemical evolution of the ocean is determined need to be expanded. In the past, inadequate spatial and temporal coverage and poor preservation has made it difficult to place quantitative constraints on various processes and biogeochemical fluxes of Paleogene oceans, including rates of organic and inorganic carbon production and burial, weathering inputs (river and eolian), and hydrothermal cycling. Distinguishing global biogeochemical events from local phenomena, such as a change in productivity or in water mass influences, requires correlative records from different basins for comparison. For the Paleogene, only a few, discontinuous, but relatively well preserved, records are currently available from the

Pacific (Sites 77, 219, 573, 574, 577), a serious deficiency considering the Pacific comprised greater than 50% of the world ocean volume at that time. More sites are available in the other basins, certain critical regions are under-represented. The view of Paleogene oceans has been limited to two dimensions, since rarely have vertically offset sites with Paleogene material been recovered from the same region.

Ideally, to characterize paleoproductivity of the Pacific, sequences aligned along a meridional transect from 0 to 30° north and south. Ocean floor of Paleogene age meeting this requirement is now in the western and north-west Pacific. Several oceanic plateaus of the western Pacific are known to have thick sequences of Paleogene sediments, including the Ontong-Java Plateau and Magellan Rise. These plateaus are located in regions that would have been positioned just to the south of the equatorial upwelling regions during much of the Paleogene. Sequences that would have been located to the north of the ITCZ under the influence of gyre waters can be drilled on the Shatsky and Hess Rises. A similar cross equatorial transect is required in the Atlantic Ocean, from the equator into the north Atlantic Gyre. Vertical depth transects are needed in the Pacific and Indian oceans to more accurately constrain changes in the levels of the lysocline and CCD. This could be achieved by drilling multiple sites between 2000 and 4000 m paleodepth on the flank of an oceanic plateau.

A critical requirement for all geochemical studies is the recovery of well preserved sediments. Excessive burial depths lead to increased lithification and chemical overprinting of primary signals. To reach Paleogene sequences at shallow burial depths (<400 m) it will be necessary to drill in locations were Neogene sediment cover is relatively thin or where sedimentation rates have been relatively low. For the latter, temporal resolution does not have to be sacrificed if high resolution sampling of cores (~10 cm) is permitted. To this end, it is recommended that "high quality" Paleogene sequences be triple cored with logging (including geochemical logging) to get complete core recovery across core breaks and provide the necessary material for high resolution sampling.

IV. Nature, History, and Impact of Changes in Ocean/Atmospheric Circulation

Evidence exists from both empirical records and modeling experiments of at least two major modes of ocean circulation in the Paleogene. One in which salinity driven density differences were most important in deep water formation, halothermal circulation, and one similar to the present day in which temperature differences were more important in determining deep water sources, thermohaline circulation (e.g., Shackleton and Kennett, 1975; Brass et al., 1982; Shackleton and Boersma, 1981; Miller et al., 1987; Kennett and Stott, 1991). The former may have been the dominant mode of operation in the early Paleogene, with transition to the latter occurring in steps during the Oligocene and Miocene (Shackleton and Kennett, 1975; Woodruff and Savin, 1989). This remains controversial, however, as benthic foraminiferal data does not support a prolonged circulation system driven by low latitude production (e.g. Thomas, in press). North Atlantic deep water formation may have initiated in the Oligocene, although its chemical signature may have been substantially weaker. It is generally believed that intermediate deep water formation occurred off Antarctica throughout the Paleogene with the possible exception of the Paleocene/Eocene boundary interval (e.g. Kennett and Stott, 1990; Kennett and Stott, 1991; Pak and Miller, 1992; Thomas in press). This is based on the fact that at most locations deep water temperatures have more or less mimicked those of the high latitude southern Oceans over the Paleogene. At locations where vertically offset sites were drilled, however, stable isotopic evidence has been found for the existence of at least two distinct water masses in the Paleogene (**Fig.13**) (Kennett and Stott, 1991). The oxygen isotopic characteristics of the water masses indicate that the deeper water mass may have been warmer and of higher salinity, raising the possibility of low latitude source and halothermal circulation (**Fig. 14**). The existence of warm saline bottom waters would be consistent with theoretical expectations of deep water circulation on a warmer planet (Brass et al., 1981). However, at present, the spatial and vertical distribution of available sites is inadequate for reconstructing the distribution of Paleogene water masses. Furthermore, benthic foraminiferal patterns suggest that the Antarctic has always (with the brief exception of the Paleocene/Eocene Boundary) been the major source of deep water to the worlds oceans (Thomas, in press).

A better understanding of the role of the deep ocean in global heat transport and chemical distributions, and corresponding changes in atmospheric circulation requires establishing the history of deep water sources and circulation. We need to also evaluate relationships between deep-water source variations and climate changes, particularly in cases of abrupt changes, and the impact on biogeochemical systems, benthic evolution, sediment distribution (CCD, nutrient distributions, etc.).

What were the causal mechanisms of major reorganizations of the deep ocean circulation system including:

1) opening and closing of epi-continental seas
2) changing basin configurations and opening/closing of gateways (both shallow and deep)
3) climate/ocean circulation interactions
4) sea-level variations

1. Scientific Justification

Because of the complex nature of the physical dynamics of small and large scale processes in thermohaline ocean circulation, and complex interaction with the biosphere the potential response of the ocean to climate change is still poorly understood. Only through investigations of ancient oceans have we become aware of how sensitive deep ocean circulation is to minor changes in physical boundary conditions. For example, a wide variety of geochemical and paleontologic evidence from Pleistocene deep sea cores show that significant changes in deep water circulation occurred between glacials and interglacials. We are also beginning to recognize that the deep ocean may have played more than a passive role in climate change (e.g. Broecker and Denton, 1989; Boyle, 1990). The deep ocean as a large reservoir of easily exchangeable carbon has the capacity to produce significant changes in atmospheric pCO_2. To improve our ability to predict future global environmental change that might involve pCO_2 we have to understand how the ocean operated under different sets of boundary conditions.

The Paleogene oceans clearly operated under very different sets of boundary conditions, meridional temperature gradients and continental geography, than exist today. Some tantalizing hints of the mode(s) of circulation have been provided in a few isolated cases; for example, oxygen isotopic records indicate that warm saline bottom water existed at certain depths of the ocean implying halothermal circulation (Kennett and Stott, 1990). The present deep sea record of the Paleocene and Eocene is presently inadequate to verify this or to completely reconstruct the circulation patterns.

2. Drilling Strategies

The structures of ancient deep to intermediate water masses are determined by reconstructing distribution of the chemical ($\delta^{13}C$, Cd/Ca) and the physical (Temperature) characteristics of water masses including patterns of erosion and dissolution (seismic profiles and $CaCO_3$ records). The basic requirements for such reconstructions are (1) good fossil preservation and (2) adequate coverage both spatially and vertically. A first step toward obtaining well preserved samples is avoiding more deeply buried sediments that have undergone the transition to limestone. Adequate spatial coverage does not necessarily mean a large number of sites representing all depths and regions; a small number of sites located in "sensitive" regions can be very effective (near major deep water boundaries, or close to source regions). Narrow ocean gateways through which deep waters must passed are often ideal locations for monitoring the chemical and migrational history of water masses. Site selection in these locations will require consideration of erosional patterns.

Vertical depth transects should be carried out along these gateways as well as on submarine highs in regions near present day sources of deep water, the northern most Atlantic and Weddell Sea. We should also explore regions near suspected ancient sources, such as the Bering Sea, the eastern extent of the Tethyan Seaway (northern Indian Ocean). Suspected times of abrupt change in ocean circulation should be specifically targeted for high resolution studies. At least triple coring should be employed to allow for high resolution sampling.

B. The Marine Sedimentary Record of Atmospheric Circulation

1. Scientific Justification

There are two parts to the planetary heat engine, the ocean and atmosphere. Through geologic time each has transported roughly half of the total heat moved from equatorial regions to polar regions. An adequate reconstruction of the earths planetary temperature gradients and the climatic regimes correlating to those gradients requires understanding the movement of both the atmosphere and ocean. The major change in eolian grain size at the Paleocene/Eocene boundary may signify an important example of the magnitude of atmospheric heat transport changes that have occurred during the Paleogene.

Sea surface circulation is driven by the winds. Thus, the Paleogene record of atmospheric circulation should help understand changes in the geostrophic currents and in both equatorial and coastal upwelling. We need to understand whether changes in biological production are the result of more nutrients mixed or upwelled (advected) into the surface layers or the result of enhanced delivery of nutrients from the continents.

A fundamentally important aspect of Paleogene (and Neogene) climates may be what Flohn has called hemispherical asymmetry - the presence of one cold pole should drive much stronger atmospheric circulation in the southern hemisphere than in the north with all the consequences to circulation that implies (ITCZ at 10 to 15 °N, productivity bands extended well north of the equator, etc.). The flux of dust to the deep sea is a record of continental supply which to the first order is controlled by continental aridity. This aspect of the eolian record serves to link continental and marine climates, an important objective of paleoclimatologists.

2. Drilling Strategy

Understanding the changing nature of the zonal wind systems during the Paleogene in both hemispheres requires a series of site specific records that do not currently exist. Cores from these transects will be examined for the grain size and mass accumulation rate of eolian grains. Precaution must be taken to site the cores far from the confusing influence of pericontinental hemipelagic silts and clays.

Latitudinal transects on the west flank of the Mid-Atlantic ridge in both hemispheres should recover eolian grains within calcareous sediments, allowing comparison of the many paleoclimatic proxies. In the Pacific it is possible to construct a whole-ocean transect of red clay cores, five of which are either in hand or planned for the 1991-92 drilling schedule. Two additional sites, one at the equator and one south of about 35° South would complete this transect. The envisioned Pacific transect would cover about 90 degrees of latitude and provide evidence on all the above questions. Recent efforts to construct zonations based on agglutinated benthic foraminifera give promise of a stratigraphy greatly improved over the current ichthyolith stratigraphies. Red clay cores can be recovered by APC, requiring only two or three days per site. All sites should be multiple piston cored, with attention paid to off setting the inter core breaks in order to recover truly complete sections. Although these records will provide a low resolution record because of the low sedimentation rates, they will provide a critical component to paleoceanographic reconstructions.

Regional Targets

The scientific questions recognized by the workshop attendees as having the highest priority have been grouped into three regional drilling targets. Each region is recognized on the basis of:
1) relevance to specific Paleogene paleoceanographic problems;
2) availability of existing data that indicates occurrence and preservational state of Paleogene sediments is appropriate for future drilling.

Within each regional target at least one major question outlined in the previous section would be addressed. With each regional target we have identified a specific drilling strategy and made recommendations concerning the scientific information that can be obtained. Three categories are included 1) drilling Legs that are already scheduled; 2) Legs that have been officially proposed; and 3) "Idea" targets (no existing proposal)
The primary targets are:

1) **Equatorial Oceans**
Scheduled Legs
A. Hess and Shatsky (Leg 145) Rises
Proposed Legs
A. Ceara Rise
"Ideas"
A. Western N. Atlantic transect along 60 million year old ridge crest.

2) **Southern High Latitude Oceans**
"Idea"
A. Maud Rise
B. Agulhas Plateau
C. Gunnerus Plateau

3) **North High Latitudes**
Scheduled Legs
B. Arctic Gateways/North Atlantic (Leg 151)
"Ideas"
A. Bering Sea

1) Equatorial Oceans (Atlantic and Pacific)

Priority Questions:

1) Nature of early Eocene Warming

2) Global Biogeochemical Cycles

3) Nature, History, and Impact of Changes in Deep Water Circulation

Rationale

The tropics are the primary energy source for the ocean-atmosphere heat engine, and the nature of the tropical climate is a governing factor in the atmospheric moisture budget. The importance of the tropics in defining the behavior of the ocean-atmosphere system is clear, yet there are substantial questions as to the stability of tropical climates. Specifically, whether the tropics have experienced significantly different temperatures during the Paleogene. The response of the tropics to a change in climatic forcing factors, such as atmospheric carbon dioxide levels, orbital variations or changes in paleogeography, is uncertain. The climate history of low latitude oceans and their response to external perturbations pose critical questions for deciphering past climates and for predictions of future global climate change. Both observations and model studies suggest that the Paleogene provides a unique opportunity for the study of this important problem.

Scientific Justification

Substantial debate characterizes the interpretation of Paleogene SSTs within the low latitudes. Matthews and Poore (1980) argued for stable tropical temperatures during earth history, largely supported by the suggestion that the strong influence of temperature on evaporation rate limits changes in tropical temperature (essentially an increase in temperature would largely be compensated for by evaporative cooling). Conversely, oxygen isotopic paleotemperature data (e.g., Shackleton and Boersma, 1981) indicate substantially cooler tropical temperatures in the Eocene compared with the present day while biotic evidence does not (Adams et al., 1990). A variety of comprehensive climate model studies (e.g. Barron and Washington, 1985) suggest that low latitude temperatures are sensitive to climate forcing by atmospheric carbon dioxide concentration changes. Complicating the interpretation of equatorial sea surface temperatures is the possibility that evaporation/precipitation patterns have varied over time which would in turn have influenced the isotopic composition of sea surface waters. influenced the isotopic influenced the isotopic composition of sea surface waters. For example, Broecker (1989) used variations in the oxygen isotopic gradient of low latitude planktonic foraminifera to argue that the Atlantic to Pacific salinity gradient was significantly different during the last glacial maximum compared to today.

Four key issues arise from the uncertainty associated with the climate history of low latitude Paleogene oceans:

(1) Tropical sea surface temperatures, through the importance of latent heating, are critical in defining the strength of the atmospheric circulation and the ocean wind-driven surface circulation. The intensity of atmospheric circulation is governed, not by the surface equator-to-pole temperature gradient, but by the vertically integrated equator-to-pole temperature gradient (e.g. Barron and Washington, 1982). Because of the strong, non linear relation between temperature and saturation vapor pressure, a small increase in tropical sea surface temperature can result in a substantial increase in evaporative flux which heats the tropical atmosphere. This increased condensational heating of the tropical atmosphere can result in a strong vertically integrated meridional temperature gradient in the atmosphere even when polar surface temperatures increase by many degrees (i.e., even when the surface meridional temperature gradient decreases with respect to the present day). Cooler tropical temperatures would have the opposite effect. Therefore, a Paleogene climate characterized by warmer polar temperatures and lower topical sea surface temperatures relative to the present day would have a substantially weakened atmospheric circulation and wind-driven ocean surface circulation. The uncertainty concerning Paleogene tropical ocean surface temperatures is a major barrier to understanding the behavior of the ocean-atmosphere system.

(2) The available Paleogene paleoclimatic and paleoceanographic data presents a number of apparent conflicts (Barron, 1987). Lower tropical temperatures produce a weaker atmospheric circulation (e.g. Sloan and Barron, 1990) and this interpretation is supported by the smaller size of eolian deep-sea sediments (Rea et al., 1990; Hovan and Rea, 1992) However, the interpretations of warmth within continental interiors from floral data (e.g. MacGinitie, 1974) would appear to support a more intense atmospheric circulation in order to maintain warmth during low winter sunlight conditions. In addition, larger foraminifera and hermatypic corals in the Paleogene tropics may support an

interpretation of warmer rather than cooler tropical temperatures (Adams et al., 1990). Lower tropical temperatures with higher polar temperatures suggests a larger poleward heat transport. If the atmospheric circulation was weaker, the requirement for greater poleward heat transport is enigmatic unless the oceans played a larger role in Paleogene poleward heat transport. Both the nature of the atmospheric circulation and the role of the ocean will govern the characteristics of upwelling, high productivity and silica deposition. Interestingly, the widespread occurrence of Eocene cherts is a unique characteristic of the Paleogene. A better record of low latitude climatic conditions is essential to resolve these conflicts and to determine the potential for the oceans to have a larger role in poleward heat transport.

(3) The Paleogene continental geometries, with large and sometimes restricted oceans within the subtropical arid zone, should have promoted significant low latitude salinity differences. These salinity differences may influenced the characteristics and distributions of tropical organisms and the interpretations of oxygen isotopic paleotemperatures. These factors may be critical in solving the conflicts presented in item (2) above.

(4) Brass et al. (1982) argued from physical principles that deep water can form within the subtropics (warm and saline waters). The source and strength of deep water formation can have a substantial influence on the distribution and character of benthic organisms and on the nature of geochemical properties of the sediments. At present, the large extinctions of benthic foraminifera at the Paleocene-Eocene boundary (Thomas, 1989; 1990; 1991) and the isotopic profiles from high southern latitudes (Stott and Kennett, 1989) have provoked substantial debate as to whether the boundary marks a transition to a low latitude deep water source. Ocean General Circulation Model studies (Barron and Peterson, 1991) also support the possibility of low latitude Eocene deep water source in eastern Tethys during the Eocene. The effect such circulation changes would have had on deep sea dissolved oxygen levels remains an important question (Herbert and Sarmiento, 1991). The fact that sufficient oxygen levels in the deep ocean to avoid anoxia remains and important question Greater study of the low latitude record is required to address the mechanisms of deep water formation in the Paleogene oceans.

The importance of these scientific issues is strong justification for a focused drilling program to recover a more comprehensive view of Paleogene low-latitude oceans.

A focused drilling program must include at least two latitudinal transects from the equator to 30 degrees of latitude. Multiple, triple-cored sites along the transects are essential in order to define the difference between modern and Paleogene sea surface temperatures and to track changes in tropical temperatures. Single sites near the Paleogene equator will be inadequate since the equatorial oceans have substantial latitudinal temperature structure, in part reflecting tropical upwelling. Isotopic temperature changes could thus reflect either changing proximity to tropical upwelling or real tropical temperature change in response to changes in the Paleogene climate. At least two transects are required if the importance of major low latitude salinity differences are to be addressed. Ocean model simulations indicate major salinity difference between the Pacific and Atlantic-Tethyan areas of the Paleogene tropics. Three drilling goals are proposed:

Site Proposal

A North-South transect from 30 degrees North to 30 degrees South paleolatitude in the Western and Central Pacific is proposed with a coring strategy dense enough to distinguish the equatorial temperature structure and the limits of the Hadley circulation throughout the Paleogene.

Locations: **(1) Hess Rise** and **Shatsky Rise**, presently located within the northwestern Pacific both contain low latitude Paleogene carbonate sequences that are shallowly buried (<100 meters). Their backtracked paleolatitudes place them in close proximity to the central north equatorial belt during the early Paleogene. **(2)** The **Magellan Rise,** presently in western north equatorial Pacific, has a back tracked Eocene position near the central south equatorial Pacific.

These rises have been drilled previously by the DSDP. Shatsky Rise was also drilled by the ODP with advanced drilling technology. The recovered sequences at both locations are marked by hiatuses that currently limit the stratigraphic continuity of the critical low latitude records. There is an obvious need to fill these hiatuses. This will require drilling in multiple locations on the rises. It will also require detailed seismic studies. Together these rises could provide an important component of an equatorial Pacific transect. The working group considers these locations as high priority sites for future drilling.

Strategy : Multiple drill hole strategy using the APC will be necessary at **Shatsky, Hess (Leg 145)**, and **Magellan Rise** in order to complete composite sections. Significant hiatuses in the upper lower and middle Eocene of Sites 47.2/577 and 167 can possibly be filled at various locations on these rises. Additionally, it is imperative that a bathymetric profile from approximately 2000 to 4000 meters be obtained in the North Pacific in order to ascertain the changes in the North Pacific CCD record. All paleoceanographic tracer studies associated with this proposal will require well preserved biogenic carbonates. The sequences at Hess and Shatsky are ideal in this regard due to shallow burial.

Deeply buried targets likely to be recovered on **guyots** and **atolls (Legs 143, 144)** inappropriate for tracer studies. 'Windows' to the Paleogene beneath thin Neogene cover are a critical priority.

Site Proposal A North-South transect from 30 degrees North into Southern Hemisphere paleolatitudes in the western Atlantic is proposed with a coring strategy dense enough to distinguish the equatorial temperature structure and the limits of the Hadley circulation throughout the Paleogene. This transect should include the region of predicted high surface water salinities located at low-latitudes. In conjunction with the western Pacific transect, the Atlantic transect will provide samples from distinctly different salinity regimes.

Locations: (1) Western North Atlantic sites following the **paleo-ridge crest along the 60 million year old crust line** in order to recover sediments above the CCD, avoid cherts and avoid early slumping and turbidites. Locations for possible drilling along the paleoridge crest require detailed site surveys for evaluation.

(2) Ceara Rise (Proposed), an aseismic high located between about 4 to 6oN in the western equatorial Atlantic lies at a critical juncture between the northern and southern Atlantic oceans on the western boundary. Today northern and southern deep water masses (NADW and AABW) mix at about 4000m depth, producing the waters that flow into the eastern Atlantic, and ultimately into the Indian and Pacific Oceans. Together with deep water sites located in "end member" locations it is possible to reconstruct the relative contributions of different source regions using stable isotopic, trace element and faunal and floral approaches (e.g. Northern and Southern components). Triple-coring using the APC is highly desirable.

Strategy: Previously recovered Paleogene biogenic sediments on Ceara Rise are composed of foram-nannofossil chalk and marly chalk, because deep burial below as much as 550m Neogene. Hence, it is necessary locate shallow "windows" to the Paleogene in order to obtain unaltered sections. A Site survey is critical in this regard.

Site Proposal The most logical site for hypothesized low-latitude deep water formation within the Paleogene is the restricted portions of the Eastern Tethys (between India, Asia and Arabia). Direct sites to interpret water mass characteristics at this location are not available. The closest site to a logical direction of water mass flow from the eastern Tethys is the Somalia Basin. Paleogene deep-water formation could be an important secondary objective if a deep hole is proposed in the Somalia Basin.

Location: Somalia Basin ("Idea")

Strategy: Drill along a bathymetric transect using the APC. Windows must be sought to access Paleogene sediments that have not been too deeply buried.

Southern High Latitudes

Rationale

The long-term pattern of Cenozoic climate change in the high southern latitudes has been documented from recent isotopic studies of sequences recovered by the Ocean Drilling Program at Maud Rise (Weddell Sea) and Kerguelen Plateau (southern Indian Ocean). The climate record from these two locations illustrates the sensitivity of the high latitudes to climate change. For example, the long term pattern of global cooling that characterized the late Paleogene did not proceed uniformly but is now known to have been marked by discrete and sudden periods of cooling and warming that may have originated in the polar regions, particularly Antarctica (Stott et al., 1990; Kennett, 1990; Barrera and Huber, 1991; Zachos et al., 1992). These changes in temperature influenced all of the oceans via the communication network of deep water circulation. There remains considerable uncertainty, however, about the relative importance of Antarctic bottom water on global deep water circulation throughout the Cenozoic. At present, too few records are available, particularly from bathymetric transects within the Southern Ocean to fully evaluate the questions concerning the water masses sources and their influence on global climate, heat budgets, circulation, and biogeochemical cycles.

The highest priority questions concerning the high southern latitudes as defined by the Paleogene working group are:

I: Global Biogeochemical Cycles

1) What was the role of the Southern Ocean in global biogeochemical cycling prior to the full development of the Circum Antarctic Circulation system?

2) What was the record of carbonate and silica deposition and dissolution throughout the Southern Ocean during the Paleogene?

II: Nature, history and impact of changes in deep water circulation

3) What were the primary sources of deep water during the Paleogene? Was the Southern Ocean the primary and high latitude source or was there a northern Atlantic source of deep water? Did a mid latitude (Tethyan) source contribute to deep water circulation during the Paleogene? Did different water masses dominate the deep oceans at various times?

III.: Nature of Early Eocene warmth

Site Proposal: Maud Rise "Idea"

This aseismic rise located at approximately 65°S is currently the highest latitude site which has provided a detailed carbonate Paleogene record for the Southern Ocean . Leg 113 drilled two sites on the rise separated by approximately 1000 meters of water. The deepest of the two sites was at 2914m. Both sites contain calcareous nannofossil ooze and chalk spanning the Paleogene except for the Oligocene when siliceous biogenic sediments become progressively more abundant. Together the records may provide an essentially complete composite section for the Paleogene. Seismic profiles indicate the occurrence of thick Cenozoic and upper Mesozoic sediments across the rise. Hence, it would be advantageous to add to the bathymetric profile begun by Leg 113 into deeper and into shallower levels in order to better define the vertical gradient patterns indicated by existing stable isotopic records (Kennett and Stott, 1991).

Strategy: To drill addition sites along a bathymetric transect using the APC. Double and triple cores should be taken at each depth in order to provide materials for high resolution, multiple tracer analyses. The sites should extend the range of water depth intersected by Leg 113 sites, including shallow (<1000 meters) and deeper (>3000 meters).

Site Proposal: Agulhas Plateau "Idea"

During the Paleogene the Algulhas Plateau was situated between 40° and 50° south paleolatitude, southeast of the southern tip of Africa. It is an aseismic, intermediate depth plateau that has not been drilled previously, due in part to political problems that may be close to being resolved. The predominant sediment type is carbonate. Sediments of Cretaceous, Paleocene, Eocene, Oligocene and younger have been recovered from 25

Lamont-Doherty piston cores, with the oldest record dating to the Cenomanian. The subantarctic setting of this plateau provides the opportunity to address a number of the paleoclimatic, paleoceanographic and tectonic issue recognized in the above section. However, existing piston cores from the Agulhas Plateau contain numerous hiatuses suggesting that the Agulhas Current has actively scoured the surface of the plateau. Site surveys are critical to evaluation of potential sites for future ODP drilling. Given the critical location of the plateau in relation to southern hemisphere paleoceanography a site survey is considered a high priority.

Strategy: A bathymetric transect approach should be adopted to:

a) intersect potential intermediate to deep water masses .

b) SST records from this region in order to define the evolution of thermal gradients in the Paleogene and the influence of the Agulhas current in relation the path of return flow of the upper limb of the thermohaline circulation system.

c) recover a CCD and hiatus history of subantarctic deep water

Site Proposal: Gunnerus Ridge

Gunnerus Ridge is a linear feature that projects northwards from the East Antarctic margin between 68° and 65°S. It is thought to represent a finger-like extension of continental crust that remained after India/Sri Lanka was rifted away from the Antarctic margin to the east. As this is an old feature, it may yield Mesozoic as well as Cenozoic sediments. The Kainan Maru Seamounts lie just north of the nose of the ridge. the configuration of these features allows a latitudinal transect to be drilled across the Antarctic margin for over 3 degrees of latitude from the nearshore to the far offshore. Climate modeling studies indicate that the earliest record of glacial activity may be obtained along this margin. It is possible that a pelagic carbonate record similar to that recovered from Maud Rise could be obtained, especially along the northern portion of the feature.

Information available for this area includes MCS, high resolution seismic, and piston core data which will be published shortly by the BGR Alfred-Wegner-Institute in the cruise report for "Polarstern" Cruise ANT-VIII/6. There is one North-South seismic line and two crossing lines which cover the feature, with piston cores sited along the seismic lines. The sedimentary cover over much of the ridge and the seamounts ranges between 300 and 800 m thick, sufficient for drilling. These cores indicate the presence of a Quaternary foraminiferal ooze or mud over most of the region, below which Neogene sediments are predominantly diatomaceous muds, clays, or oozes. The only Paleogene core is from the Kainan Maru Seamounts, and contains upper Oligocene diatomaceous ooze and diatomaceous mud (water depth = 2224m). Cores from the northern Gunnerus Ridge were taken in water depths between 1100 and 1300 meters.

The results of drilling the Paleogene on Maud Rise demonstrated the dramatic change in biogenic sedimentation across the Eocene/Oligocene boundary as carbonate deposition gave way to diatomaceous sediments. The pursuit of carbonates records from Gunnerus should not be precluded by the lack of recovery of carbonates in piston cores that only reached the upper Oligocene.

Strategy: Up to four sites could be drilled along the transect, beginning with one or more on the Kainan Maru Seamounts, which are isolated from the margin and which should yield sequences with the most pelagic sediment and the highest carbonate content. If possible, a depth transect along the Kainan Maru seamounts would be desirable if Paleogene carbonate sediments are encountered and exist on the flanks as well as on the higher elevations of the feature.

Expected Results from southern high latitude drilling:

The limited number of existing drill cores from the high southern latitudes has provided an important component to reconstructions of temperature gradients, biogeographic gradients, and potential deep water source changes in the Paleogene. However, the available cores fall short of providing the depth and geographic coverage needed to answer outstanding questions. It is expected that with additional drilling at sites outlined above:

1) it will be possible to determine when the gateway opened between the Indian, Pacific and Atlantic Oceans and the exchange of deep waters between the three major ocean basins began.

2) it will be possible to determine if low latitude-derived water masses contributed to ocean circulation and to geochemical cycling within the oceans.

3) the drilling gap between 40 and 70 degrees south in the southern hemisphere will be filled. This gap precludes the completion of climate reconstructions that attempt to understand how latitudinal temperature gradients varied in the Paleogene.

4) information will be obtained that will establish when major Antarctic ice sheets originated and provide a more complete record of ice sheet expansion and retreat. This information is needed in order to understand the relationship between continental breakup,

circulation changes and the climatic transition from a 'greenhouse' climate to a 'ice house' climate in the middle to late Paleogene.

5) information will be obtained that will allow researchers to understand if and how faunal and floral evolution in the high latitudes was related to the long term and/or short term climate changes?

Northern High Latitude Oceans

Rationale

Where as the high southern latitudes have now been drilled by the Ocean Drilling Program, the high northern latitude oceans remain unstudied from deep drilled records. These regions provide a similarly sensitive record of climate and paleoceanographic change to that of the southern high latitudes and played a unique role in the evolution of deep water production and geochemical cycling within the oceans. Much of the Cretaceous and Paleogene record of the north Pacific Ocean has been subducted. Remainders of Paleogene sediments are of lower latitude origin (i.e. Hess and Shatsky Rise).This severely limits reconstructions of ancient deep water formation and circulation, distribution of nutrients and nutrient cycling and the relationship between northern and southern hemisphere biotic evolutionary patterns.

In the North Atlantic a similar void exists in the Paleogene sediment record, particularly with respect to the origins of northern component deep water formation. For this reason the working group considers regions of the North Atlantic, Arctic Ocean and the Bering Sea in the North Pacific Sector two of the highest priority locations for future drilling to address Paleogene paleoceanographic questions.

The highest priority questions to be addressed by high northern latitude drilling are:

I. <u>Nature, History, and Impact of Changes in Deep Water Circulation</u>

Site Proposal :<u>North Atlantic Arctic Gateways</u>

Within the context of existing proposals and approved legs to drill in the North Atlantic (Joides Journal XVII, N2) the working group recognizes and supports the scientific objectives already setforth. All three of the major objectives of North Atlantic drilling are considered relevant to priority issues in Paleogene paleoceanography described above. These include:

1) understanding deep water circulation patterns in a warm ocean, and

2) studying the mechanisms of climatic change in a predominantly ice-free climatic system.

Site Proposal: Bering Sea **"Idea"**

The Bering Sea plays an important role in controlling the circulation and water masses of the North Pacific and Arctic Oceans. North Pacific water enters through the eastern island passes and diverges, part of it flowing northward across the shelf and into the Chukchi Sea and part around the deep basin in a cyclonic gyre, exiting through the far western pass. In the course of flow, the water is greatly modified by continuous upwelling and continental runoff, so that surface water leaving the Bering Sea is colder, fresher, and richer in nutrients that entry water. Annual formation of sea ice on the Bering and Chukchi shelves produces dense brines which, in the latter case, result in generation of Arctic Deep Water. The Bering Sea, is the Pacific compliment of the North Atlantic. Climate changes in this region over time may have had a major impact upon surface and deep circulation of the North Pacific and Arctic oceans.

The Bering Sea contains a unique record of the Cretaceous and Paleogene marine sedimentation for the North Pacific, a region devoid of detailed paleoceanographic information. Dredges and sediments recovered in COST wells on the Bering slope and shelf contain Paleogene calcareous microfossils. A transition from calcareous to siliceous biogenic sedimentation is not precisely known but is likely to have occurred in the Miocene.

Two Sites are proposed within the Bering Sea. One lies on the Sounder Ridge, the other on Shirshov Ridge.

Strategy: Sounder Ridge **(Proposed)**

Sounder Ridge is covered by Neogene turbidites that may be 300 meters thick. Below the turbidites the section is believed to be composed on pelagic sediments containing Oligocene through Paleocene biogenic carbonates. Regions in which the Neogene sediment cover is thinnest are the most desirable locations in order to obtain well preserved carbonates for tracer studies. There is no seismic evidence of a diagenetic front, so that preservation may be quite good. Hiatuses may occur, as is universally true for basin highs. The preferred site is located in a promising small basin atop the ridge.

Sounder Ridge have been completely mapped with GLORIA side-scan sonar and both SCS and MCS lines. No further survey data is required.

Specific Recommendations

The Paleogene paleoceanography working group submits the following recommendations:

1) Stratigraphic Resolution. Paleogene paleoceanographic research is now emphasizing higher stratigraphic resolution. Allowance should be made by ODP to accommodate the need for more sample material than is currently allowed. Sampling at high resolution should be done after the Leg and at the core repository.

The Paleogene paleoceanographic community recognizes the need to conduct multidisciplinary analyses on the same samples in order to maximize available material and provide more precise intercomparisons.

Drilling strategies for Paleogene targets should emphasize multiple piston coring for sites that will provide:

a) high resolution information and therefore, require high density sampling of multiple holes

b) improve stratigraphic recovery by overlapping cores.

Detailed seismic surveys will be required to adequately identify Paleogene targets and stratigraphic thicknesses.

2) Preservational quality. Preservation is of the highest priority in recovering Paleogene sequences. Deeply buried sequences are of little value in tracer studies and should not be given priority. The working group recommends that on drilling Legs that include both Neogene and Paleogene targets specific accommodation be made to identify optimal sites for recovery of Paleogene through thinner Neogene sequences.

3) Technology and Equipment.

One of the major obstacles to recoverying complete Paleogene and older sequences is the hard-soft alternations that inhibit core recovery. Chert horizons are the most problematic in this regard. A high priority is to continue engineering and development of technologies that can overcome this problem.

Logging of holes, especially with geochemical logging tool is critical to the next generation of high resolution Paleogene paleoceanographic research. This will provide another independent high-frequency data set. The multisensor track (MST) should be used on split cores as soon as feasible. Color scanning equipment on board the drill ship for continuous color records is considered to be an important addition to existing capabilities. Measurement of magnetic susceptibility should be conducted continuously.

One of the most important ship-board additions should include software for micropaleontological data bases together with a reference slide collection for the major microfossils groups (foraminifera, nannofossils, diatoms and radiolaria).

Paleogene Priority Targets

The priority issues outlined above can be addressed through a multidisciplinary approach and with the acquisition of complete, well-preserved sequences from key regions. Within the context of the priority issues and the projected Planning Committee's long range plan for ocean drilling the following represent the highest priority Paleogene paleoceanography targets as identified by the working group.

1) Lower through middle Eocene sediments. The late early through late middle Eocene is poorly represented in the core archives and represents the highest priority to address the questions outlined above. Complete records through this interval are needed in order to address the questions of deep water circulation/formation and the nature of the Greenhouse world during the Eocene.

2) The Paleocene/Eocene boundary. This boundary represents one of the largest deep-sea biotic turnovers associated with large-scale climatic and oceanographic events during the Cenozoic. To address the cause of the event and assess requires additional geographic and bathymetric coverage.
3) Low latitude (equatorial) sites in the Atlantic and Pacific

Within the context of the Planning Committees 5 year plan for ocean drilling, the Paleogene Working Group submits the following list of Paleogene priority sites

1) Atolls and Guyots

through April 1994

2) Arctic Gateways/ North Atlantic
3) Ceara Rise
4) Equatorial transect 0-30^{o}N along the paleoridge crest

to April 1995 (Atlantic and adjacent seas to eastern Pacific)

5) Maud Rise, Antarctic Ocean
6) Agulhas Plateau, South Atlantic
6) Gunnerus Ridge, Antarctic Ocean
7) Magellan Rise, Pacific
8) Shatsky and/or Hess Rise, North Pacific

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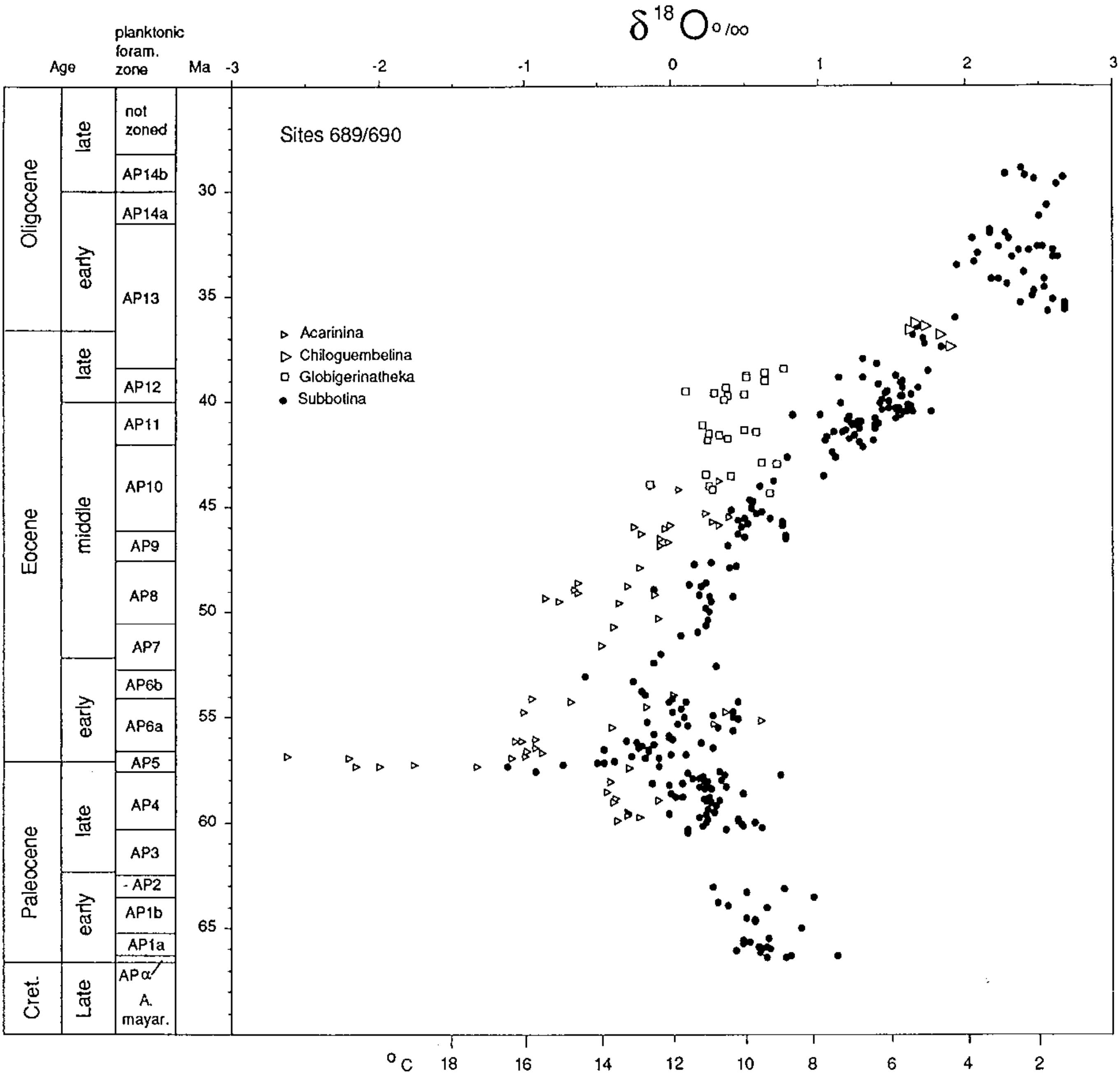


Figure 1 Composite Paleogene oxygen isotope and paleotemperature record of planktonic foraminifers for ODP Sites 689 and 690 on Maud Rise in the South Atlantic (Stott et al., 1991).

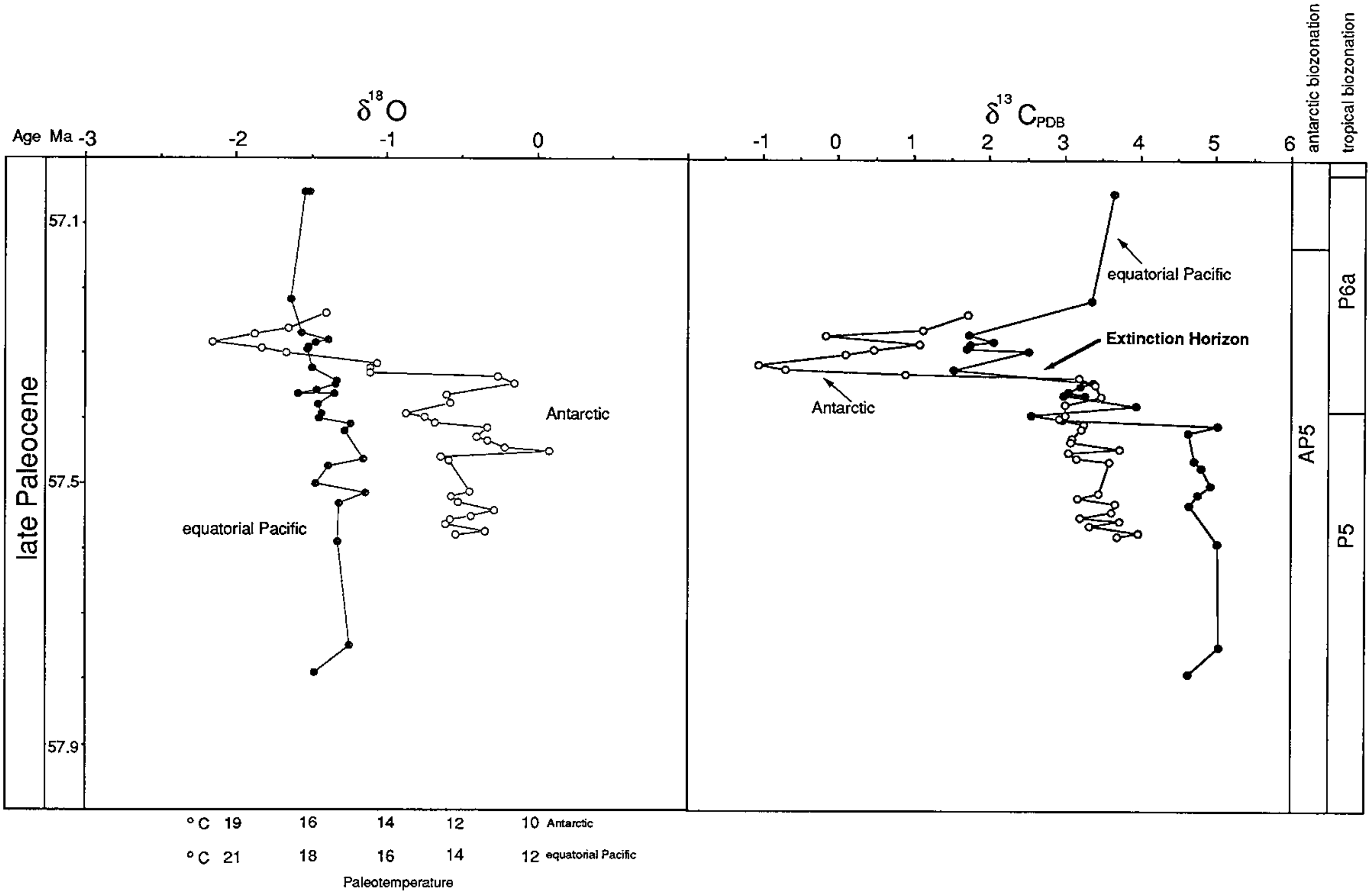


Figure 2 Oxygen and carbon isotopic composition of surface-dwelling (*Morozovella*) planktonic foraminifera from equatorial DSDP site 47.2 and Antarctic ODP site 690. Note the temperature scale at the bottom. During the Paleocene/Eocene boundary 'event' the high latitude surface temperatures increased to approximately 22°C, producing an essentially isothermal surface ocean (from Stott, in press).

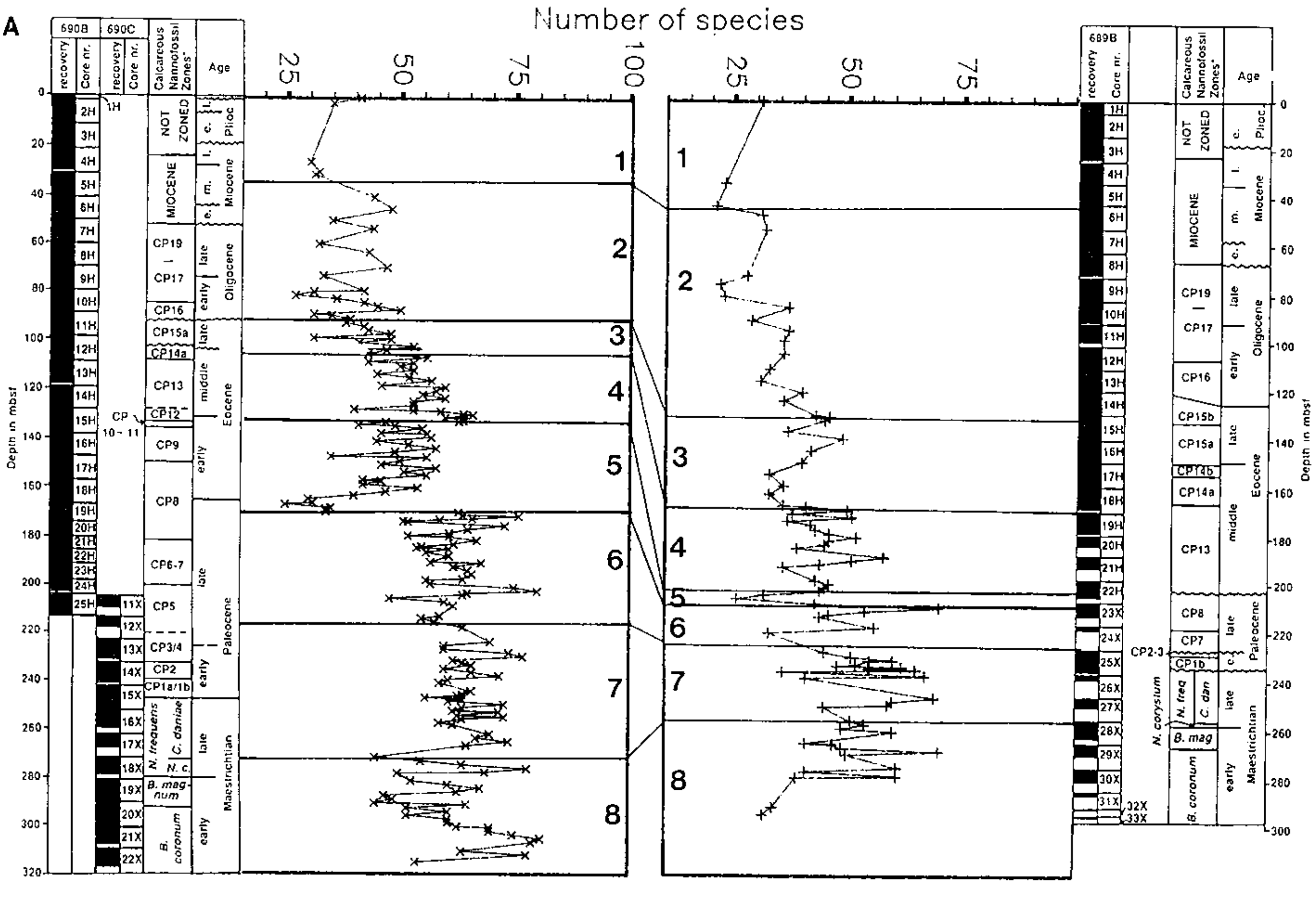


Figure 3 Number of benthic foraminiferal species present in samples from Sites 690 and 689 Maud Rise (Thomas, 1991). The largest decrease in species diversity of the Paleogene is recorded just below the Paleocene-Eocene boundary.

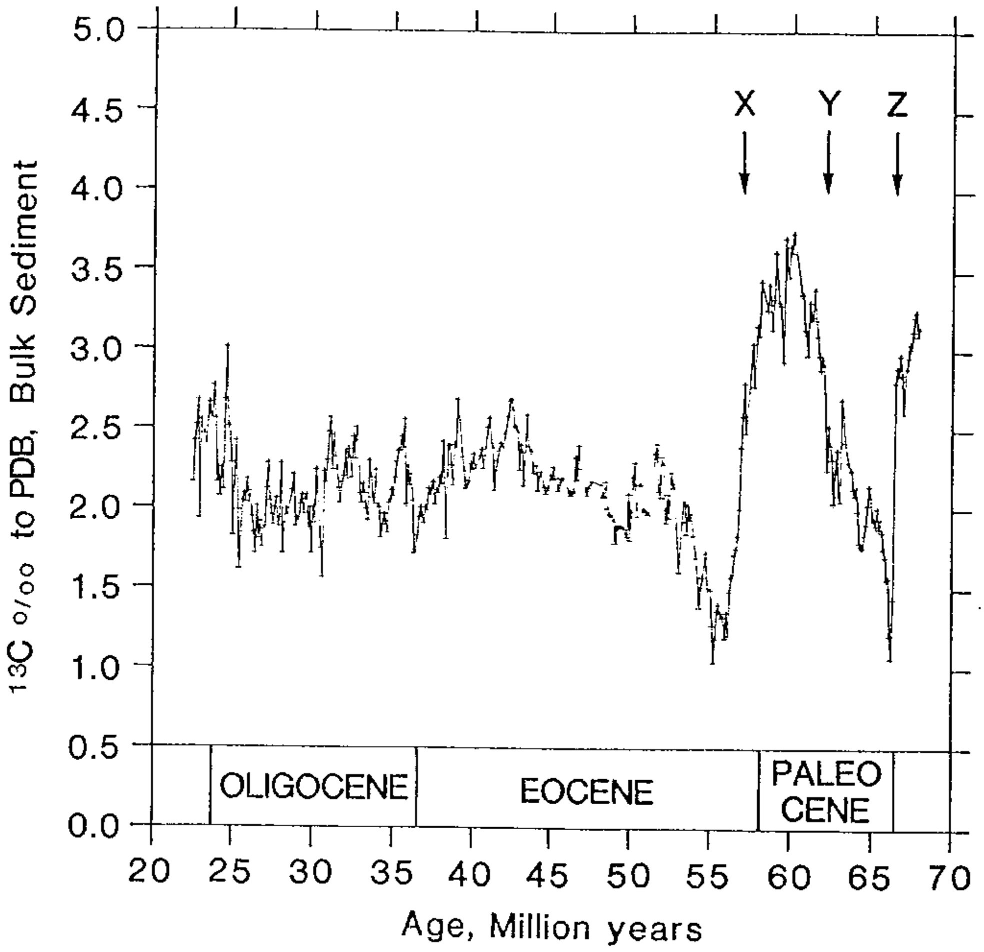


Figure 4 Paleogene carbon isotope record for bulk sediment from DSDP sites 522, 523, 525, 527, 528, and 529 (Shackleton, 1986).

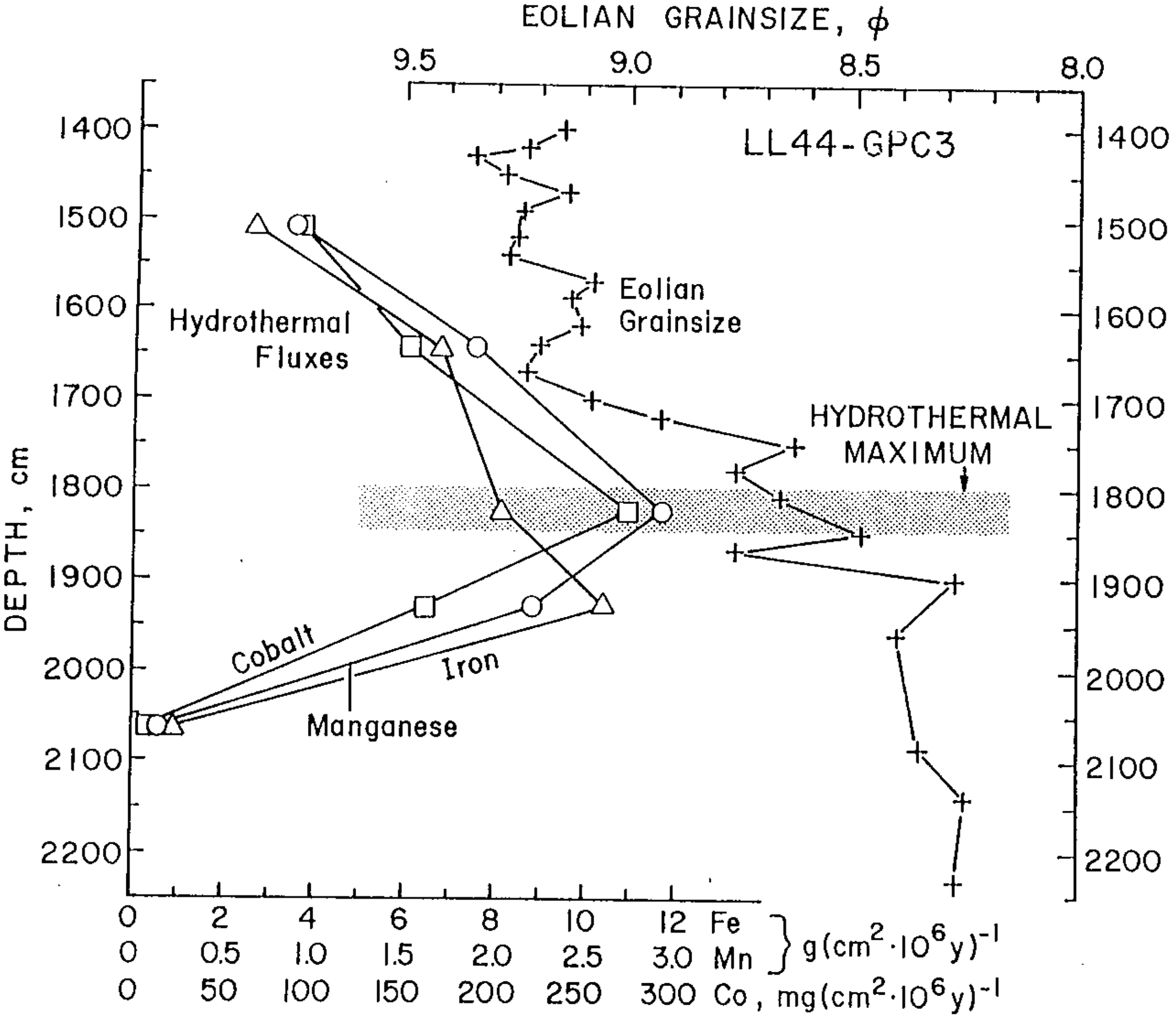


Figure 5 Hydrothermal and eolian data from the North Pacific core LL44-GPC3. Fluxes of selected hydrothermal materials and level of maximum hydrothermal component (shaded) as indicates by multivariate analyses conducted by Leinen (1987). Eolian grain size data from Janecek and Rea (1983). The depths (thus timing) of the hydrothermal maximum and of the change in dust size coincide at the Paleocene/Eocene boundary (Rea et al., 1990).

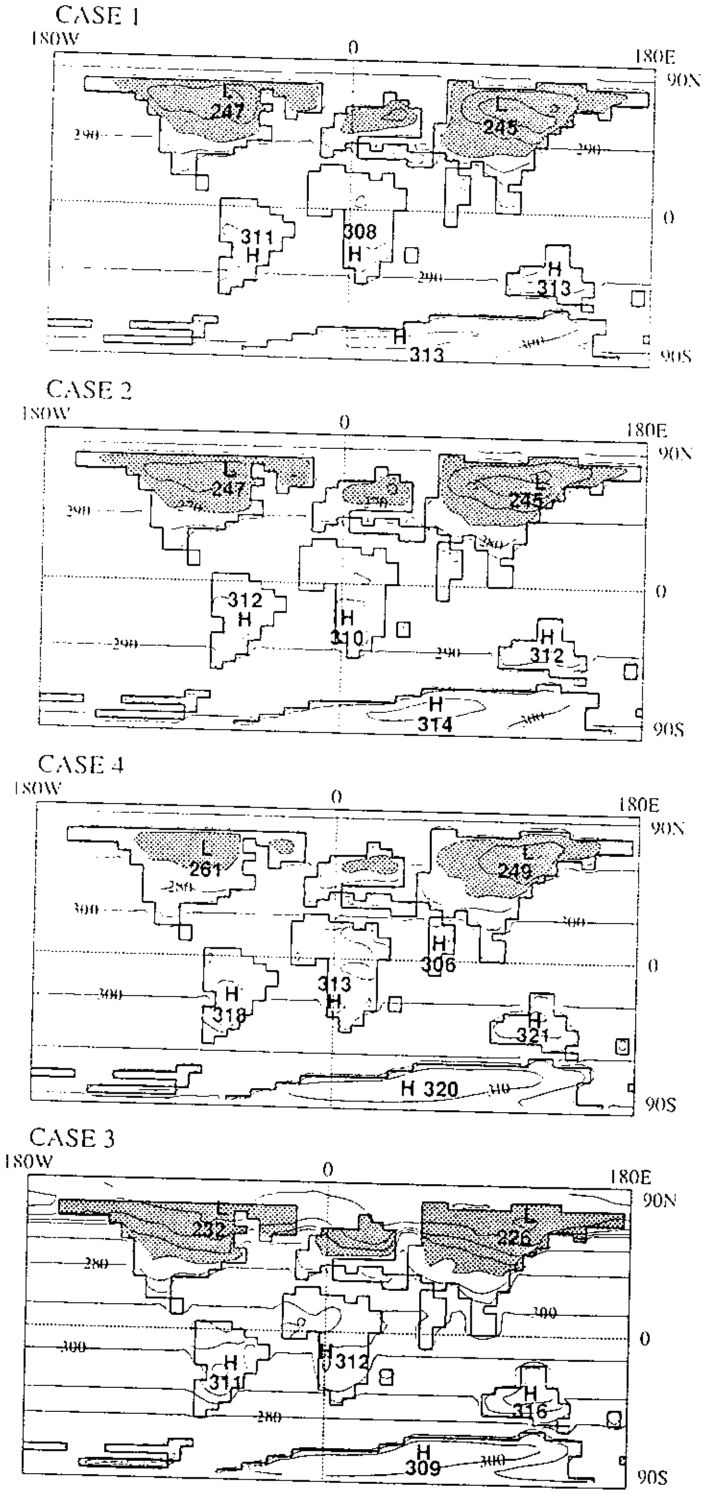


Figure 6 Surface-temperature distributions for Eocene cases 1 through 4 (from Sloan and Barron, 1990). Case 1, cooler tropical and warmer high latitude sea surface temperatures than modern. Case 2, sensitivity experiment using reduced continental elevations. Case 3 sea surface temperatures similar to modern and no continental ice. Case 4, experiment with extreme warm tropical temperatures. Temperatures represent 100-day time-averaged model results. Shaded areas indicate surface temperatures less than 270 K (-3°C). Temperatures are contoured at 10°C intervals; relative maximum (H) and minimum (L) temperature are indicated in kelvins .

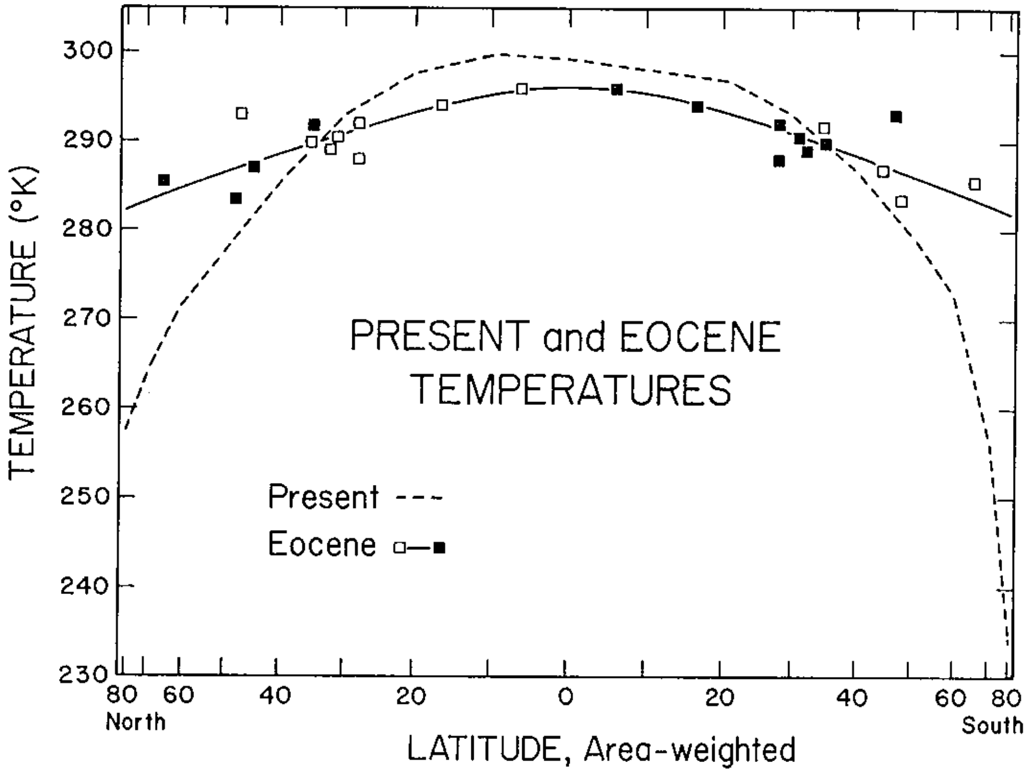


Figure 7 Isotopic paleotemperatures of the Eocene surface ocean from Shackleton and Boersma (1981) in comparison with modern values (Barron, 1987). Northern and southern hemisphere data are plotted in both hemispheres.

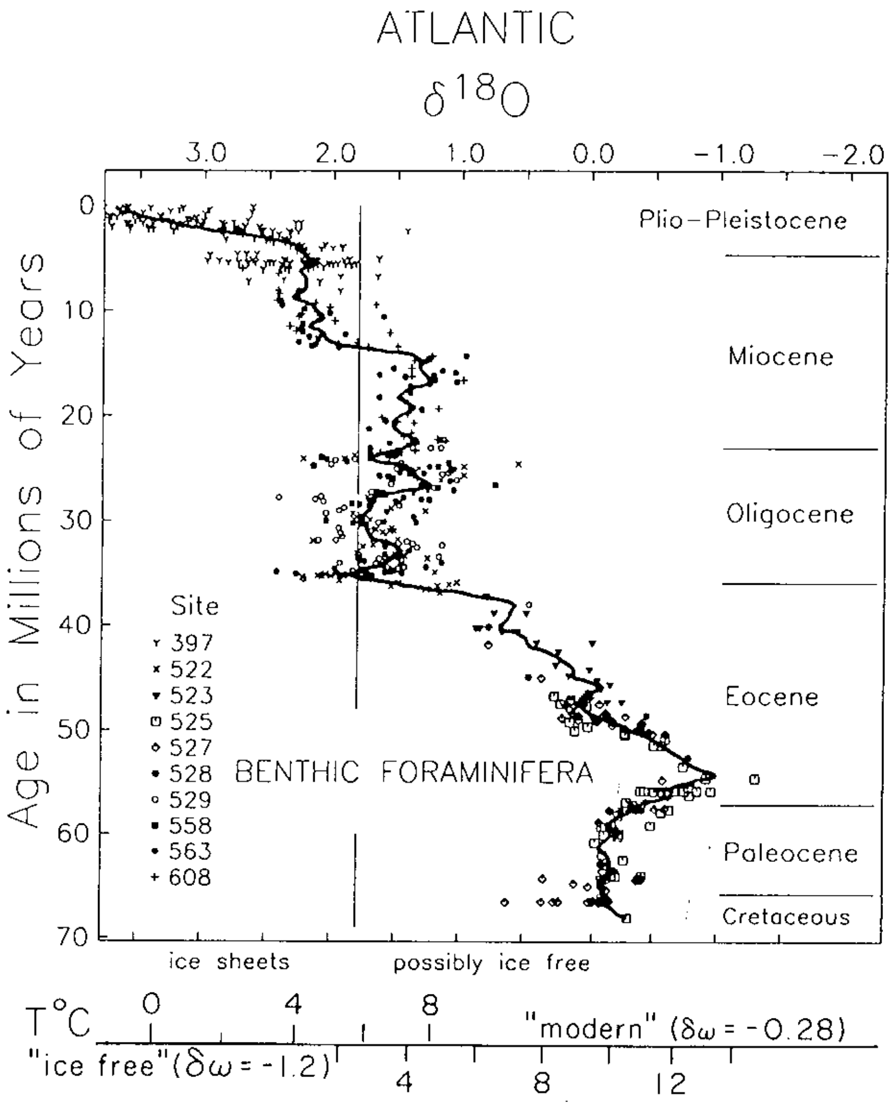


Figure 8 Cenozoic benthic foraminifera oxygen isotope record (Millller et al., 1987). Deep sea temperatures assuming modern ice volume and ice-free conditions.

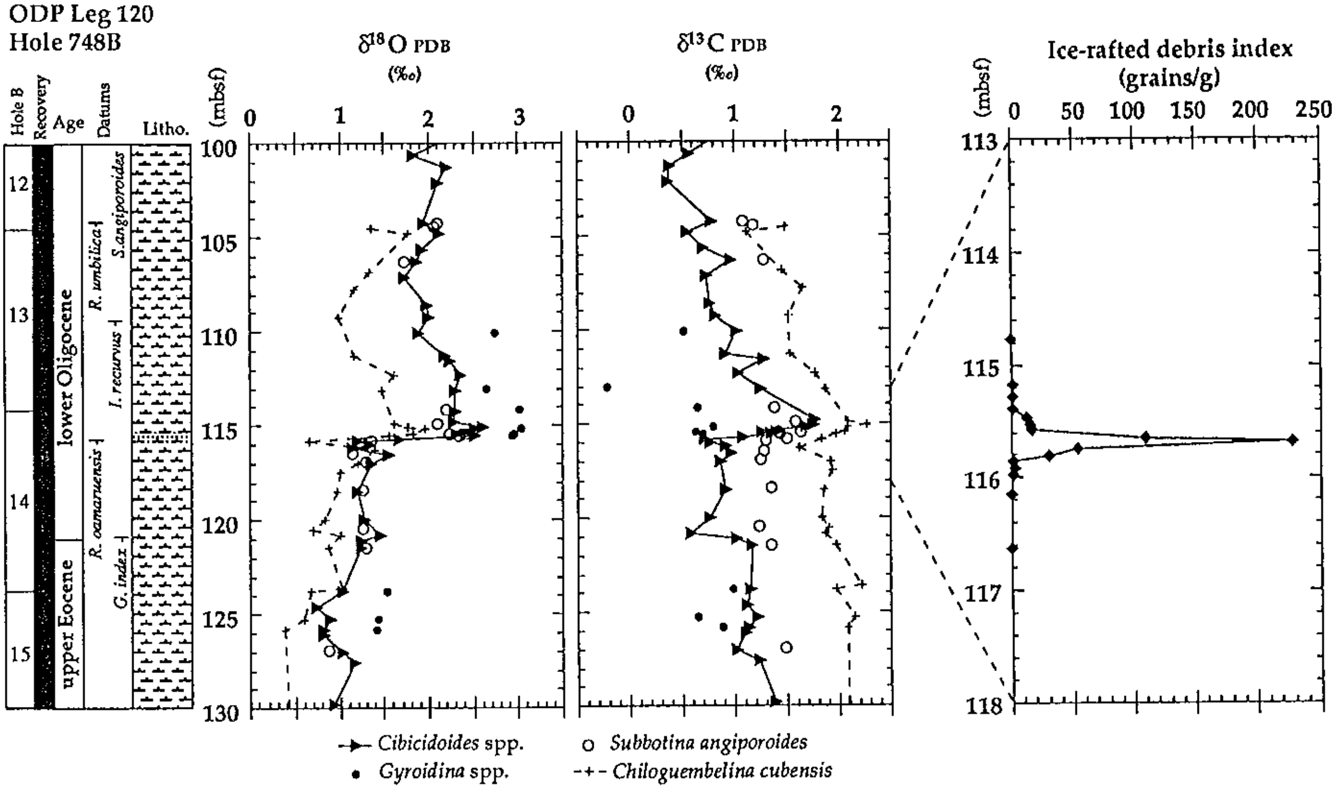


Figure 9 Oxygen and carbon isotope record of planktonic and benthic foraminifera, and ice-rafted debris record from Site 748, Kerguelen Plateau in the southern Indian Ocean. The increase in oxygen isotope values was accompanied by ice-rafted debris deposition at this site indicating widespread glacial activity on Antarctica (Zachos et al., 1992).

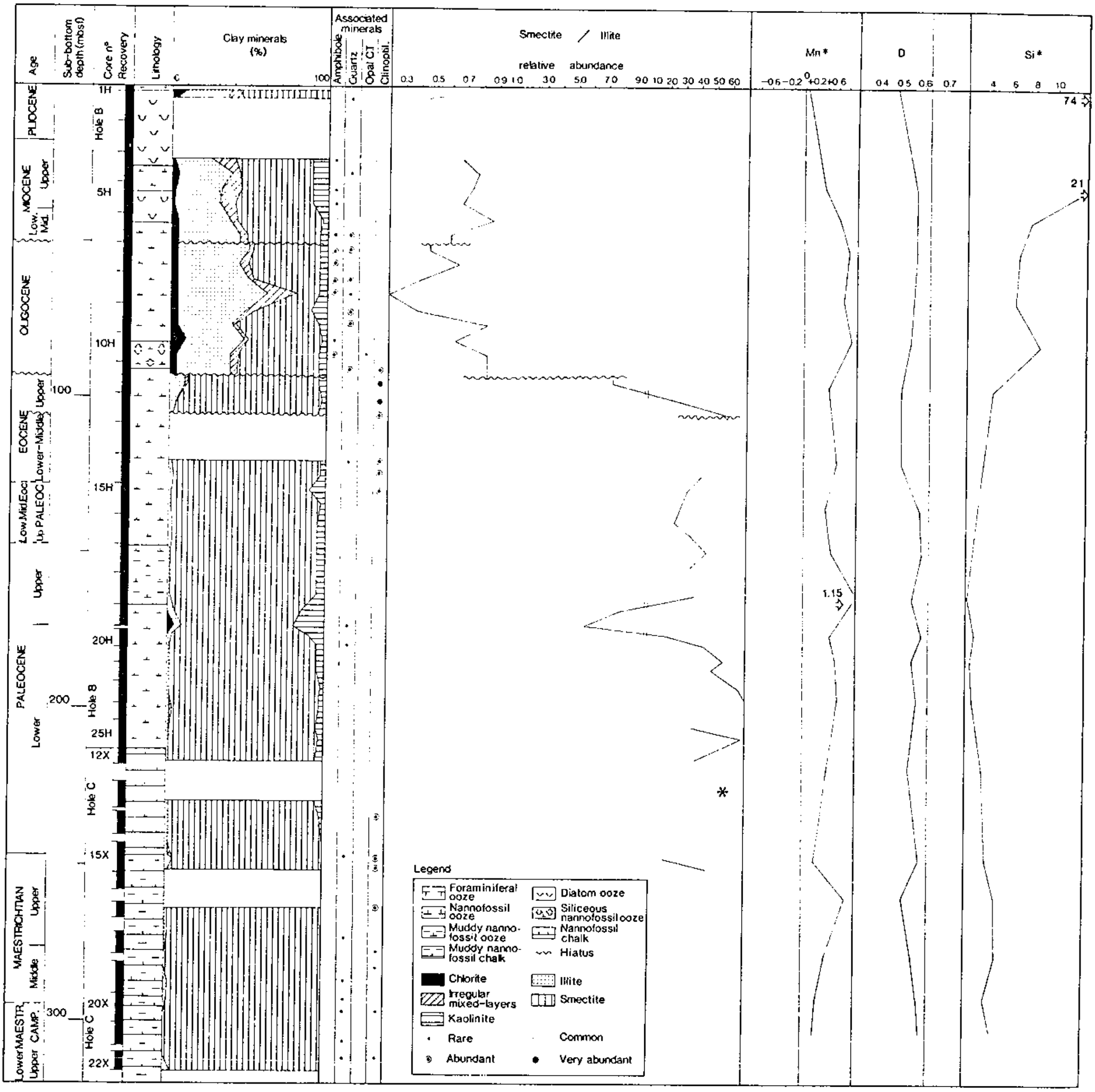


Figure 10 Clay mineral and geochemical record of Site 690 , Maud Rise (Robert and Maillot, 1991). Note the distinct transition from smectite dominated to illite dominated clay assemblage between the Eocene and Oligocene.

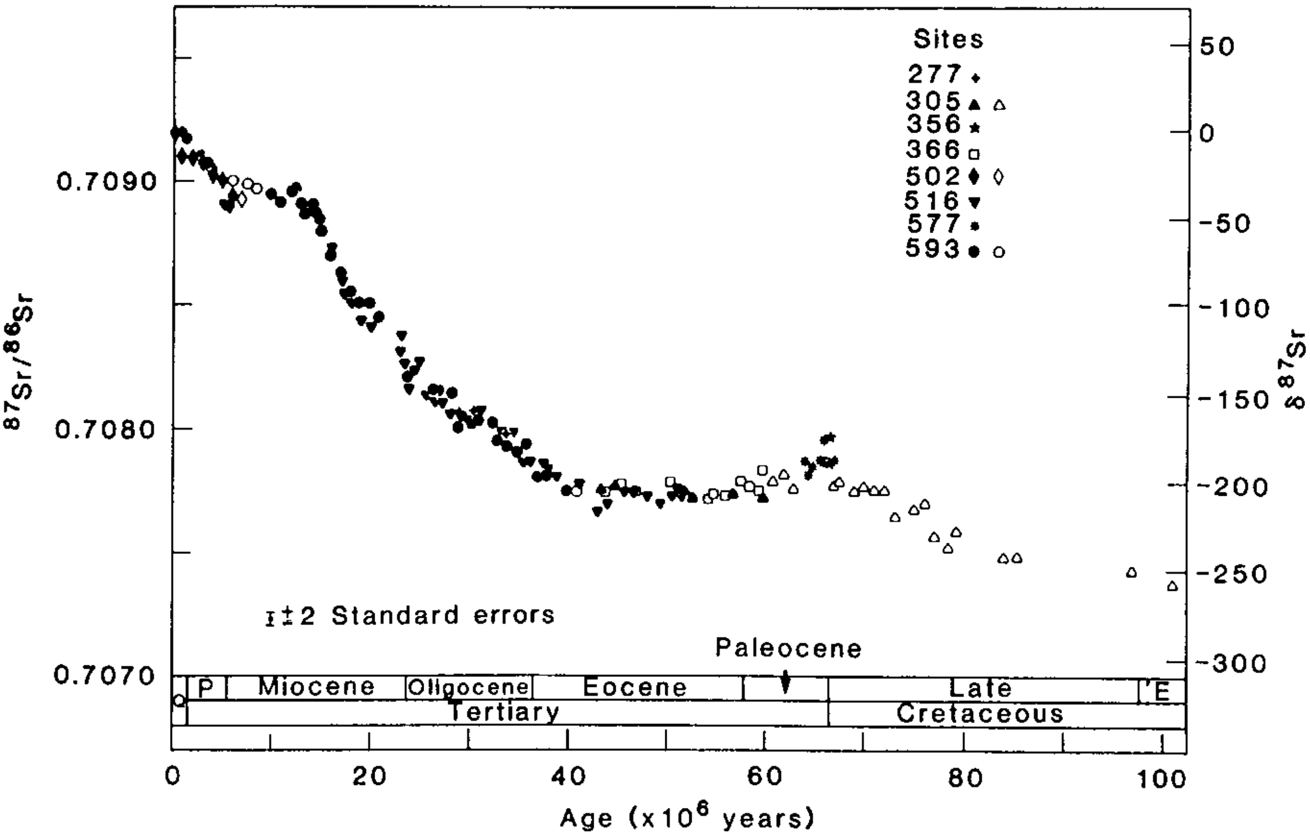


Figure 11 Sea water strontium isotope record of late Cretaceous and Cenozoic planktonic foraminifera from DSDP sites (Hess et al., 1986).

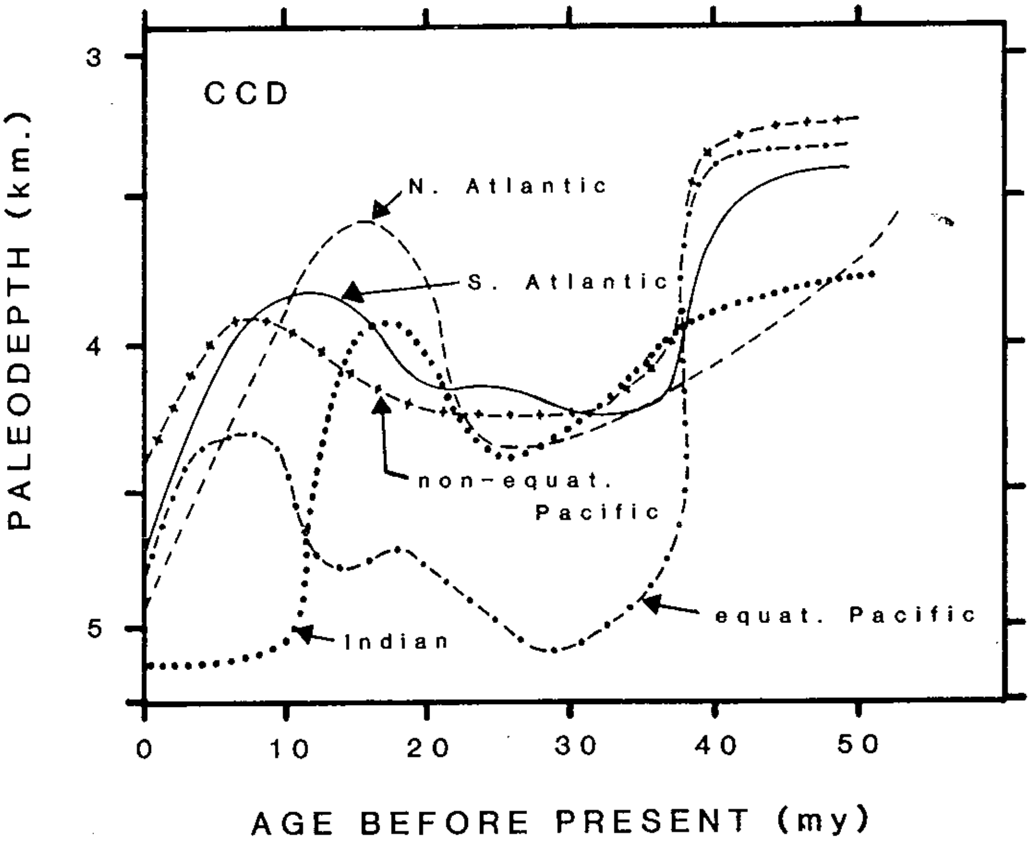


Figure 12Variation of the calcite compensation depth (CCD) over the Cenozoic for the various ocean basins (van Andel et al., 1975; van Andel, 1975; van Andel et al., 1977; Berger and von Rad, 1972).

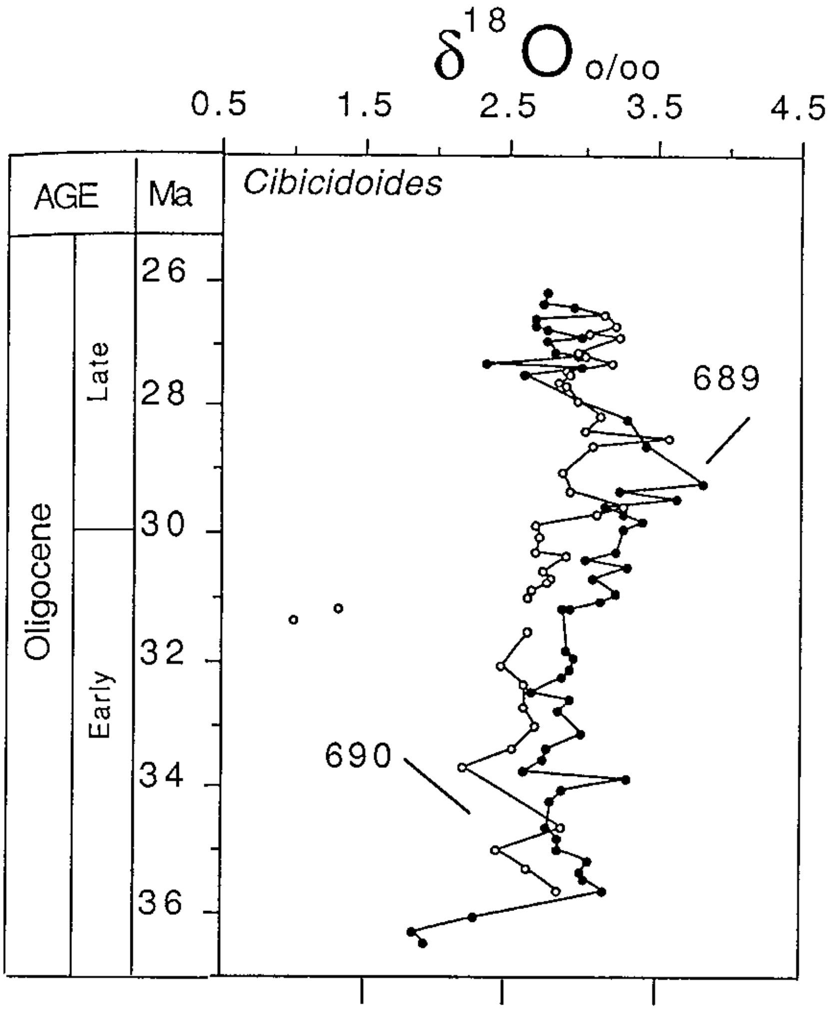
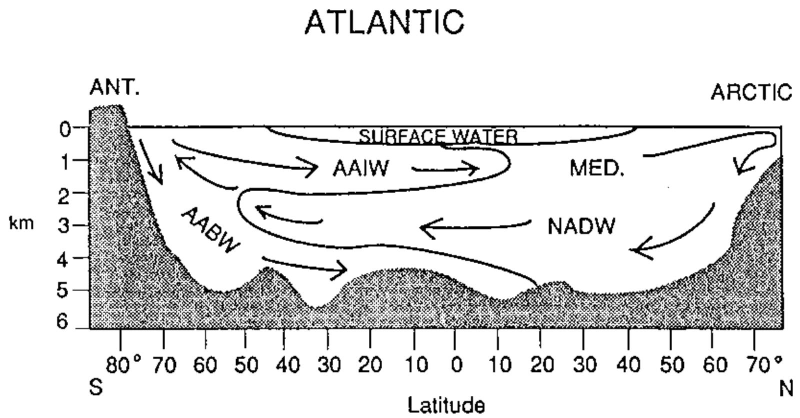
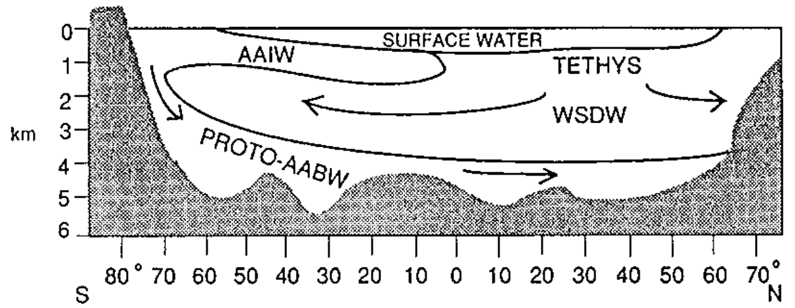


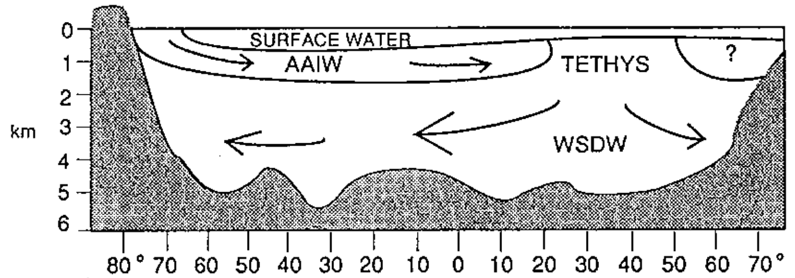
Figure 13Oxygen isotope records of Oligocene benthic foraminifera from two vertically offset sites, 689 and 690, on Maud Rise (Kennett and Stott, 1991). Note that the more negative values consistently occur at the deeper site 690 indicating the presence of a warmer, more saline water mass.



OCEANUS: Modern, psychrospheric (Thermohaline circulation)



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



PROTEUS: Eocene (Halothermal circulation)

Figure 14Panels depict the major modes of deep water circulation that may have existed during the Paleogene (Kennett and Stott, 1991). The three major modes are halothermal circulation, mixed halothermal and thermohaline, and thermohaline. AABW=Antarctic bottom water; AAIW = Antarctic intermediate water; NADW = North Atlantic deep water; WSDW = Warm saline deep water; MED. = Mediterranean.