THE ROLE OF ANTARCTICA IN GLOBAL CLIMATIC CHANGE

CONFERENCE REPORT ON PAST AND FUTURE ANTARCTIC DRILLING

J. P. Kennett and J. A. Barron

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CONFERENCE REPORT ON PAST AND FUTURE ANTARCTIC DRILLING

A white paper compiled by J. P. Kennett and J. A. Barron

On behalf of participants of the International Conference on "The Role of the Southern Ocean and Antarctica in Global Change: An Ocean Drilling Perspective," Santa Barbara, California, August 28 - 30, 1991.

CONVENERS: James P. Kennett, Marine Science Institute and Department of Geological Sciences, University of California, Santa Barbara, CA 93106

and

John A. Barron, U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025

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INTRODUCTION

In many respects the polar regions, especially Antarctica, have been a major driving force in the evolution of global climates that, in turn, have had an enormous effect on the earth's environmental evolution. The influence of Antarctica on surface to bottom water circulation in the global ocean during the last 50 m.y. is well established and apparently extends well back into the Late Cretaceous. In the past two decades, a better understanding of the evolution of the cryosphere has helped to define the timing and direction of Cenozoic global climatic history and associated sea level change.

Themes critical to this area of knowledge are as follows:

- The sequence and timing of the breakup and dispersal of the Gondwanaland continents
- Development of surface and deep water circulation around Antarctica
- Climate evolution of the Antarctic continent and ocean
- Cryospheric development and evolution
- Sea level history
- Bottom water origin and circulation history
- Evolution of surface and deep water chemistry
- Vertical water mass structure
- Evolution of oceanic productivity
- Evolution of the Antarctic biota in relation to environmental changes
- Paleobiogeographic development of Antarctic faunas and floras
- Cretaceous anoxic basins in the Antarctic

It is now well known that Antarctica has also influenced global climatic change on short (10^3 yr) time scales. Partial deglaciations and changes in the dynamics of the polar ice sheet can affect albedo and atmospheric changes that affect the global heat budget. The Northern Hemisphere, primarily the North Atlantic, has been the source of much detailed information on paleoceanographic and climatic changes over the last several million years, but similar continuous, high-resolution climatic records have not yet been obtained from Antarctic and Subantarctic regions. Such records will allow comparison of climatic and glacial history between the northern and southern polar regions in order to better understand driving mechanisms for global climate change. Better understanding of the leads and lags between changes in the two polar regions will help develop predictive models and determine response rates for short duration (10^3 to 10^4 yr) events of global importance. Of utmost importance is the need to evaluate the sedimentary record to determine the history of relative stability or instability of the West Antarctic ice sheet during late Neogene intervals warmer than the present day, including the early Pliocene. Collapse of the relatively unstable West Antarctic ice sheet could cause a global 6 m rise in sea level in perhaps as little as 500 yr.

Numerous national and international programs have been established to address major global change issues, e.g., in oceanic and atmospheric sciences, coastal oceans and terrestrial ecosystems. There is a strong need to address questions related to the influence of the Antarctic and Subantarctic regions in global climatic change. Antarctica is clearly critical in global change concerns. This document has been produced, with the assistance of the workshop participants, to define specific research topics of major importance, that, if carried to fruition, would provide a better understanding of the role of Antarctica in influencing global environmental evolution both on short (10^2 yr) and long-term (10^6 yr) time scales.

ACCOMPLISHMENTS OF ODP ANTARCTIC DRILLING PROGRAM

Four Ocean Drilling Program (ODP) Legs were drilled in the Antarctic region: Leg 113 in the Weddell Sea, Leg 114 in the Subantarctic South Atlantic, Leg 119 in Prydz Bay and Kerguelen Plateau, and Leg 120 on Kerguelen Plateau. These expeditions were enormously successful and resulted in numerous advances that include:

- The character of Antarctic paleobiogeographic patterns of planktonic micro-organisms prior to the development of circum-Antarctic circulation.
- Evidence that at times during the Paleogene there was a reduction in production of deep waters in the Antarctic regions and a dominance of deep water derived from low or mid-latitude regions (warm saline deep water). Fluctuations in region and dominance of sources of deep ocean waters are much more complicated than previously believed.
- Evidence for changing vertical water mass characteristics in the Southern Ocean, especially during the Paleogene.
- History of biogenic silica and carbonate ocean productivity and sedimentation.
- Evidence for initiation of biogenic silica production during the late Eocene and its subsequent evolution.
- Evidence for the presence of eastern Antarctic ice sheets by the earliest Oligocene, and critical data to show subsequent variability of the cryosphere.
- Evidence for diachronism of development of East and West Antarctic glaciation. Comparison with the record in the Ross Sea region.

- High-resolution isotope and ice rafting record for the Pliocene and Pleistocene in the Subantarctic region. Comparison with the Northern Hemisphere record.
- Evolution of Cretaceous through Cenozoic marine biosphere including extinction, evolution and migration patterns.

SPECIFIC MAJOR DISCOVERIES INCLUDE:

- Discovery of middle Cretaceous anoxic sediments in the Weddell Sea.
- Discovery of the oldest known (middle Cretaceous) diatoms and silicoflagellates, in pristine condition and of critical importance in the understanding of their early evolution.
- Discovery of basement character and tectonic history of several oceanic rises e.g., Kerguelen, Broken Ridge.
- Discovery of middle Cretaceous non-marine sediments on Kerguelen Plateau indicative of a relatively warm regional climate; documentation of colonization by land plants and their succession to a canopied forest.
- Establishment of magnetobiostratigraphy for the Late Cretaceous to Quaternary for Antarctic and Subantarctic regions in Atlantic and Indian Oceans.
- High-resolution stratigraphic studies across several Cretaceous/Tertiary boundaries demonstrate important climatic changes preceding the iridium anomaly and inferred ocean paleoproductivity changes following the boundary.
- Discovery of brief global warming/carbon cycle/paleoceanographic event that caused latest Paleocene mass extinctions in the deep sea.
- Conclusion that there were warm, wet climates on the Antarctic Continent during the Paleocene/Eocene transition.
- Development of a weathering record (chemical vs. physical) for the Antarctic Continent using clay mineralogy.
- Establishment of first oxygen isotopic temperature records for the Late Cretaceous and Paleogene of the Antarctic. Also, quality records from the Neogene and Paleogene of the Subantarctic.
- First oxygen isotopic evidence for the existence of warm saline deep water during Paleogene intervals.
- Documentation of Eocene - Oligocene plant assemblages on Antarctica.
- Discovery of brief interval of ice-rafted debris at Eocene/Oligocene boundary and climate history in Kerguelen Plateau sequences. Implications for major East Antarctic ice sheet.

- Discovery of earliest Oligocene and younger glaciomarine sediments in Prydz Bay: Implications for long-term glacial climates on East Antarctica.
- Evidence for the initiation of West Antarctic ice sheet during the late Miocene.
- Refinements of polar to equator Cenozoic meridional isotopic temperature gradients.
- Late Cenozoic evolution of the polar frontal zone (PFZ).
- Establishment of a high resolution oxygen isotopic record for the Pliocene and Quaternary of the Subantarctic.
- Documentation that the Late Gauss (~2.7 Ma) represents a profound change in paleoceanographic conditions of northern Antarctic and Subantarctic regions, including northward migration of the PFZ, ice volume growth on Antarctica, and reduction of North Atlantic deep water (NADW) flux to the Southern Ocean.
- Discovery of intervals of Quaternary carbonate ooze in Weddell Sea (Leg 113) sites that may correlate with "super-interglacial" conditions of Stages 7, 9, or 11.

ACCOMPLISHMENTS FROM EACH REGION

Weddell Sea

Drilling in the Weddell Sea sector of Antarctica during Leg 113 provided a rich data base employed in studies of the environmental history of Antarctica and the adjacent ocean, from the Early Cretaceous (120 Ma) to the present. The sites form a southernmost anchor for Atlantic biostratigraphy, biogeography and isotopic studies. Lower Cretaceous sediments included Valanginian-Barremian laminated black shales, containing nannofossils, ammonites, mollusca and benthic foraminifers. The latter are very similar to coeval faunas from the Madagascar area, and include several species formerly described as being endemic to this area. Aptian sediments contain the oldest silicoflagellates and diatoms ever observed. A wide range of sedimentologic, biotic, and isotopic evidence indicates that sequential cooling and cryospheric development of the Antarctic region during the Cenozoic profoundly affected the ocean/atmosphere circulation, sediments and biota. Important cooling steps occurred during the latest Cretaceous, the middle Eocene, near the Eocene/Oligocene boundary, in the middle Oligocene, the middle Miocene, the early late Miocene, the latest Miocene, and the late Pliocene.

A remarkable polar warming event occurred at the end of the Paleocene, inferred to have been associated with unusual deep ocean circulation changes and massive extinctions in the deep sea. This event is of interest in global change considerations because it occurred very rapidly (in less than a few thousand years) and was clearly linked to changes in the broader earth environmental system. Oxygen isotopic evidence suggests the presence of warm saline deep water in the Weddell Sea at this time and during other Paleogene intervals: Antarctica may not have been the primary source of deep waters during parts of the Eocene and Paleocene, although presently available faunal and isotopic evidence do not always agree as to the timing and duration of the possible intervals of dominance of warm saline deep waters. At the beginning of the Oligocene, or perhaps during the late Eocene, cold deep waters began to form and strongly compete with lower latitude sources. Evidence from the Weddell Sea sector suggests that cryospheric development began early in the Oligocene (~34 Ma), although the sites provide no evidence for major ice accumulation during the Oligocene. The combined evidence from the Leg 113 sequences indicates that the middle to late Paleogene climate change was dominantly, although not exclusively cooling, while latest Paleogene-Neogene change was dominantly cryospheric development (ice accumulation).

Prydz Bay, East Antarctica

The major objective of drilling on the continental margin of East Antarctica at Prydz Bay was to study the initiation and subsequent evolution of East Antarctic glaciation. This objective was partially met with the recovery of glaciomarine sediments as old as early Oligocene at Sites 739 and 742, demonstrating that major cryospheric activity has occurred since the earliest Oligocene (~34 Ma). Evidence from the Kerguelen Plateau, in combination with that from Prydz Bay, indicates the formation of a major ice sheet in the earliest Oligocene. The stratigraphic record from Prydz Bay, including episodes of sediment erosion and over-consolidation, also provides evidence of significant oscillations in the extent of cryospheric activity including the size of the ice sheet since the early Oligocene. Glacial sediments of possible late Eocene age were also cored. The lack of recovery of pre-glacial marine sediments to determine the inception of cryospheric development and the absence of upper Oligocene to middle Miocene glacial sediments in Prydz Bay were major disappointments.

A second objective of Prydz Bay drilling was study of the early rifting history of India from East Antarctica. Recovery of pre-rift (possibly Upper Permian, but still undated) red beds at Site 740 and pre-rift Lower Cretaceous coal-bearing sediments at Site 741 provided important data to help constrain models of this early evolution when used in combination with seismic stratigraphy in the Prydz Bay region.

Kerguelen Plateau, Southern Indian Ocean

The two legs devoted to the inaugural drilling of the Kerguelen Plateau (119 and 120) were intended to clarify the origin, nature and tectonic history of the plateau as well as its paleoenvironmental history. Basement rocks sampled at four sites proved to be hot-spot related middle Cretaceous tholeiites erupted between 114 and 110 Ma during the separation of India from Antarctica. Dipping reflectors in the basement denoted subaerial basalt flows rather than the continental crust that had been predicted in some publications; no continental crust was sampled and none is believed to be present. The objective to better understand paleoceanographic evolution at high latitudes in the southern Indian Ocean was met and exceeded with the recovery of a composite middle Eocene to Holocene section at Sites 736 and 737 (50°S) and a composite Late Cretaceous to Holocene section at Sites 738 and 744 (60°S). In addition, a deep-water reference section spanning the last 10 m.y. was recovered at Sites 745 and 746.

A major surprise was the recovery of Upper Cretaceous non-marine sediments at Sites 748 and 750 on opposite sides of the Raggatt Basin on the Southern Kerguelen Plateau. Pollen and spore, organic geochemistry, and subsidence studies indicate that volcanic peaks up to 2000 m high were colonized by land plants that developed through plant succession into canopied forests that were subject to fires. Charcoal, unburned wood and organic debris constitute up to 10% of the non-marine (fluvial) sediments, which also contain high percentages of kaolinite and some gibbsite. The latter are indicative of relatively warm climates with seasonal, orthographic rainfall.

A second surprise was an extraordinarily thick (400 m), shallow-water glauconitic Upper Cretaceous sequence at Site 748 in the western Raggatt Basin. The upper 200 m of this sequence is of Campanian-Maestrichtian bryozoa-rich, bioclastic facies in which distinct bioherms (up to 5 km across) were developed along a carbonate platform margin that extends out to the center of the basin.

At several sites (738, 747, 748, and 750) the appearance of a distinctively austral (cold water), calcareous planktonic microfossil assemblage in the upper Campanian-Maestrichtian just above a mid-Campanian regional disconformity denotes an important paleoceanographic event marked by the decoupling of the Southern Ocean surface water mass from those to the north. This event may be related to the initial rifting of Australia from Antarctica and the development of a narrow ocean partially between these continents.

Debris flows composed of eroded volcanic basement rocks at Site 747 on the central plateau are associated with the same extensional tectonics that caused the rifting between Australia and Antarctica; crustal stretching was eventually followed by the rifting of Broken Ridge from Kerguelen Plateau during the middle Eocene (~43 Ma). Rapid subsidence of the plateau at the close of the Cretaceous is evident from changes in benthic foraminiferal assemblages at all sites that reached the Cretaceous.

A complete Cretaceous/Tertiary boundary section cored at Site 738 is unique in that the iridium-rich boundary clay is immediately overlain by 15 cm of laminated sediments. These laminated sediments show little bioturbation and allow high-resolution studies of the recovery of biota immediately following the K/T event. A nearly complete K/T boundary was also recovered at Site 748. Together with the K/T sections from Maud Rise (Site 690) and Site 752 on Broken Ridge (which was contiguous with the Kerguelen Plateau at that time), these sites allow the first high southern latitude biogeography studies across this boundary. Nannofossil studies of this interval demonstrate a pronounced provincialism of both the latest Cretaceous and early Danian assemblages that increased progressively poleward.

Surprisingly, there is little evidence of a major disconformity or bathymetric change of the plateau coincident with the rifting of Broken Ridge during the middle Eocene. Rather than finding a middle Eocene to middle Miocene unconformity predicted from seismic stratigraphic models for Site 737 on the northern Kerguelen Plateau, a latest Oligocene to middle Miocene disconformity was drilled instead above a nearly complete Oligocene section. The southern plateau sites also revealed no direct evidence of the middle Eocene rifting event that is documented by a well-dated angular disconformity at Sites 752-755 on Broken Ridge.

Despite the success and surprises in drilling the Mesozoic, the necessity to interval core the ~50-m-thick non-marine sediments at Site 750 and the lack of core recovery except for a few drilling chips in the bottom 50-m at Site 748 were disappointments. Likewise, the failure to recover Cretaceous sediments and basement on the northern Kerguelen Plateau leaves major gaps in our knowledge.

Stratigraphic objectives were met and exceeded with the recovery of a composite Upper Cretaceous to Holocene section at several sites (738, 744, 748, 750, and 751; 58° - 60°S) and a composite middle Eocene to Holocene section at sites further to the north (736 and 737; 50°S). In addition, a deep-water reference section spanning the last 10 m.y. was recovered at Sites 745 and 746. This sequence accumulated at high rates (>40 m/m.y.), has yielded an excellent magnetostratigraphy, and contains an excellent high-resolution record of sediment drift material suitable for study of deep ocean circulation history. It also contains an extensive record of rhythmic biogenic and pelagic sedimentation. As no other deep water sites were drilled along the plateau, these represent excellent sites for even deeper drilling in the future.

As a result of the outstanding core recovery in the Cenozoic, excellent magnetostratigraphic records were obtained at Sites 745, 746, 751 (0-19 Ma) and Sites 744 and 748 (0-40 Ma). As sediments at Site 745 accumulated at rates >40 m/m.y., this section is useful for high resolution studies of polarity transitions. A composite record has also been excellent for isotopic studies of oceanic circulation history from the Paleocene to the Miocene.

A major paleoceanographic finding was the discovery of appreciable lowest Oligocene ice-rafted debris (IRD) at Sites 744 and 748 on the Southern Kerguelen Plateau. Well documented and authenticated by size and electron optical analyses, these materials demonstrate the drift of large icebergs at least 1000 km beyond the margins of Antarctica. Coupled with the discovery of lower Oligocene IRD at Site 693 on the Weddell Sea margin, these occurrences denote the existence of an extensive earliest Oligocene ice sheet that reached sea level at several points around the margin of East Antarctica. These discoveries have led to a consensus among specialists that an extensive ice sheet was present, however fleetingly, on the Antarctic continent as early as 36 Ma.

Subantarctic South Atlantic

Drilling during Leg 114 in the Subantarctic sector of the South Atlantic led to a number of important advances. These include the establishment of a high resolution magnetobiostratigraphy from the Late Cretaceous to the Pleistocene, although some gaps remain in the Eocene. Furthermore, the resulting sequences have enabled the establishment of a high resolution stable isotopic record (Site 704) for the late Pliocene and Quaternary nearly comparable to records from the North Atlantic.

Some of the more significant results from the high-resolution, late Neogene record from Site 704 include:

(1) The late Miocene, between ~6.2 and 4.8 Ma, was marked by high-frequency variations in $\delta^{18}O$ and planktonic microfossil assemblages, including a major dissolution zone during the early Gilbert (5.35 - 4.8 Ma).

(2) The interval from 4.8 to 3.2 Ma was marked by a low-amplitude $\delta^{18}O$ signal (0.5°/oo range) with values less than the Holocene, suggesting ice volume was less than today but did not fluctuate widely during this period.

(3) The latest Gauss (~2.7 to 2.4 Ma) represents the time of greatest paleoceanographic change in northern Arctic and subantarctic regions during the Neogene. At this time, the Polar Front Zone (PFZ) migrated to the north, ice volume increased on Antarctica and Northern Hemisphere continents, and the flux of NADW to the Southern Ocean was reduced during glacial stages.

(4) During the late Pleistocene, oxygen isotopic Stages 7, 9, and 11 were "super-interglacial" periods in the South Atlantic sector of the Southern Ocean when warm surface waters penetrated far poleward, perhaps as far as the Weddell Sea. In contrast, Stage 12 was a very strong glaciation that marked maximum northward extent of the PFZ. Carbon isotopic gradients suggest that the flux of NADW to the Southern Ocean was strongest during Stage 12 and

weakest during Stages 7, 9, and 11, supporting the hypothesis that production of NADW has a profound influence on climatology of the Southern Ocean.

Drilling also has provided suitable sequences to study Cenozoic oxygen and carbon isotopic history to complement those drilled during Leg 113, to the south, in the Weddell Sea. In combination, these sequences have been particularly useful in establishing late Eocene-early Oligocene vertical water mass gradients. The results suggest that at times during the Paleogene the production of cool deep waters in the Antarctic region was limited. Instead, warm saline deep water was produced in semi-enclosed basins at middle latitudes by the mixing of warm saline water with colder water during downward advection or by winter cooling of saline water produced during summer in restricted basins.

Other results include the analysis of Oligocene to lower Miocene sediments that help constrain the timing of the opening of the Drake Passage, the discovery of the oldest but very rare ice-rafted debris in sediments of early Miocene age at these Subantarctic latitudes (no IRD was observed in the Oligocene), and the evolution and biogeography of Paleogene planktonic assemblages. Drilling also helped to establish the age and history of subsidence of major oceanic promontories in the Subantarctic region including Northeast Georgia Rise, Islas Orcades Rise and Meteor Rise.

IMPORTANT REMAINING QUESTIONS AND PROBLEMS

Drilling of four high latitude legs in the Southern Oceans resolved a multitude of paleoenvironmental and biostratigraphical questions, but the preliminary results helped identify new complexities in the record and pose important new questions.

Paleoclimates/Paleoceanography

1. Development of the Antarctic Ice Sheet: Consensus has emerged that major ice accumulation on East Antarctica began in the earliest Oligocene and that there has been at least some ice on the continent since that time. But was there appreciable ice on Antarctica before the early Oligocene? Pre-glacial marine sediments were not recovered on the Prydz Bay continental margin (Leg 119), nor on the Weddell Sea continental margin (Leg 113), because of the presence of Cretaceous to Oligocene hiatuses. This question could be addressed by drilling other shallow parts of the continental margins. Such areas might include the Ross Sea area, where it will also be possible to study the effects of uplift on the Transantarctic Mountains on Antarctic climate and cryospheric development. Were there open seaways across the Antarctic continent, and if so, at what times were they open?

2. Stability of the Antarctic Ice Sheets: Once formed, were the ice sheets permanent? Did they fluctuate much in volume? Did partial deglaciation of the East Antarctic ice sheet occur at times during the early and latest Oligocene or the early Miocene (the warmest interval of the Neogene)? What is the history of stability of the West Antarctic ice sheet under climatic conditions that were warmer than the present day? Was there major deglaciation of the West or even the East Antarctic ice sheets during the early Pliocene, another episode of relative global warmth? (The West Antarctic ice sheet appears to have remained relatively stable during Quaternary interglacial episodes.) If major deglaciation occurred during the early Pliocene, why is there no major signal present in the deep sea oxygen isotopic record? Is there a record of sea-level change in response to such large-scale ice-volume fluctuations?

3. Deep Water Sources: How much change was there in the vertical water mass structure of the world oceans during the Cenozoic? There are a number of indications for the formation of warm saline deep water during Paleogene intervals, but conflicting evidence exists, including the nature of carbon isotopic gradients, and of development of benthic foraminiferal faunas, and a consensus has yet to emerge. If warm saline deep water was a major component of deep ocean waters during the Paleogene, at what depths did it largely reside? What were the spatial differences in deep-water-mass characteristics between the major ocean basins, and what source areas were functional at what times? How do glacial-interglacial changes in Southern Ocean water mass paleochemistry affect the rest of the world ocean? (e.g., the iron hypothesis). Additional depth transects of drilled sites are essential, including further sites on Maud Rise.

4. Stable Isotopic Records: How much of the earliest Oligocene oxygen isotopic shift can be explained as ice volume, how much as temperature effects? What complexities in the oxygen isotopic record need we consider (e.g., salinity effects, precipitation effects)? Presently, there are discrepencies between temperature gradients based upon floral and faunal evidence, as compared with oxygen isotopic evidence. Is it possible to resolve certain ambiguities in the oxygen isotopic records by comparison of carbonate and silicate records? This represents a promising new development, especially at the high latitudes where mixed carbonate-silicate sedimentary records are available.

5. Influence of Antarctica on Ocean Geochemical Evolution: Many of the estimates for global Mesozoic and Cenozoic continental shelf and slope sediment accumulation rates are based on available records from the other continents. The erosional history and sedimentary/geochemical contribution of Antarctica has been overlooked due to a lack of

information on thicknesses and ages of shelf and slope sediments. This is a critical oversight considering the large amounts of debris that have been glacially eroded off the continent and deposited into the ocean since the early Oligocene.

6. Relations between Oceanic and Atmospheric Development: There are no good records of eolian fluctuations from the Southern Hemisphere (e.g., southwest Pacific) to compare with those from the Northern Hemisphere. What was the east-west variation in oceanographic gradients in the southern Pacific, Indian and Atlantic ocean gyres? Is it possible to obtain proxy records on the presence and extent of sea-ice during the pre-Pliocene?

7. Northern and Southern Hemisphere Correlations: How do climatic development and fluctuations compare between the Northern and Southern Hemispheres (leads, lags) during the Neogene, especially the latest Neogene? To answer these questions more high-resolution carbonate records are required from Antarctic and Subantarctic regions for comparison with low-latitude and Northern Hemisphere records.

8. Gondwana Breakup: How and when did the break-up of Eastern Gondwanaland occur? When and where did rifting begin, and what was the character of the early oceanic basins resulting from this breakup? Anoxic, shallow Valanginian-Hauterivian basins are now known to have existed in the Weddell Sea region and benthic foraminiferal evidence suggests a close connection with basins near Madagascar. More information is required on the Mesozoic biostratigraphy of both calcareous and siliceous microfossils, as well as organic and inorganic chemical data on the "black shales" to answer questions of paleobiogeography as well as paleoproductivity and paleocirculation.

9. Evolutionary Processes: What events took place during intervals of major environmental change such as at the K/T and P/E boundaries and at the end of the Eocene? How did deep-water extinction events such as at the Paleocene/Eocene boundary relate to changes in the shallow-water and terrestrial environments? How did repopulation occur following extinction events, both for planktonic and benthic organisms? What effect did cryospheric development of Antarctica have on the evolution of pelagic as well as benthic assemblages, including migrations to and from the Antarctic? What were the effects of paleoceanography on endemism (isolation) of Antarctic faunas and floras during the Late Mesozoic and Cenozoic?

10. Biostratigraphy: Enormous strides have been made in southern polar marine biostratigraphy and isotope stratigraphy as a result of the recent drilling. Nevertheless,

important gaps remain and need to be addressed. Also needed are better correlations between siliceous and carbonate microfossil biostratigraphic schemes, preferably based upon sedimentary sequences that contain both elements together. A search is also needed for distinct short-term "events" that are very useful in assisting with high-precision correlations. The detection of the short-term carbon and oxygen isotopic excursion in the latest Paleocene coeval with the benthic foraminiferal extinction, for instance, will help clarify the highly confused biostratigraphy over this interval. Use of micropaleontological, tectonic, paleomagnetic, and basement geochemical data is needed to help establish the timing of the opening or closing of oceanic gateways including those south of the South Tasman Rise, the Drake Passage and the Scotia Sea.

11. Evolution and Nature of Oceanic Frontal Systems: Response to glacial-interglacial cycles; effects on gradients in temperature, productivity, silica vs. carbonate and other parameters.

12. Erosion and depositional history of continental shelves and slopes using lithostratigraphy and other approaches.

13. High Resolution Late Quaternary Paleoclimate History: Marine sequences need to be recovered that can be correlated and compared with ice core data.

14. Climate Models: In the last instance, all of this new information is available for input into climate models, to delineate possible modes of operation of the ocean-atmosphere-biosphere system, and to use the past to help evaluate possible future changes in climate.

Biological Evolution in the Antarctic

COSOD II recommended studies of evolutionary processes, especially in the Neogene, through use of drilled material, the early evolution of plankton groups, and macroevolutionary patterns. The objectives listed below address each of these recommendations specifically for the Antarctic:

1. Early Cretaceous deposits of biogenic silica on the Weddell Sea margin (Site 693) contain a remarkable and unique record of the early evolution of the siliceous plankton. This deposit can be considered the "Burgess Shale" of the siliceous plankton. The sequence contains a well-preserved record of the early evolution of diatoms. Also, the silicoflagellates in this

material represent ancestral stock never observed before and extend the known range of the group by 30 m.y. The recent drilling in the area off Dronning Maud Land was unable to dedicate sufficient time to core this sequence and a return would be of great benefit.

2. Late Cretaceous extinctions and following Early Tertiary radiation of Antarctic siliceous and calcareous plankton and correlation and integration of this record with that of the shallower Seymour Island sequence of the Antarctic. A potential site for this investigation is on Campbell Plateau, southwest Pacific.

Ocean drilling in the Antarctic and Subantarctic has not yet provided any materials of Aptian, Cenomanian, Turonian and middle Campanian age. Understanding of biotic and paleoenvironmental evolution would benefit from the availability of such material.

3. Documentation of Neogene biotic evolutionary events leading to the unique modern Antarctic benthic biota. This objective requires coring of a shallow-water (<500 m) site close to the continent with well preserved benthic microfossils.

4. Further studies are needed in the Antarctic to define, at high stratigraphic resolution, the remarkable extinctions that occurred near the Paleocene-Eocene boundary and the following radiation of planktonic and benthic microbiota during the early Eocene. During the Eocene, radiations occurred in calcareous as well as agglutinated benthic foraminiferal faunas, and in the phyletically non-related deep-sea ostracodes, suggesting that these radiations might be related to deep-water paleoceanographic events. Potential sites for this investigation include an expanded section on Broken Ridge or off the northeast tip of the Antarctic Peninsula. This will help tie the deep sea sequences to those at Seymour Island.

5. Completion of biogeographic documentation of Cenozoic planktonic assemblages in the Subantarctic of the Pacific. Potential sites occur in the Ross Sea, on Tasman Rise and to the northeast of the Antarctic Peninsula.

6. Investigations of the evolution of the terrestrial flora through studies of pollen and spores in Cretaceous through Pliocene sequences. Reworking represents a problem but the objective is possible with careful site selection. Potential sites occur in the Ross Sea and near the Antarctic Peninsula.

7. "Monospecific" oozes of diatoms, silicoflagellates, and calcareous nannofossils remain an enigma. What significance do these have in evolutionary and paleoceanographic processes? Potential sites occur in the area of the Falkland Plateau (Sites 329 and 701).

POTENTIAL DRILLING LOCATIONS

Participants of the workshop suggested several drilling locations in Antarctic waters and in the Southern Ocean. Other critical sites have been recognized and widely discussed by other working groups, especially on the Antarctic continental shelf and slope where large seismic-data compilations and analyses are currently in progress by the Antarctic Offshore Acoustic Stratigraphy project (ANTOSTRAT). Many of these continental margin sites are not described in this document, because of limited participation of continental margin specialists at the Santa Barbara workshop. Descriptions of potential continental margin sites are being prepared by investigators associated with ANTOSTRAT project.

Antarctic Region

Gunnerus Ridge

Gunnerus Ridge is a linear feature that projects northward 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 meridional transect to be drilled across the Antarctic margin for over three degrees of latitude from nearshore to far offshore. Climate modeling studies indicate that the earliest record of glacial activity may be obtained along this margin. It is likely that a pelagic carbonate record of Mesozoic and Paleogene age can be drilled in this area, especially on the northern part of the feature.

Information available for this area (*Polarstern* Cruise ANT-VIII/6) includes MCS, high resolution seismic, and piston core data which will be published in the Antarctic Research Series (American Geophysical Union). One north-south seismic line and two crossing lines cross 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. Piston core data 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 (water depth = 2224 m), and contains upper Oligocene diatomaceous ooze and diatomaceous mud. Cores from the northern Gunnerus Ridge were taken in water depths between 1100 and 1300 m.

General Objectives

1. Obtain a record of the initiation, growth and decay of the East Antarctic ice sheet during the Cenozoic based on analysis of biosiliceous sediments, ice-rafted debris, clay and if possible, biogenic carbonate sediments.

2. Obtain a near-shore/off-shore (south-north) record along a transect from hemipelagic to pelagic Cenozoic sediments, probably with a diminishing influence of glacial-marine sedimentation and ice-front erosional effects to the north.

3. Obtain a stratigraphic record to be compared with that of Maud Rise, the highest latitude pelagic (carbonate/siliceous) sequence yet recovered.

Specific Objectives

1. Age and duration of the oldest Cenozoic glacial-marine sediment, and implications for the nature and persistence of the first ice sheets on Antarctica.

2. Details of the history of cryospheric evolution as expressed by the distribution in time and space of glacial-marine sediments, IRD, sedimentary structures and other criteria along the transect.

3. Vertical water mass history, including upwelling, changes in vertical stratification, and major isotopic events.

4. Early evolution and development of cold Antarctic surface waters and attendant faunas and floras.

5. Record of the biotic, chemical, and climatic changes that occurred across the Cretaceous/Tertiary and Paleocene/Eocene boundaries in a potentially expanded section.

6. Older Mesozoic history of the Antarctic biota and evolution of the southern high latitude ocean basins.

7. Recover Quaternary foraminiferal ooze to study ages and implications of this remarkable layer.

Drilling 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. 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.

Antarctic Peninsula Region

General Objectives

1. To examine the evolution of Antarctic climate using a transect from south to north along the continental margin. Presently this transect includes the transition from polar to subpolar climates, however, there is some evidence for the establishment of a temperate climate in the northern part of the Peninsula during the early Pliocene.

2. To examine the development of overdeepened and foredeepened shelf topography as it relates to the establishment and stability of marine ice sheets, which has a direct bearing on high frequency sea-level events and the development of Antarctic water masses.

3. To acquire a complete Pliocene to Pleistocene stratigraphic record of climatic, paleoceanographic and paleobiologic events in this part of the Antarctic.

4. To evaluate time of formation and stability of the West Antarctic ice sheet during the Neogene.

5. To evaluate effects of Drake Passage opening and possible shallow intracontinental seaways in west Antarctica during the Cenozoic.

Specific Objectives

1. Core a transect extending from the area offshore of Marguerite Bay (between the Heezen and Tula Fracture Zones) where a thick accretionary sequence exists dating back to 27 Ma to Bransfield Basin where there occurs a thick (~1 km) Plio-Pleistocene (<4.0 Ma) sequence of pelagic and hemipelagic sediments with abundant volcaniclastic material.

2. Core an expanded record across the late Pleistocene to Holocene transition. Accumulation rates of 5 mm/yr are common in bays of this region and preliminary results indicate that reliable radiocarbon dates can be acquired from both carbonate and organic carbon in these sediments. This will provide an opportunity to correlate high frequency climatic changes to the ice-core record, and, in turn, to global biotic events. This record could also be correlated with ice-core records being obtained along a parallel transect on the adjacent continent in a joint British-U.S. investigation.

3. Test the hypothesis of Eocene glaciations in this region: Is there marine evidence of glacial activity during the Eocene in this part of the Antarctic? Drilling during Leg 113 to the northeast of the Antarctic Peninsula uncovered evidence for a relatively warm Eocene climate, and there is a lack of evidence for glaciation during the Eocene in the West Antarctic region. To help resolve these different observations, sites are needed closer to the Peninsula.

4. Study the development of endemic populations of marine and terrestrial faunas and floras in association with climatic evolution. This may have been a site of coastal refuge for Neogene terrestrial vegetation.

5. A continent-to-deep ocean transect intended to study the linkages between glaciation on the continent to deep ocean processes and the sedimentological, paleontological and geochemical expression of those processes. Existing DSDP Leg 35 sites could be incorporated within such a transect.

6. To acquire a sequence offshore from Seymour Island to sample the Oligocene and younger strata of this important region. Such a sequence will help complete the stratigraphic record of biotic evolution at and near Seymour Island. This is one of the most complete existing composite paleontological records involving shallow marine and terrestrial assemblages of the Late Cretaceous through Paleogene in the Antarctic, but it stops short of the important evolutionary changes that took place during the onset of glacial conditions in the Antarctic region.

Drilling Strategy

The area is relatively ice-free for about two to six months during the year, but this ice window decreases from north to south. The most southern sites could be drilled during January and February. The more northern sites could be drilled earlier or later in the field season. Icebergs pose a minimal problem. The Seymour Island area would be the most difficult to drill because of heavy sea ice and abundant icebergs.

Abundant seismic reflection survey coverage exists for this region. This includes high quality MCS and high resolution data (water gun and deep-tow records) as well as side-scan and *Gloria* data. Initial interpretations of these data have already been published and include some specific models for climatic and glacial evolution as well as detailed seismic stratigraphic analyses. There are also many piston cores from the region on which considerable work has been conducted and these provide an important framework for understanding glacial-marine sedimentary processes.

Ross Sea Region

General Objectives

A number of major objectives have been formulated for drilling in the Ross Sea region in a specific proposal. These are listed below:

1. Relationships between Antarctic Climatic, Cryospheric and Ocean Histories

a. Onset and history of the East and West Antarctic cryosphere including early glacial development and later ice sheet accumulation. The timing and character of interglacial episodes. There are a number of specific requirements related to this objective including the acquisition of suitable Miocene and Pliocene sections, the definition of glacial/interglacial cycles and characterization of the climatic changes that occurred over the Pliocene/Quaternary transition. Of utmost importance, however, is the need to evaluate the sedimentary record to determine the history of relative stability or instability of the West Antarctic ice sheet.

b. Linkage between ice volume changes and global eustatic variations. Characterization of related sequence stratigraphy.

c. Correlation between onshore, continental margin and deep sea records.

2. Paleoceanographic Objectives
   a. Characterization of changes in circulation using paleontological and geochemical parameters.
   b. Timing and development of the overdeepening shelf profile and bottom water formation.
   c. Relations between biogenic productivity and sea ice extent.
   d. A Cenozoic stable isotope record needs to be established for the continental margin in the Ross Sea region.

3. Stability and Style of Glaciation
   a. Characterization of subglacial depositional processes including times of relative warmth.
   b. Dynamic Controls of Ice Sheets: Characterization of the extent of ice sheets and of subglacial ice dynamics.

4. Rifting history of the Antarctic Plate
   a. Evolution of the West Antarctic rift and its associated basin downfaulting, rift-flank uplift, and volcanism.
   b. Evolution of the Campbell/Tasman/Antarctic continent to ocean boundaries.
   c. Relationship between regional unconformities, tectonism, and crustal loading in the West Antarctic rift.

Drilling Strategy

A number of sites have been proposed in detail in separate proposals for the Ross Sea region. Previous drilling in the Ross Sea has demonstrated its feasibility and importance.

Subantarctic Region

Our knowledge of the evolution of late Neogene climate change in the Southern Ocean pales in comparison to the well-documented history from the high-latitude North Atlantic. This gap can be explained largely by the scarcity of carbonate-bearing sequences from the high-latitudes of the Southern Ocean, whereas superb records have been obtained in the North Atlantic. An important objective of future drilling in the Southern Ocean should be the recovery of continuous, carbonate-bearing sequences from the Subantarctic that can be correlated and compared to the now classic sites from the North Atlantic (e.g., Sites 552, 607, and 609). A number of key questions require clarification by further drilling in the Subantarctic. These include the following:

- What was the role of Scotia Arc development (late Miocene) and its western migration on deep water communication through the Scotia Sea into the Atlantic? Recent work suggests that during early history the Scotia Arc may have been a major impediment to deep water circulation when contiguous with Scotia Ridge. This event (during Messinian to pre-Messinian) would have been brief but of great importance to Messinian events. This question requires a deep site east of the Scotia Arc.

- Cretaceous to middle Eocene vertical water mass history. The present distribution of sections is inadequate and many suffer from diagenesis. Potential sites are available with a history of shallow burial.

- Late Miocene to Pliocene oceanographic homogeneity or heterogeneity across the South Atlantic? A companion site to Site 704 is needed in the western Subantarctic region of the South Atlantic for comparison of isotopic and floral and faunal development. This should help constrain models of oceanographic history across the South Atlantic during the late Neogene.

General Objectives

1. Compare timing of climatic and oceanographic events between the high-latitude Northern and Southern Hemispheres and determine inter-hemispheric lead/lag relationships and coupling mechanisms.

2. Generate high-resolution stable isotope records for the Plio-Pleistocene of the Southern Ocean that can be correlated with similar records from the North Atlantic. Isotope stratigraphy will also provide time control for inter-hemispheric comparison.

3. Decipher the history of the Polar Front Zone (PFZ) during the late Neogene.

4. Link low-latitude and high-latitude biochronologies.

5. Use carbon isotopes and Cd/Ca of benthic foraminifers to monitor the relative flux of NADW to the Southern Ocean and ventilation rates of Southern Ocean deep waters. Evaluate whether NADW flux is an important inter-hemisphere linking mechanism.

6. Study changes in Southern Ocean productivity, nutrient cycles, and pCO_2 (using opal, Ge/Si, $\delta^{13}C$ of organic biomarkers, and other parameters) and its implications for global biogeochemical cycling.

7. Address questions regarding glacial-interglacial changes in carbonate equilibria of the Southern Ocean (i.e., polar alkalinity hypothesis) and its implications for pCO_2.

8. Recover mixed siliceous-calcareous lithologies that can potentially be used for combined oxygen isotopic analyses of SiO_2 and $CaCO_3$ components for a unique solution of both paleotemperature and oxygen isotopic composition of seawater.

General Drilling Strategy

1. Drill north-south meridional transects to delineate changes in the position of the Antarctic Polar Front Zone and to trace geochemical and biogeographic changes across the PFZ.

2. Drill depth transects to examine faunal, physical oceanographic, and chemical changes with depth and to delineate the vertical water mass structure.

3. Transects should begin north of the present-day position of the PFZ to ensure a continuous carbonate record and a number of the sites must be relatively shallow to minimize the effects of carbonate dissolution on the fossil record.

4. Complete recovery is vital to obtain a continuous section. Even under ideal drilling conditions with apparent complete recovery rates, sections can be missing at core breaks. For this reason, double or triple APC/XCB is suggested to ensure 100% recovery.

5. Proper identification of isotopic stages is dependent on proper age determinations. The sites must have high quality paleomagnetic control to "peg" the isotopic stages.

Southeast Pacific Sector (Pacific-Antarctic Ridge)

This region represents a major gap in the distribution of ocean drilled sites on a global basis. Carbonate sediments of Neogene and Paleogene age have been recovered by *Eltanin* Cruises 13 and 24. Seismic records are available from *Eltanin* and *Conrad* cruises from the 1960's.

Objectives

Well preserved upper Neogene carbonates in this region are suitable for isotopic stratigraphy. Related investigations will assist in describing the increase in tempo of Antarctic glaciation during the late Neogene. Correlation of isotopic records and distribution of ice-rafted debris can also be accomplished.

1. Well preserved Paleogene carbonate sections that were originally close to Antarctica can be recovered, permitting paleoclimatic studies that include analysis of the early development of the Antarctic cryosphere.

2. Drill sites should contain an IRD record derived from the adjacent West Antarctic ice sheet. Such a record is required for comparison with that derived from the Weddell Sea during Leg 113.

3. Very little is known about the Cenozoic history of ocean circulation in this region. Of particular interest are the effects of the opening of the Drake Passage on the strength and character of the Peru-Chile Current and other oceanographic features of the southeast Pacific.

4. Studies of the late Pliocene asteroid impact in this region at ~2.4 m.y. Drilling in this region will help date and characterize this event. The event needs to be integrated with oxygen and carbon isotopic stratigraphy so as to determine detailed climatic relationships between time of impact and formation of the Northern Hemisphere ice sheets.

Requirements

There is a need to review old seismic profiles to determine optimum sediment thicknesses on the flanks of the Pacific Antarctic Ridge. New site surveys are required. Also needed is a review of stratigraphy of cores from the region and evaluation of German and Soviet surveys in the region for more recent seismic profiling and coring results.

Southwest Pacific Sector

An important issue to be addressed by drilling in this region is the general one of integration of low, middle and high latitude zonations, especially between those based on carbonate and siliceous microfossil groups. Where both types of microfossils occur together, the difference between the isotopic signals of these two groups will enable the ocean isotopic composition to be determined and hence the overall ice volume evaluated. Interrelationship between terrestrial and marine records can be solved by drilling at sites that contain sediments derived from both sources.

The Campbell Plateau and Chatham Rise are excellent areas for the recovery of Neogene carbonates in the Subantarctic region. For example, a continuous late Pleistocene oxygen isotope stratigraphy has been developed at DSDP Site 594, but Neogene core recovery was poor and a continuous record is not available. With advanced drilling technologies, it should be possible to obtain a complete upper Neogene record on the Chatham Rise (at or near Site 594) by triple APC/XCB. High sedimentation rates provide opportunities for paleoclimatic studies at high stratigraphic resolution. The Chatham Rise also offers the opportunity to drill a depth transect.

Campbell Plateau provides a location for integration of carbonate/siliceous microfossil stratigraphies and to document, using several holes, the migration north/south, and on/off the plateau of the oceanographic frontal systems.

Likewise, Macquarie Ridge offers important drilling targets. Macquarie Ridge is a unique tectonic feature, the evolution of which has led to the development of a gateway for the passage of water from the Indian to the Pacific Oceans. The feature is of interest in both paleoceanographic and tectonic questions. The paleoceanographic features to be examined by a Macquarie Ridge transect are (1) the question of whether the deep gateway opened only once or was open intermittently; (2) if so when did it originate and how often has it been open since?; (3) what has been the evolution of water masses?; (4) what has been the pattern of erosion and deposition?; (5) what has been the pattern of water velocity change through time?; and (6) evolution and migration of frontal structures with time.

Tectonic questions relate to:

- The link between Macquarie Ridge and the New Zealand Alpine Fault.
- The type of compressional regime that exists in the region at present and how that has changed with time.
- The processes involved in the initiation of subduction, especially between regions of oceanic crust.
- The importance of this to early island arc evolution.
- Interactions between the Pacific and Indian Ocean crust through time.
- History of the Macquarie Triple Junction.
- Characteristics of the magnetic quiet zones in the region.

This region is of particular interest because of:

- Its role in blocking communication between the Indian and Pacific upper mantle as evidenced by the different isotopic ratios (Sr, Nd, Pb) and possibly the implications for isolation of large scale mantle heterogeneities.
- Possible presence of thick sections of oceanic crust
- Temporal changes in ridge chemistry/role of hot spot influences.

Drilling Requirements

There is ample coverage of the area with seismic surveys and there is the possibility that the Australian BMR will be able to conduct specific site surveys should a Macquarie Ridge proposal gain favorable consideration.

South Indian Ocean Sector

The Southeast Indian Ridge provides an opportunity for an upper Neogene, latitudinal transect in the Southern Ocean. Some advantages include:

1. Well-preserved carbonate and opal sediments in close proximity to the Antarctic PFZ.

2. Already-established, complete late Pleistocene records tied to a reliable chronostratigraphic framework.

3. *Eltanin* or *Conrad* seismic profiles that indicate several hundred meters of fairly transparent sediments below upper Quaternary piston cores.

4. Kerguelen Plateau, with judicious choice of sites, could provide a wide depth range for construction of Neogene and Paleogene paleodepth transects and the characterization of the vertical depth profile.

5. Previous work indicates that, at least for the Quaternary, PFZ latitudinal migrations are wide enough on glacial-interglacial time scales that paleoceanographic indicators of surface circulation would have a useful "dynamic range."

6. French groups have made significant contributions to seismic data and piston core collection in this area over the past few years.

South Atlantic Sector

Several regions of the South Atlantic appear suitable for obtaining reasonably complete, carbonate-bearing sequences of Neogene age

1. The eastern or western **flank of Mid-Atlantic Ridge** holds promise for obtaining a N-S latitudinal transect across the PFZ. DSDP Site 514 on the western flank recovered a high-quality Neogene section, but the considerable depth of this site (4318 m) resulted in sporadic carbonate preservation. A site (or series of sites along a N-S transect) on younger crust (10 Ma) and at shallower water depth (3 to 3.5 km) should provide the required high-resolution carbonate records.

2. The **Meteor Rise** and **Subantarctic Ridges** have been shown to preserve a superb record of Neogene sedimentation of mixed siliceous-calcareous lithologies. Although Leg 114 already recovered a fine sequence at Site 704, the record is unique and valuable enough to consider re-occupation. Shortcomings of Site 704 include incomplete core recovery and disturbance during part of the lower Brunhes and upper Matuyama. Many of these shortcomings could be improved upon by re-drilling the Meteor Rise and/or the Subantarctic ridges to the southeast. In contrast to the Meteor Rise, the ridges to the south are known to contain highly expanded upper Quaternary sections with excellent calcareous and biosiliceous records. For example, Core RC23-271 contains at least 700 cm of Holocene and has a planktonic oxygen and carbon isotope record that extends back to at least Stage 3. Recovery of a complete upper

Neogene sequence on the Meteor Rise or Subantarctic Ridges is important because the Atlantic sector of the Southern Ocean represents a critical gap in our understanding of the geographic response of orbital forcing on sedimentary biogenic signals. The depth (~2500 - 3000 m) of such a sequence is also optimal to monitor NADW flux to the Southern Ocean.

3. **Northeast Georgia Rise** - Only a thin and relatively deep portion of the Northeast Georgia Rise was drilled during Leg 114 at Site 698 in order to reach basement objectives. However, extensive site survey of this feature reveals a thick and shallow Neogene section. This section lies between 1600 and 2000 m and between 51° and 52°S and displays various thicknesses and sediment characteristics. Piston cores at greater depth confirm carbonate as young as Chron 6, suggesting that the shallower sequences should contain mixed carbonate and silica throughout the lower Pliocene and perhaps younger. The shallow depth of 1600-2000 m offers additional insight as to vertical watermass structure of the Neogene when combined with data from Site 704 (~2500 mbsf). This site also offers a means of detecting variations in NADW flux to the western South Atlantic and east - west asymmetries in surface temperatures and oceanographic boundary positions and migrations. Together with Site 704, the total flux across the South Atlantic of NADW supply to the circum-Antarctic may be modeled and its heat, salinity, and productivity influence on the region's glacial history better understood. Subantarctic sites to complement Site 704 are the key to understanding the NADW influence on the Southern Ocean region as this is the critical area where it mixes and becomes entrained in the Antarctic Circumpolar Current (ACC), after which its character is permanently modified.

4. **Agulhas Plateau** - The Agulhas Plateau is situated between 40° and 50°S paleolatitude, southeast of the southern tip of Africa. It is an aseismic, intermediate depth plateau which has not been drilled previously, due in part to political problems which are currently being resolved. The predominant sediment type is carbonate. Sediments of Cretaceous, Paleocene, Eocene, Oligocene and younger have been recovered in piston cores, with the oldest record dating back to the Cenomanian. The Subantarctic setting of this plateau provides the opportunity to address a number of important paleoclimatic, paleoceanographic and tectonic issues. The following are some important drilling objectives:

(A) The age, origin and evolution of the Agulhas Plateau could be established with certainty. Is it entirely a volcanic edifice? If so, exactly when was it emplaced and what is its nature? What is its relation to the breakup history of Gondwana? Is there any continental material underlying the feature? Basement drilling and petrographic studies are necessary to resolve these questions.

(B) Sediment history on the plateau could provide insight into the history of gateway opening between the Indian and Atlantic Oceans and development of deep water masses between these two basins. Additional information would record paleoproductivity and bottom water anoxia of this sector of the Southern Ocean. Therefore, a depth transect would (a) sample intermediate and deep water masses to determine such questions as to whether warm saline bottom waters impinged on its flanks during various times in the Mesozoic and Cenozoic; (b) recover a calcite compensation depth (CCD) and hiatus history of Subantarctic deep water; and (c) document the history of deep water chemistry change for comparison with the Indian Ocean and Atlantic records.

(C) The position of the Agulhas Plateau fills an important drilling gap between 40° and 50°S paleolatitude in all Southern Hemisphere oceans and provides a unique signal of climatic evolution dating from the early breakup history of Gondwanaland. Sediments recovered from this feature will allow us to (a) reconstruct surface water thermal gradients based on meridional and depth transects; (b) bridge the biogeographic boundary between the Austral and Transitional Biogeographic Realms; (c) document N-S changes in the Austral/Transitional Realm boundary, which in turn can be related to climate/water mass history and paleocirculation history; (d) draw inferences on the history of changes in wind and precipitation patterns for the adjacent African and Antarctic continents; and (e) document the Paleogene transformation from a hot-house to an ice-house world.

(D) The plateau provides a unique middle latitude link between established low and high latitude zonal schemes. No such link was forged during previous ODP drilling in the Indian Ocean. This would (a) improve cross-latitude biostratigraphic correlations; and (b) improve middle and high latitude biostratigraphic resolution.

Participants:
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John Anderson
Geology and Geophysics
Wiess School of Natural Sciences
Rice University
P.O. Box 1892
Houston, TX 77251-1892

Robert Arends
Unocal Oil and Gas Division
UNOCAL Corporation
P.O. Box 6176
Ventura, CA 93006

Rosemary Askin
Department of Earth Sciences
University of California
Riverside, CA 92521

Jack Baldauf
Ocean Drilling Program
Texas A&M University Research Park
1000 Discovery Drive
College Station, TX 77845

Enriqueta Barrera
Department of Geological Sciences
University of Michigan
1006 C.C. Little Building
Ann Arbor, MI 48109-1063

John Barron
U.S. Geological Survey, MS 915
345 Middlefield Road
Menlo Park, CA 94025

Philip Bart
4825 Caroline Street, #5
Houston, TX 77004

Louis Bartek
10430 Parthenon Court
Bethesda, MD 20817

Anne Boersma
540 Gate Hill Road
Stony Pt., N.Y. 10980

Demetrio Boltovskoy
Dto. de Ciencias Biológicas
Facultad de Ciencias Exactas y Naturales
Universidad de Buenos Aires
1428 Buenos Aires
Argentina

Charles Breitsprecher
Earth Sciences Department
American River College
4700 College Oak Drive
Sacramento, CA 95841

Lloyd Burckle
Lamont-Doherty Geological Observatory
Columbia University
Palisades, N.Y. 10964

Judd Case
Department of Biology
St. Mary's College
Moraga, CA 94575

Jean-Pierre Caulet
Laboratoire de Geologie
43 rue Buffon
F7S 005 Paris
France

Steven Chambers
Scripps Institute of Oceanography
University of California
La Jolla, CA 92093

Paul Ciesielski
Department of Geology
1112 Turlington Hall
University of Florida
Gainesville, FL 32611

Alan Cooper
U.S. Geological Survey, MS 999
345 Middlefield Road
Menlo Park, CA 94025

Paul Dauphin
Submarine Geology and Geophysics
National Science Foundation
1800 G. Street, N.W.
Washington, D.C. 20550

Patrick De Deckker
Department of Geology
Australian National University
GPO Box 4
Canberra ACT 2601
Australia

Liselotte Diester-Haass
Fachrichtung Geographie
Universität des Saarlandes
6600 Saarbrücken
Germany

Eugene Domack
Department of Geology
Hamilton College
Clinton, N.Y. 13323

Robert Douglas
Dean of Science
University of Southern California
Los Angeles, CA 90089-0740

Helmut Ehrenspeck
7259 Del Norte Drive
Goleta, CA 93117

David Elliot
Byrd Polar Research Center
Ohio State University
Columbus, OH 43210

Julianne Fenner
Bundesanstalt für Geowissenschaften
und Rohstoffe
Stilleweg 2
D-3000, Hannover 51
Germany

Benjamin Flower
Department of Geological Sciences
University of California
Santa Barbara, CA 93106

Phillip Froelich
Lamont-Doherty Geological Observatory
Columbia University
Palisades, N.Y. 10964

Roy Fulwider
Unocal Oil and Gas Division
UNOCAL Corporation
P.O. Box 6176
Ventura, CA 93006

Joseph Gasperi
Department of Geological Sciences
University of California
Santa Barbara, CA 93106

James Hagadorn
Department of Geological Sciences
University of Southern California
Los Angeles, CA 90089-0740

Michael Hambrey
Scott Polar Research Institute
Lensfield Road
Cambridge CB2 1ER
England

Norman Hamilton
Department of Geology
University of Southampton
Highfield
Southampton SO9 5NH
England

David Harwood
Department of Geology
University of Nebraska
Lincoln, NE 68588-0340

Chris Hendy
Department of Chemistry
University of Waikato
Private Bag, Hamilton
New Zealand

David Hodell
Department of Geology
1112 Turlington Hall
University of Florida
Gainesville, FL 32611

William Howard
Department of Geological Sciences
Brown University
Box 1846
Providence, R.I. 02912

Brian Huber
Department of Paleobiology, NHB-121
Smithsonian Institution
Washington, D.C. 20560

Jeffrey Hyland
Marine Science Institute
University of California
Santa Barbara, CA 93106-6150

Scott Ishman
Byrd Polar Research Center
The Ohio State University
125 South Oval Mall
Columbus, OH 43210

John Jasper
Department of Geology, Rm. 307
Indiana University
Bloomington, IN 47405-5101

D. Graham Jenkins
The Old Chapel
Pitton, Rhossili
Swansea SA3 1PH
Wales, United Kingdom

Diana Kennett
Department of Geology
University of California
Santa Barbara, CA 93106

James Kennett
Marine Science Institute
University of California
Santa Barbara, CA 93106-6150

Lawrence Lawver
Institute for Geophysics
8701 Mopac Blvd.
Austin, TX 78759-8345

David Lazarus
Geologisches Institut
ETH-Zentrum
CH-8092 Zürich
Switzerland

Hsin Yi Ling
Department of Geology
Northern Illinois University
DeKalb, IL 60115

Jere Lipps
Museum of Paleontology
University of California
Berkeley, CA 94720

Douglas Long
Museum of Paleontology
University of California
Berkeley, CA 94720

Bruce Luyendyk
Department of Geological Sciences
University of California
Santa Barbara, CA 93106

Stephen Macko
Department of Environmental Sciences
University of Virginia
Charlottesville, VA 22903

Karen Margolis
Department of Geology
University of California
Davis, CA 95616

Stanley Margolis
Department of Geology
University of California
Davis, CA 95616

Kevin McCartney
Department of Geology
University of Maine at Presque Isle
Presque Isle, ME 04769

Andrew McMinn
Institute of Antarctic and
and Southern Ocean Studies
University of Tasmania
Box 252C, Hobart
Tasmania 7001
Australia

Gregory Mead
Department of Geology
1112 Turlington Hall
University of Florida
Gainesville, FL 32611

Hedwig Oberhaensli
Max-Planck Institut für Chemie
Abt. Biogeochemie
D-W-6500, Mainz 21
Germany

Suzanne O'Connell
Department of Environmental Sciences
Wesleyan University
Middletown, CT 06457-6034

Robert Oglesby
Department of Geological Sciences
Brown University
Box 1846
Providence, R.I. 02912-1846

Robert O'Hara
Division of Birds
National Museum of Natural History
Smithsonian Institution
Washington, D.C. 20560

Dorothy Pak
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, N.Y. 10964

Christopher Pereira
Department of Earth Sciences
Memorial University of Newfoundland
St. John's, Newfoundland
Canada A1B 3X5

Michael Prentice
Department of Geological Sciences
University of Maine at Orono
Orono, ME 04469

Douglas Pyle
College of Oceanography
Oregon State University
Corvallis, OR 97331-5503

Patrick Quilty
Australian Antarctic Division
Channel Highway, Kingston
Tasmania 7050
Australia

Frank Rack
Ocean Drilling Program
Texas A&M University Research Park
1000 Discovery Drive
College Station, TX 77840

Christian Robert
Geologie du Quaternaire
CNRS - Luminy
Case 907
13288 Marseille Cedex 9
France

Annika Sanfilippo
Scripps Institute of Oceanography
University of California
La Jolla, CA 92093

Reed Scherer
Byrd Polar Research Center
The Ohio State University
125 South Oval Mall
Columbus, OH 43210

Cynthia Schneider
Department of Geological Sciences
University of California
Santa Barbara, CA 93106

David Scholl
Branch of Pacific Marine Geology
U.S. Geological Survey, MS 999
345 Middlefield Road
Menlo Park, CA 94025

Daniel Schrag
Department of Geology
University of California
Berkeley, CA 94720

Aldo Shemesh
Department Environmental Science
and Energy Research
Weizmann Institute of Science
76100 Rehovot
Israel

Elizabeth Sikes
I.A.S.O.S.
University of Tasmania
GPO 252 C, Hobart
Tasmania 7004
Australia

Lisa Cirbus Sloan
Department of Geological Sciences
University of Michigan
1006 C.C. Little Building
Ann Arbor, MI 48109-1063

Christine Smith
Department of Geology
University of California
Berkeley, CA 94720

Lowell Stott
Department of Geological Sciences
University of Southern California
University Park
Los Angeles, CA 90089-0740

William Stout
1468 Loma Vista
Pasadena, CA 91104

Atsushi Takemura
Geoscience Institute
Hyogo University of Teacher Education
Yashiro-Cho, Kato-gun
Hyogo 673-14
Japan

Carol Tang
Department of Geological Sciences
University of Southern California
Los Angeles, CA 90089-0740

Ellen Thomas
Department of Earth Sciences
University of Cambridge
Downing Street, Cambridge CB2 3EQ
England
United Kingdom

Elizabeth Truswell
Bureau of Mineral Resources
P.O. Box 378
Canberra, ACT 2601
Australia

Dietz Warnke
Department of Geological Sciences
California State University
Hayward, CA 94542

Peter-Noel Webb
Dept. of Geological Sciences
Ohio State University
107 Mendenhall Laboratory
125 South Oval Mall
Columbus, OH 43210-1398

Wuchang Wei
Department of Geology
Florida State University
Tallahassee, FL 32306

Sherwood Wise
Department of Geology
Florida State University
Tallahassee, FL 32306

Thomas Wolf
GEOMAR Research Center for Marine Geosciences
Wischhofstrasse 1-3
D-2300, Kiel 14
Germany

Fay Woodruff
Dept. of Geological Sciences
University of Southern California
Los Angeles, CA 90089-0740

James Wright
Lamont-Doherty Geological Observatory
Columbia University
Palisades, NY 10964

Andy Wyss
Department of Geological Sciences
University of California
Santa Barbara, CA 93106

Elizabeth Semele Yuan
Department of Geological Sciences
University of Southern California
Los Angeles, CA 90089-0740

James Zachos
Department of Geological Sciences
University of Michigan
1006 C.C. Little Building
Ann Arbor, MI 48109-1063

Herman Zimmerman
Polar Earth Sciences, Div. Polar Programs
National Sciences Foundation
1800 G. Street, N.W.
Washington, DC 20550

William Zinsmeister
Dept. of Earth and Atmospheric Sciences
Purdue University
West Lafayette, IN 47907