International Council for Science

SCAR report

No 16
April 1999

Contents

SCAR Antarctic Offshore Statigraphy Project (ANTOSTRAT)

Published by the

SCIENTIFIC COMMITTEE ON ANTARCTIC RESEARCH

at the

Scott Polar Research Institute, Cambridge, United Kingdom

INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS

SCIENTIFIC COMMITTEE ON ANTARCTIC RESEARCH

SCAR Report

No 16, April 1999

Contents

Published by the

SCIENTIFIC COMMITTEE ON ANTARCTIC RESEARCH

at the

Scott Polar Research Institute, Cambridge, United Kingdom

SCAR Antarctic Offshore Stratigraphy Project (ANTOSTRAT)

Report of a Workshop on

ANTARCTIC LATE PHANEROZOIC EARTH SYSTEM SCIENCE

Hobart, Australia

6-11 July , 1997

Compiled by

Peter-N. Webb[1] and Alan K. Cooper[2]

[1] Department of Geological Sciences and
Byrd Polar Research Center,
The Ohio State University
Columbus, OH, 43210 USA
E-mail: webb.3@osu.edu

[2] U.S. Geological Survey
MS 999
345 Middlefield Road
Menlo Park, CA 94025 USA
E-mail: acooper@usgs.gov

CONTENTS

EXECUTIVE SUMMARY

In June 1996, the Antarctic Offshore Stratigraphy Programme (ANTOSTRAT) was tasked by the Scientific Committee on Antarctic Research (SCAR), to convene a workshop in Hobart, Australia. The purpose was to gather a representative group of interested Antarctic Earth scientists to outline critical themes for investigation of Antarctic paleoenvironments during Cretaceous and Cenozoic times (the last 130 million years), and to recommend objectives and priorities for the next decade. A group of 40 scientists from 11 countries met for this purpose in July 1997 along side a parallel workshop for the Antarctic Ice Margin Environment Group (ANTIME), which focuses on the last 200,000 years. This report details the background, discussions, findings and recommendations of the ANTOSTRAT workshop.

The workshop recognized the extensive seismic database already organized through ANTOSTRAT, and the value of the Seismic Data Library System (SDLS), in developing Ocean Drilling Program (ODP) proposals for circum-Antarctic drilling (Antarctic Peninsula, Ross Sea, Wilkes Land, Prydz Bay, Weddell Sea), as well as the fast-ice drilling of Cape Roberts (McMurdo Sound). Participants reviewd and confirmed the necessity for geologic sampling of continental shelf and rise deposits, acknowledging the direct but incomplete record of the shelf and the indirect but more complete record of the rise. They also supported the importance of shallow drilling and coring of different sectors of the Antarctic, recognizing the major differences in behavior and timing of glaciation between East and West Antarctic ice. With the new round of large-scale drilling programs about to begin (ODP Leg 178 (Antarctic Peninsula) and Cape Roberts drilling), it was considered important to maintain momentum toward future drilling. At the same time, the group saw the need to focus on the use of data from sediment cores (age, depositional environment, paleoclimate) in improving scenarios of past ice and climate behaviour through ice sheet and climate modeling.

The workshop concluded that the focus for the next decade (1998-2008) should be the onset and development of Antarctic glaciation, and that this was best pursued through the following activities:

- Gathering geoscience data [especially cores of sedimentary sequences beneath the Antarctic margin] for working with climate and ice sheet modelers in order to
  - a. prepare a series of maps of the Antarctic region to illustrate ice and climate scenarios at selected intervals through Cretaceous and Cenozoic time, and
  - b. identify the main linkages with the rest of the planet throughout this period.
- promoting and coordinating ODP drilling proposals, as well as interacting with ODP bodies.
- promoting the use of existing sampling systems (coring, Cape Roberts Project drilling etc)
- encouraging the development and the use of new shallow drilling systems.

The plan for the next 4 years (1998-2002) is to work principally on core and sample recovery and interpretations, with some involvement of modelers and sector by sector assessment, followed by a broad review of results at a dedicated symposium in 2002.

The workshop report also outlines the evolution of the project from the initial ANTOSTRAT initiative under the Group of Specialists (1989-1996) to the current ANTOSTRAT committee, under the joint Working Groups on Geology and Solid Earth Geophysics, that was approved by SCAR in July 1998. It is hoped that this document will be a useful tool for all National Antarctic Programs.

INTRODUCTION

Since the early 1970's, offshore drilling by the Deep Sea Drilling Project and Ocean Drilling Program, and fast-ice drilling in McMurdo Sound, provided major advances in our understanding of Antarctic climatic and tectonic history through Cenozoic times - a period of geographic isolation for the Antarctic continent and one which witnessed the replacement of relatively diverse marine and terrestrial environments by ice sheets. Also during the 1970's and 1980's, seismic surveys of strata beneath the Antarctic continental shelf were conducted by many countries and raised concerns about the use of these data for oil exploration as well as investigation of Cenozoic history. In 1986, a Workshop on Cenozoic Palaeoenvironments was held at the SCAR meeting in San Diego, and from that meeting emerged a plan for a Group of Specialist to coordinate and promote research on this broad topic. This was approved by SCAR and the Group began work in 1988.

At an early stage, it was realized that there needed to be a focus on the growing body of seismic data being collected around the Antarctic margin, both because of its scientific value and also the political sensitivity to possible misuse. This led to the formation of ANTOSTRAT (Antarctic Offshore Stratigraphy Project), which, during a meeting at Asilomar (California) in 1990, set up a series of regional working groups to organize the seismic data in five regions of the Antarctic margin (Fig. 1), and to use these data as the basis for proposals for coring key strata in each region, under the aegis of the Ocean Drilling Program (ODP).

In August 1996, the Group of Specialists on Cenozoic Paleoenvironments of the Southern High Latitudes (GOSC) concluded its 10-year term, by reporting its activities to the Working Group on Geology, the Working Group On Solid-Earth Geophysics, and the SCAR delegates at XXIV SCAR, Cambridge. GOSC was able to point to an extremely active decade of workshops, conferences, and successful initiatives involving Ocean Drilling Program and non-ODP drilling programs. However, there was a general feeling within the SCAR Earth Science Working Groups that continuing coordination of seismic activities and strenuous promotion of drilling activities would be required well beyond 1996 in order to maintain the momentum achieved over the past decade.

The Group of Specialists (GOSC) proposed, via a document circulated in advance of the SCAR meeting, that the joint working groups request that a new Group of Specialists on Late Phanerozoic Earth System Science be established. After extensive discussions, the joint working groups concluded that (SCAR Bulletin No. 126, July 1997, page 20, item 8a through d)

"such prioritization and coordination (of future Late Phanerozoic science activities) require further thought that is probably best organized through the medium of an open Workshop, and that a new Group of Specialists is highly desirable, but could be much better formulated as an outcome of the Workshop deliberations, and then proposed to XXV SCAR." (Item 8d)

SCAR Delegates then recommended that the successful ANTOSTRAT Project be extended for two years as the ANTOSTRAT Programme to accomplish two principal tasks:

- Coordinate scientific drilling/coring projects, including those of the Ocean Drilling Program, for the Antarctic margin and
- Convene a workshop in Hobart, Australia, during the period 6-11 July 1997 to outline important topics and priorities for the next decade of geoscience research in Antarctica.

ANTOSTRAT convened such a workshop at Hobart, at the same time as the ANTIME (Antarctic Ice Margin) group conducted a similar meeting. The two groups have many earth science thematic, climatic, and process-oriented interests in common but work on distinctly different time scales. Whereas ANTIME focuses on the last 200,000 years, the ANTOSTRAT group considers relationships and interactions within the Geosphere-Hydrosphere-Biosphere over the past 130 million years (Cretaceous-Cenozoic) of Earth history. The ANTOSTRAT Workshop at Hobart identified and discussed the most critical Cretaceous-Cenozoic earth science issues, priorities and goals for the next decade. Scientists from eleven SCAR nations contributed to this planning workshop. This report provides a record of the meeting and its recommendations.

Before the workshop, coordinators for each major thematic issue and geographic region were identified. These individuals compiled background information and lists of important unresolved research topics. Their contributions, mostly as submitted, form Appendix 7 of this report. The draft report was circulated to all participants prior to the workshop. In Hobart, the thematic issues and regional imperatives were discussed, priorities were assigned to research directions, and recommendations made. The body of this report lists the results of those discussions. The final task of the workshop was to attain a consensus statement from the research community, as to how SCAR could facilitate this research.

The consensus statement from the workshop (see next section) emphasized the need for acquiring geologic samples via coring and drilling in support of paleoenvironmental studies. The statement was subsequently reviewed by SCAR Executive and then rephrased by the ANTOSTRAT Steering Committee into a series of three recommendations to SCAR (Appendix 6A,B), to establish a special SCAR subgroup that, like its predecessor ANTOSTRAT would facilitate and coordinate implementation of the above field and laboratory studies.

A revised version of the draft workshop report, including the three recommendations, was circulated to all members of SCAR Executive and the Working Groups on Geology and Solid Earth Geophysics prior to the SCAR XXV meeting (Concepcion, Chile; July, 1998). In Concepcion, extensive discussions led to a formal recommendation from the Joint Working Groups (JWG) (Appendix 6C) that an ANTOSTRAT Subcommittee under the JWG be established to accomplish the above tasks. The JWG recommendation was subsequently approved by SCAR delegates during the SCAR XXV meeting.

The activities of the Hobart Workshop and the actions at SCAR XXIV and XXV described in the following report reflect the major efforts by a broad cross-section of Antarctic earth-science community to define important research directions for the coming decade, and how they can best be accomplished.

It is hoped that this report will be a useful tool for all National Antarctic Programs.

CONSENSUS STATEMENT DEVELOPED AT WORKSHOP PLENARY SESSION

The following statement was developed during the Hobart workshop and accepted by a consensus vote of all workshop participants, representing 11 countries.

"*Coordinating Committee on Antarctic Glaciation - Onset and Development

The Antarctic continent has, on account of its polar position over the last 130 million years, had a profound and fundamental effect on the Earth's climate history and palaeoenvironments over this time. It is also a region most sensitive to future climate change. Therefore it is of extreme importance to document the variations in Antarctic ice sheet history since the transition from the warm Cretaceous period (130-65 million years) through the "dynamic" ice sheets of the early Cenozoic to the more or less persistent ice sheet of the present, as well as to understand the mechanisms behind ice volume fluctuations within this time frame. The long time perspective is necessary because temperature-forcing atmospheric gases, such as CO^2, have already exceeded Quaternary interglacial values by around 30% and continue to rise. Climate scenarios for the next centuries should therefore take into account scenarios for pre-Quaternary Antarctica.

Past SCAR-sponsored activities (the Group of Specialists on Cenozoic Paleoenvironments and its ANTOSTRAT project) have set a solid basis for a qualitative documentation of the evolution of the Antarctic ice sheet, through syntheses of seismic stratigraphic studies around the Antarctic margin. These studies have led to an appreciation of the complexity of behavior of past ice sheets, with the possibility of substantial variations from one region to another. There is now a need to go beyond the reconnaissance level of understanding reached, by identifying new research approaches, both thematically and geographically. An essential requirement is obtaining "ground truth" by drilling in order to calibrate and extend our seismic interpretations, which have been largely responsible for present models of glacial processes.

We wish to propose through the Working Groups of Geology and Solid Earth Geophysics that SCAR establish a new *Coordinating Committee to promote and coordinate a range of programs to investigate the onset and development of Antarctic glaciation. These would include ground-truthing our seismic interpretations through the Ocean Drilling Program, through other existing coring and drilling systems, and through shallow drilling techniques currently under development.

The ultimate goal of the group is a series of scenarios illustrating Antarctic geography, climate, ice and sheets at selected intervals through Cretaceous and Cenozoic time. This will need to involve close interaction with climate and ice sheet modelers. In addition, the work proposed will lead to improvements in the range of models used for interpreting the sedimentary record, as well as to a much improved understanding of links between geography, climate, ice sheet and sea level responses, along with interactions with other parts of our planetary system.

Task for the new group

To investigate the onset and development of Antarctic glaciation by:

- Gathering geoscience data for working with climate and ice sheet modelers to
- a. prepare a series of maps of the Antarctic region to illustrate ice and climate scenarios at selected intervals through Cretaceous and Cenozoic time, and
- b. identify the main linkages with the rest of the planet throughout this period.
- promoting and coordinating ODP drilling proposals, as well as interacting with ODP bodies.
- promoting the use of existing sampling systems (coring, Cape Roberts Project drilling etc)
- encouraging the development and the use of new shallow drilling systems."

* the statement from the Hobart Workshop called for either a Group of Specialists or a Coordinating Committee. Subsequent discussion has persuaded the ANTOSTRAT Steering Committee that a Coordinating Committee would be the appropriate body to set up to achieve the goals of the community. As a postscript, at SCAR XXV (July 1998), the name approved was the ANTOSTRAT Subcommittee.

SUMMARY STATEMENTS ON DATA BASES, CURRENT AND PLANNED PROJECTS, TECHNOLOGY, AND THEMATIC ANDREGIONAL EARTH SCIENCE ISSUES

Introduction

Late Phanerozoic Global Change Challenges

The last 130 million years of the Phanerozoic Eon (Cretaceous, Tertiary, and Quaternary Periods) were marked by major latitudinal and longitudinal transport of continents, significant interaction between plates, very active sea floor spreading and evolution toward modern ocean configurations (Fig. 2). Further, these global events were also associated with ever-evolving ocean current circulation systems, eustatic oscillations, major biotic adjustments, at time rapid organic evolution, significant shifts in the demarcation of biogeographic province boundaries, and the transition from a "warm" hothouse Earth to a "cold" bipolar icehouse Earth. It is generally accepted that these and other geological phenomena are linked in an over-arching Earth System that involves an interrelation between the paleo-geosphere, atmosphere, hydrosphere and biosphere.

What has been the role of continental Antarctica and the south polar oceans in global late Phanerozoic earth system science? The earth science community in general, and the south polar research community in particular accept, that the Antarctic region has affected geological history in other regions of the globe, particularly during the last ~50 million years. Geologic and climatic events in the lower latitudes also impacted the southern high latitude record intervals of the Late Phanerozoic.

The Hobart Workshop provided an opportunity for a cross-section of the earth science community to review the vast progress made in the southern high latitudes in the past four decades since the International Geophysical Year (1957-58), and to identify and discuss the most important unresolved earth science research issues. Earth scientists have advanced from the initial reconnaissance phases to now, when we have diverse and comprehensive data bases, and advanced land- and sea-based technologies.

Most importantly, the south-polar earth-science sub disciplines have recently moved to promote investigation of thematic and process issues, generate hypotheses, test hypotheses, and consider linkages between related and disparate data bases within and beyond the south polar realm.

The central concept behind the 1997 Hobart Workshop was a comprehensive preview of the next decade (1998-2008), with special emphasis on where and how to promote the further development of thematic and geographic data bases in all sub disciplines; and integration of these with major global programs that share the same basic objectives (Webb, Appendix 7.1, this report).

Data Bases, Current and Planned Projects, and Technology Issues

ANTOSTRAT Seismic Data Library System (SDLS): The Antarctic Seismic Data Library System provides open access to multichannel seismic reflection data collected by all countries (Fig. 3) that have been involved in Antarctic geophysical research, to facilitate large-scale cooperative research programs. In 1991 the SDLS was formally implemented under Antarctic Treaty Consultative Meeting (ATCM) Recommendation XVI-12. The SDLS has established library branches in 10 countries and provides three principal functions, i.e. education, data protection, and data storage. The SDLS operates under the general auspices of the Scientific Committee on Antarctic Research, and is currently overseen by the ANTOSTRAT Project. Management costs are underwritten by the U.S. National Science Foundation, U.S. Geological Survey, and the Osservatorio Geofisico Sperimentale (Trieste, Italy). Until the end of 1998 SDLS will be overseen by the SCAR ANTOSTRAT Project; thereafter the SDLS will be associated with either the Working Group On Solid-Earth Geophysics or a new SCAR-appointed Group of Specialists or Coordinating Committee (Cooper and Brancolini, Appendix 7.2, this report).

Priorities and goals:

- A Workshop should be convened, with the participation of the entire MCS data collection community, to review the Seismic Data Library System (SDLS) operating guidelines and technologies to be used in the coming decade. An ad-hoc committee should be established to work on technical issues of updating and upgrading the Seismic Data Library System. New procedures need to be outlined and implemented to assure timely submission of data to the SDLS.
- Establish links to the SCAR Antarctic master data directory and their associated data management groups.
- Complete submittal and input of all onshore and offshore multichannel seismic-reflection (MCS) data in SEG-Y format, with navigation, older than 4 years to the SDLS.
- Make images of Antarctic MCS data openly accessible via the World Wide Web, at a resolution compatible with the SDLS policies of assuring intellectual property rights.

ANTOSTRAT Antarctic Margin Ocean Drilling Program Initiatives: During the early 1990's it was apparent that the ANTOSTRAT seismic data base was mature enough to be used in planning a comprehensive stratigraphic drilling strategy for several regions of the Antarctic margin. Prime objectives of the coordinated effort were broadly defined to include deciphering the glacial history of the Antarctic continent, to link this history to global records of sea-level oscillations, paleoclimates, paleoceanography, organic (evolution, and atmospheric circulation. Another critical objective was to correlate Antarctic seismic stratigraphy with well-documented and dated sedimentary successions. The ambitious undertaking and acquisition of sedimentary records to depths of 1000m below the sea floor in abyssal water depths demanded involvement with the Ocean Drilling Program (ODP). Direct interactions between ANTOSTRAT and ODP resulted in the preparation and submission of five region drilling proposals. These proposals called for drilling legs on the Pacific margin of the Antarctic Peninsula, in the Weddell Sea, Prydz Bay, the Wilkes Land margin, and the Ross Sea. At the present time (July, 1998), the Antarctic Peninsula program has been completed as ODP Leg 178 (Fig. 4), a drilling leg (Leg 188) in Prydz Bay has tentatively been scheduled for 2000, and the proposals for the three remaining regions are in advanced stages of review and consideration by panels of the Ocean Drilling Program (Barker, Appendix 7.3, this report).

Priorities and goals:

- Continue to strengthen and promote the remaining ANTOSTRAT/ODP proposals as they continue through ODP's panel-review structure, to becoming mature proposals ready for drilling, if scheduled by ODP.
- Seek support from National Antarctic Programs to provide an ice-picket ship (or a National Program vessel) for each of the ODP drilling legs. The ice-picket ship is mandatory for aiding high-latitude drilling.
- Maintain close and active interactions with ODP as this organization charts its future global drilling program and operations schedule; and continue to develop thematic arguments for continued deep ship-based drilling early in the next century.

Deep Stratigraphic Drilling in Antarctica Outside the ODP Organization: Knowledge of geology of the Antarctic continental shelf and surrounding deep ocean basins has benefited from past DSDP and ODP drilling campaigns (Legs 28, 35, 113, 114, 119, 120, and 178) between 1972 and 1998. Terrestrial programs such as the land-based Dry Valley Drilling Project, and littoral sea ice-based MSSTS, CIROS and Cape Roberts Project have also contributed a wealth of additional stratigraphic, chronostratigraphic, basin history and paleoclimate data to the Ross Sea sector of Antarctica, and strengthened linkages with the above-mentioned DSDP and ODP activities. (Barrett, Appendix 7.4, this report).

Priorities and goals:

- Maintain a strong technical and organizational knowledge base on drilling operations in many environments, e.g. on-land, ice sheets, ice shelves, marginal sea ice, etc.
- Due to the fact that such drilling ventures are complex, costly, and that planning and execution normally extend over five or more years, it is considered a priority that the effort be an international rather than a single national program undertaking.
- Consider ways in which a variety of advanced drilling and ancillary equipment can be purchased by the Antarctic community, maintained at a high level of operational and maintenance readiness, and in near-constant use.
- Initiate communication with Arctic earth science communities to ascertain whether a degree of shared use of the more modular and portable equipment might be possible.
- Continue to develop a strong science rationale for new drilling areas and sites; at the same time ensuring that adequate site seismic data is available for favored drilling targets.
- Identify priorities for future drilling such as, deep sampling of the Neogene record below Ross Island, sampling the remote sea floor deeps from sea and ice shelf platforms (e.g. Skelton , Beardmore , Byrd, and Drygalski deeps, in up to 1,000m of water), and the Amery Graben basins.

Shallow Drilling Technology and Sampling of Late Phanerozoic Targets: A variety of conventional bottom sampling devices, such as grabs and corers, have encountered pre-Holocene or pre-Quaternary sediments at or close to the sea floor on Antarctic continental shelves. Seismic stratigraphic data indicate that Neogene, Paleogene and Cretaceous sediments are very widely distributed and may be sampled by devices capable of up to 50 meters penetration. A variety of ship-mounted shallow drilling rigs are used in industry and might be suitable for use in Antarctic waters. The Norwegian Terra Bor System (A/S Terra Bor-Namsos, Norway), now called Geo Drilling, is under development for use in polar environments, with prototypes having undergone one Arctic and two Antarctic seasons of testing. Shallow drilling procedures will allow transect drilling and sampling along dip and strike lines, and allow the construction of composite successions. It will also allow much broader areal coverage of targets than is possible with conventional single site deep drilling techniques (Kristoffersen, Appendix 7.5, this report).

Priorities and goals:

- Develop a portable shallow drilling unit that may be mounted on ships and deployed under Antarctic conditions, and over most areas of the Antarctic continental shelf.
- Verify the existence and availability of suitable ship platforms for shallow drilling equipment.
- Encourage a qualified group of scientists obtain the necessary funding for a pilot venture.
- Conduct tests of drilling procedures and ship handling under Antarctic conditions.
- Obtain undisturbed sediment cores more than 50 m in length and in water depths up to 1,000 m.
- Use drillcore recovered by shallow drilling procedures in ground-truthing seismic stratigraphic data.

Thematic Issues

Late Mesozoic and Cenozoic Plate Tectonic and Crustal History of Antarctica: Much of the Late Mesozoic and Cenozoic geologic history of Antarctica is contained in the sedimentary sequences on the continental shelves. That history, however, in a large measure reflects the evolution of the Antarctic Plate, including both its plate tectonic and its crustal development. The Antarctic Plate was created by the break-up of Gondwanaland and today, except for the Scotia region, is bounded by spreading ridges. The Antarctic continental shelves rimming the East Antarctic craton are passive margins resulting from the separation of southeastern Africa, India, and Australia. The remaining part of the continent has a complex history, which includes fragmentation into microcontinents or blocks, rotations and displacements of those blocks, and subduction and passive margin evolution. In general, the post-break-up history can be divided into: the mid Jurassic to mid Cretaceous, by which time the Antarctic continent had attained its present configuration and essentially polar position; and the mid Cretaceous (130 Ma) to Recent. During the latter time interval break-up between Antarctica and Australia/New Zealand occurred, the link between South America and the Antarctic Peninsula was severed, and events leading up to the present day rift system through West Antarctic ensued (Elliot, Appendix 7.6, this report).

Priorities and goals:

- Examine linkages between whole plate-to-regional scale tectonic and structural deformation histories and phases, on the major terrestrial paleotopographic, paleoceanographic, sedimentary basin development, and paleoclimate phases and events, within, around, and well beyond Antarctica; and present these data in a form and scale that is useful in future climate modeling activities.

- Comprehend the relationships between deep ocean circulation gateways and regional tectonic events, in regions such as the East Antarctica-Australia passive margins, and the South America-Antarctic Peninsula connection.
- Investigate the evolution and timing of major rift system development and the histories of associated sedimentary basins, in regions such as the Amery Graben-Prydz Bay, Ross Embayment, and Weddell Embayment.
- Decipher regional and larger scale vertical movements of the Antarctic crust and the role these phases and events played in determining paleoclimate, location of major sedimentary basins and regional climate, in such areas as Marie Byrd Land, Ellsworth Mountains, Transantarctic Mountains, and the margins of East Antarctica from 20 degrees West to Prydz Bay.
- Establish the existence, extent, glacial-deglacial, and sedimentary record of epicontinental seas on Antarctica, in such regions as the Wilkes Land continental shelf margin and in the Wilkes Subglacial Basin.

Geological Time, and Relative and Absolute Dating Systems: The primary objective of "ground-truthing" seismic stratigraphy, through coupling these data with well documented drillhole data, must involve consideration of geological time at several resolution scales. The ANTOSTRAT mandate cannot be attained without the existence and application of a robust chronostratigraphic framework in the five Antarctica regions of principal interest. As a minimum standard, the chronostratgraphic framework should be capable of resolving problems of correlation, recognition of time spans, establishing rates of processes, etc, to at least a resolution of 2 million years. Such a capability would allow solution of major earth science problems and issues within Antarctica; and the accurate relating of Antarctic marine and terrestrial events with coeval events elsewhere on Earth. Regrettably, Antarctic Cretaceous and Cenozoic chronostratigraphy still lags far behind that available to workers in other regions of the globe (Webb, Appendix 7.1, this report).

Priorities and goals:

- Identify from among continuously cored drillholes in several regions, those successions that provide near continuous records of marine sedimentation and might serve as representative regional standard sections. Develop detailed data bases on biostratigraphy, magnetostratigraphy, biochronostratigraphy, geochronology and chronostratigraphy, etc, for each regional standard section.
- Where possible, and in the interests of providing longer spans of time coverage in a specific regions, several regional standard sections might be combined to provide a comprehensive regional standard section. This will require a sound understanding of stratigraphic overlap and gap problems between regional standard sections.
- Attempt, by use of a wide variety of correlation and dating tools, to relate Antarctic comprehensive regional standard sections with high (time) resolution schemes developed and successfully used in the Southern Ocean, Australia and New Zealand.
- Identify and encourage investigation and use of new absolute and relative dating technologies that might contribute to improved chronostratigraphy of Antarctic Cretaceous and Cenozoic rocks.

Continental Shelf Sedimentary Basins: The most direct record of Antarctic climatic history over the past 130 million years is to be found in the blanket of sediment that covers the Antarctic continental shelf. The sediment pile ranges in thickness from zero up to approximately 14 km. The location of greatest thickness, the sedimentary basins, are typically tens to hundreds of kilometers across and vary in shape from subcircular depressions to half grabens to linear troughs. From limited knowledge obtained thus far on the age of the sediments in the basins, there appear to have been two main periods of basin development: the first a consequence of Gondwanide fragmentation during the Cretaceous resulted in the syn-rift episode of basin filling; and the second, post-rift phase, occurred during the Paleogene and or Neogene. Understanding the differential subsidence history of the numerous continental shelf basins around the Antarctic margins is important for two reasons. First, basin subsidence was active in the different basins at different times and a combining of stratigraphic records is necessary for the reconstruction of complete histories in any single region. Second, rapid subsidence has the potential for providing complete and high resolution records. However, success in piecing together records from different basins requires unambiguous correlation and an accurate chronology, for which data from both seismic surveys and drillhole must be combined (Barrett, Appendix 7.7, this report).

Priorities and goals

- Identify drillsites and obtain cores from sedimentary basins on the Antarctic continental shelf likely to provide a stratal record representing syn-rift post-rift and other tectonic phases or events in individual basin evolution, and likely to offer complete or near complete coverage of the Cretaceous and Cenozoic time span.
- Recover Cretaceous-Cenozoic marine successions from continental shelf environments that portray the principal geological events in terrestrial (or continental) and near-shore marine Antarctica; and at the same time were directly connected to the circum-Antarctic oceans throughout their history.
- Identify specific marine successions from continental shelf basins in different regions which because of their

high sedimentation rates, lack of hiatuses, and fossil content, might be designated as regional standard sections, and offer potential for improving Antarctic chronostratigraphy, geochronology, biostratigraphy, and magneto-stratigraphy.

- Identify sedimentary basins likely to provide drillcore successions that span the pre-glacial and glacial phases of Antarctic Late Phanerozoic history.
- Identify sedimentary basins likely to provide a highly conformable stratigraphy that might be utilized in advancing understanding of sequence stratigraphy and eustatic oscillations at 2nd order supercycle and cycle (3rd order and higher) resolutions; and which is directly related through lithofacies analysis of the same successions to glacial-deglacial cycles driven by changing terrestrial climates.
- Identify high sedimentation-high resolution successions that permit detailed investigation of ice sheet-shelf or glacier driven depositonal systems and cycles, where cycles might represent centenial and millenial durations.

Paleoceanography and Circum-Antarctic Deep-Sea Marine Biosphere History: Significant Mesozoic-Paleogene global and regional paleoenvironmental events that help delineate the evolution of the Southern Ocean are discussed in detail by Harwood and Wise (1995, in P.-N. Webb and G.S. Wilson, editors, Byrd Polar Research Center, Report No. 10, pp. 47-53). A selection of primary objectives is provided here. See also Wise, Appendix 7.8, this report)

Priorities and goals:

- Recover core from Jurassic-Lower Cretaceous successions in the Weddell Sea-Dronning Maud Land region that will contribute knowledge of the early break-up history, the development of anoxic black shale basins and ventilation of these basins later in the Early Cretaceous.
- Recover core from any part of the continental margin that provides complete stratigraphic coverage for the Upper Cretaceous; thereby contributing to the development of high latitude chronostratigraphy and biostratigraphy, and improved understanding of latest Mesozoic ocean circulation patterns; and also contributing to biogeographic distribution of taxa and their evolutionary details.
- Recover core from uppermost Cretaceous (Maastrichtian)-lowermost Tertiary (Danian) successions anywhere along the continental margin, to be used in deciphering the biotic impact at high latitudes of the hypothesized Chicxulub (Mexico) impact structure, including records of extinction and survival among planktic and benthic fossil groups; and consider the possibility that Antarctica served as a refugium from K/T devastation so apparent in the lower latitudes.
- Recover core from Paleocene-Eocene boundary marine successions anywhere along the Antarctic margin that permits further investigation of the hypothesized Late Paleocene Thermal Maximum Event (first proposed from Maud Rise), the associated reversal of latitudinal global circulation patterns, and the accompanying massive global benthic extinction event.
- Recover core from Paleogene successions anywhere along the Antarctic marine margin that provides further data on the inception of glaciation, particularly regional data on the pre-glacial-glacial transition, and the relationship between these events and the global shift from greenhouse to icehouse climates. Current interpretations based on in situ evidence suggests that this threshold occurs within the Upper Eocene.
- Using new core materials from Southern Ocean sites around Antarctica, continue the development of high resolution biostratigraphic schemes based on both calcareous and siliceous microfossil groups; direct attention to studies which emphasize relationships between Cretaceous-Cenozoic marine faunal biogeography, high latitude seaway circulation paths around and through Antarctica, and the tectonic influence on ocean water gateways and barriers; and consider the evolutionary relationships between Paleoaustral and Neoaustral biogeograhic elements to lower latitude shelf to abyssal provinces.

Glaciomarine Sedimentary Processes, Events and Stratigraphy: Glacial and climatic records are best inferred by using quantitative, predictive models based on well documented processes that are active today. In the high latitude marine there is potential for major variability on environments and processes in both time and space. This translates as rapid vertical and lateral changes in stratigraphy and lithofacies (Powell, Appendix 7.9, this report)

Priorities and goals:

- Execute closely coordinated programs of three dimensional seismic surveying and stratigraphic drilling and core recovery at very high resolutions.
- Establish a series of standard successions in which characterization of unique seismic and sedimentologic stratigraphies, structures and geometries are linked.
- Characterize subglacial and grounding line depositional systems with a view to interpreting glacial dynamics in this crucial environment.
- Develop quantitative models for accumulation of glacial sedimentary packages on the Antarctic margin, with the aim of integrating glacial geological and glaciological modeling.

Terrestrial Geology: The Late Phanerozoic terrestrial record is the most poorly understood of all major continental landmasses. Perhaps as little as 15 percent of the last 130 m.y. is documented, even to a reconnaissance level. Prior to the Pliocene, terrestrial environmental and climatic scenario's depend almost enirely on analyses of proxy data recovered from the continental shelves and deep sea by the Deep Sea Drilling Project and Ocean Drilling Program. Because of the probability of recycling and other problems, such data cannot usually be used to make high time resolution interpretations of events in specific regions of Antarctica. Much of the existing Cretaceous and Cenozoic terrestrial data is derived from locations along the margins of West and East Antarctica, e.g. Antarctic Peninsula, Amery Graben-Prince Charles Mountains, and the Transantarctic Mountains. Central themes of the ANTOSTRAT initiative involve consideration of past climates (glaciation and deglaciation), sediment budgets, tectonic histories, and sea level oscillation, etc, all interpreted primarily from the continental shelf data but strongly influenced by the terrestrial record. It follows then, that investigation of Antarctica's terrestrial realm must be accorded renewed urgency (Webb, Appendix 7.10, this report).

Priorities and goals:

- Accord the highest priority to geophysical surveying beneath the West and East Antarctic Ice Sheets; with emphasis on close contour sub-ice sheet topographic mapping, structural geology, delineation and extent of possible Cretaceous-Cenozoic sedimentary basins, recognition of mountain uplands and principal drainage systems, and the existence of major tectonic features. Such a program might be couple with glaciology programs.
- Plan sub-ice deep stratigraphic drilling legs. Any future drilling on land should be well distributed geographically in the initial phases. The basic geology for vast areas of the Antarctic interior is unknown and all regional programs should maintain a strong reconnaissance survey element.
- Geophysical and geological drilling activities should have a strong regional element,
- on the assumption that the terrestrial record in different parts of Antarctica is not identical and involved histories that evolved within discrete mega-drainage systems. It is recommended that regional Southern Ocean ODP drilling and on-land drilling programs in the same region or sector be closely coordinated and perhaps treated as linked longitudinal transects.
- Encourage the development and testing of drilling systems that are capable of operating through a 2,000 to 3,000 meter ice column and sampling a variety of rock in sub-ice sheet environments.
- Immediate priority should be accorded plans to conduct geophysical and geological drilling in the trunk drainage systems that occur at many localities around the periphery of Antarctica, and might have served the role of sediment traps or basins, e.g. Beardmore and Amery valley systems.
- Refine existing outcrop geology in the continental margin areas, placing emphasis on those locations where stratigraphy and volcanic geology (ash deposits) can be combined to improve chronostratigraphy
- Using new drillhole/drillcore data obtained in terrestrial settings, compile stratigraphies, biostratigraphies, and chronostratigraphies; correlate these with offshore marine basins; and address time/space issues related to tectonic events, paleotopography, landscape evolution and weathering, glacial history and paleoclimate, and past marine invasions of the continent

Antarctic Seismic Stratigraphy: Seismic stratigraphic surveys have been completed across nearly all accessible regions of the Antarctic margin, resulting in the collection of more than 300,000 km of small-airgun single-channel data (SCS) and nearly 200,000 km of large-airgun multichannel seismic reflection data (MCS). A very detailed discussion is provided in (Cooper, Appendix 7.11, this report,).

Priorities and goals:

- Collect drillhole and sediment core data to contribute to the ground-truthing of seismic data.
- Expand and intensify acoustic data in some areas to support drillcore studies (e.g. high resolution site studies); and tie drillhole sample sites to seismic grids.
- Establish standard profiles in each geographic region for calibration of acoustic systems.
- Develop a catalog of acoustic facies and geometries for seismic features on all segments of the Antarctic margin, to establish, with ground truth information, a circum-Pacific seismic sequence stratigraphy model.
- Systematically drill and core characteristic facies and features to determine their depositional paleoenvironments (e.g. marine, proximal glacial, subglacial, etc) and relation to ice and sea level change.
- Develop a circum-Antarctic model for the evolution of the Antarctic icehouse seismic stratigraphies, i.e. the up-section progress from "normal-depth nonglacial" to overdeepened glacial" margin.
- Establish "global" stratigraphic links, i.e. shelf to abyssal basin; circum-Antarctic, etc.
- Extract additional information from seismic data using seismic waveform information, e.g. amplitude, phase, etc.

Seismic Characterization and Physical Properties: Physical property measurements are particularly well suited for down-hole logging. It provides advantages in that records are continuous stratigraphically and results will be much closer to real in situ conditions. A number of different sensors, combined in a variety of ways are available. For studies of Cenozoic sediments the most essential parameters to measure are, P-wave velocity, bulk density, lithology and magnetic properties (susceptibility and polarity). These are all standard parameters measured in ODP logging operations. Acoustic velocity can be measured with a vertical resolution of 20 cm and magnetic susceptibility with a resolution of 25 mm. Lithology and porosity information can be obtained from natural gamma tools combined with neutron tools (Solheim, Appendix 7.12, this report).

Priorities and goals:

- Improve interpretation of depositional environments and extend these regionally via correlation of core data to seismic stratigraphy.
- Measure a standardized set of physical properties and geotechnical parameters for all drill core
- Include a downhole logging program (using slimline tools in most measurements) in all drilling operations on the Antarctic continental margin. Define a minimum number of parameters that should be measured and standardize these to the highest degree possible.
- Obtain near-continuous, high resolution (1cm) non-destructive MST (Multi Sensor Track) measurements of stratigraphic variations in cores. Parameters such as velocity, density, natural gamma radiation and magnetic susceptibility, may provide direct records of paleoenvironmental variations.
- Where appropriate, use MST data in producing composite records from multi-hole drill sites. This procedure is especially useful in linking multiple shallow drillholes on transects. MST data should be used in choosing sampling intervals for geotechnical testing.
- Geotechnical tests should be an integral part of the drillhole physical properties program, and will provide information on compaction (ice and or sediment loading), permeability, and erosion

Paleoclimate Modeling of Glacial and Climatic History: The major deficiencies that remain outstanding in paleoclimate modeling of Antarctica center on model inadequacies and insufficient or poorly understood data by which to establish model boundary conditions and evaluation. A coordinated plan is required for meshing improved geological data and improved models. The central goal of the exercise is to use global and regional climate models to help understand glacial and other climatic events important in the history of Antarctica, and to relate these to past and possible future global climate. Climate models play a key role in helping to synthesize and integrate our understanding of major glacial and climatic events and can also be used to suggest correspondences and inconsistencies in the interpretation of these events from the geologic record. Model results can also be used as a guide to where future geologic data needs are greatest (Ogelsby, Appendix 7.13, this report).

As a result of deliberations at the Hobart Workshop, a series of time slice or time interval window modeling targets were identified. These were selected because reasonably well documented global, hemispheric and or regional events, phases or trends can be associated with each. These significant "moments" in past time provide logical starting points for a large scale modeling experiment.

Priorities and goals:

- *Early-Late Cretaceous (130 Ma-75 Ma)* – This is a particularly critical interval in the structural (plate tectonic), terrestrial, paleoceanographic and biological evolution of the southern high latitudes. It marks a significant transition from a single polar located Gondwanide supercontinent to a gradually more fragmented array of large landmasses, separated by new seaways and oceanic circulation patterns. Details of climate trends and episodes are poorly understood. Both marine and terrestrial Paleoaustral paleontological data point to relatively high diversity and productivity, and relative warmth at very high latitudes, despite strongly developed seasonality and low light levels during much of the year. There is no evidence for Cretaceous glaciation in Antarctica and a major question centers on whether hothouse conditions so prevalent in other parts of Earth were also a feature of the Antarctic region.
- *Mid Campanian cooling (~75 Ma)* – This event was marked by the development of an highly provincial Austral flora and fauna, and represents the likely beginning of a general global cooling that continued into the Cenozoic. The effect of this cooling on Antarctica is currently uncertain, but may represent the first "excursion" of a thermally isolated Antarctica toward eventual icehouse conditions.
- *Cretaceous-Tertiary boundary (~65 Ma)* – Current consensus suggests that this boundary represents a major impact event and is associated with biotic mass extinction. The effect in Antarctica is uncertain, and it is currently debated as to whether the extinctions were instantaneous or step-wise, or as severe in high Austral latitudes relative to the rest of the global system.
- *Late Paleocene-Eocene thermal boundary (~52 Ma)* - This boundary represents a large global anomalous warming event (Cenozoic thermal maximum and level of a major extinction in the benthic environment) from which progressive Cenozoic cooling commenced. A major question is the degree to which this warming affected Antarctica and it flora and fauna. More significant is the impact of this event on the organization of global ocean circulation patterns.
- *Eocene (~52 to ~34 Ma)* – Onset of major glaciation in Antarctica. This entails a diachronous phase of climate deterioration that probably occurred at different times and places in the interior and at margins of Antarctica.

- *Eocene-Oligocene boundary (~34 Ma)* – This represents a major global cooling threshold that is strongly delineated in oxygen isotope data. The distinction between ocean water temperatures and ice volume is uncertain. This boundary is a culmination of temperature decline during the Eocene. What role did Antarctic glaciation play in this event, particularly in relation to an apparent continent-wide ice sheet expansion to the continental margins.
- *Mid Oligocene transition (~30 Ma)* – This represents a major global cooling, and of more significance for Antarctica, it is associated with a major eustatic fall that represents a likely large expansion in the ice volumes on Antarctica.
- *Mid Miocene transition (~15 Ma)* – This represents a major global cooling that may also point to "full" thermal isolation of Antarctica from the remainder of the globe, and possibly related to the full development of the Circum-Antarctic Current, and possibly as well or instead of, to a significant sea ice apron around Antarctica. It may also be associated with the complete re-glaciation of Antarctica.
- *Latest Miocene-Earliest Pliocene (~6 to 4.2 Ma)* – Possibly this interval involved the development of full glaciation of West Antarctica; and possibly also, the closure of the intercratonic seaways linking the south Atlantic and Pacific oceans.
- *Early-Mid Pliocene climate amelioration (~4.2 to 2.5 Ma)* – Global warming during this interval may be associated with major reduction in ice volume on Antarctica and with possible elimination of ice sheets in some areas.
- *Pliocene-Pleistocene boundary (<2.5 Ma)* – Onset of significant Northern Hemisphere ice sheet glaciation occurred during this interval, however, the influence on and by Antarctica is less certain and requires clarification.

In all these experiments, global and regional paleogeographic, paleotopographic and paleobathymetric data are needed to establish boundary conditions as accurately as possible. Information on external forcings, such as broad estimates of atmospheric carbon dioxide and changes in solar luminosity, etc. are also needed. Detailed site reconstructions will be essential for subsequent evaluation and interpretation of model simulations.

Regional Earth Science Issues

Antarctic Peninsula: The Antarctic Peninsula is a narrow upland region, comparatively well exposed, with broad flanking continental shelves. Study of the onshore geology is actively pursued by many SCAR countries, and a considerable marine data base exists for the readily accessible Pacific continental margin. Geoscience research is, in many fields, well beyond the reconnaissance stage, and ready for more focused attention. The original ANTOSTRAT Antarctic Peninsula Working group concerned itself with subduction neotectonics, and both past and present back-arc extension as well as investigations of the glacial margin. The Antarctic Peninsula region contains an excellent onshore Late Cretaceous and Paleogene shallow-water section with few breaks, in the James Ross Island region, which has already been investigated but has further potential. The Paleogene and Neogene onshore record is less continuous but compares well with other regions of Antarctica. The record of "full" glaciation offshore is extremely well-ordered and well-preserved, and was recently investigated during ODP Leg 178 operations (Fig. 4). It is estimated that the onset of grounded ice sheet extension to the continental shelf edge dates from late Miocene (7-10 Ma), significantly later than in East Antarctica. Barker, Appendix 7.14, this report).

Priorities and goals:

- Execute ODP margin drilling to examine Antarctic glacial history. Develop a margin transect of validated acoustic/lithologic facies comparisons for use in other regions of Antarctica.
- Extend ODP glacial transect inshore and to earlier Cenozoic successions by drilling mid-shelf sedimentary basins, and compare with other regions of Antarctica. This goal could possibly be achieved by shallow drilling of the shelf between Anvers Island and Adelaide Island.
- Develop a broad chronostratigraphic and paleo-environmental record for the Late Cretaceous and Paleogene in the northern Antarctic Peninsula region, and thereby support future generations of numerical models of Antarctic climate change. This will require additional onshore geological investigations, supplemented by offshore sampling by shallow drilling techniques.
- Examine sediment provenance as a way of establishing the uplift history of the Antarctic Peninsula. Numerical models suggest that an elevated Antarctic Peninsula is an important influence on continental climate. ODP and shallow drilling at inshore sites will be required.

Weddell Sea: The Weddell Sea region was involved in the earliest rifting events associated with the break-up of the Gondwana supercontinent. After South America and Africa had separated from Antarctica, the rifting process continued into the recent Lazarev and Riiser Larsen seas to split off India. The break-up of these continental masses resulted in the creation of new restricted basins. At approximately 130 Myr a major reorganization of the seafloor spreading occurred and Maud Rise, a large volcanic feature developed. A hiatus lasting from 110-120 to 40 Myr was documented in ODP holes 692 and 693.

During the same time span oceanic crust formed along the South Atlantic/Indian ocean sector of East Antarctica. Although Cenozoic glacial conditions are thought to have occurred in the region during the late Paleogene and Neogene this is not well documented. For example, it is not known with precision when and how often phases of the Filchner-Ronne Ice Shelf extended to the shelf break in the late Neogene. (Jokat, Appendix 7.15, this report).

Priorities and goals:

- Investigate post-Cretaceous environments along the Weddell Sea margin of East Antarctica; examining the early rifting event in the Mesozoic and the subsequent glacial history; and comparing this evolution with other Antarctic margin sites. This will require acquisition of high quality seismic data with sufficient spatial coverage to define the seismic architecture in several wide swaths across the continental margin. Locate optimum sites where ground-truthing of seismic data (age calibration of acoustic units) may be undertaken via deep and possibly shallow drilling.
- Elucidate the glacial history record in the deep basin off Dronning Maud Land (East Antarctica) by correlating seismic data and drillhole information along channel levee complexes, date the W4 unconformity in order to comprehend the onset and timing of glaciation in East Antarctica, and core the pelagic sediments of the Polarstern seamounts to basement, to reveal a long term climatic record for the Atlantic sector of East Antarctica. The large amount of multichannel seismic data available in this area has been interpreted in glacial history terms but stratigraphy, environments and age control demands a comprehensive drilling program. A drilling program rationale is set forth in ODP proposal 503 (Fig. 5).
- Improve knowledge of the glacial history of marine continental shelf sediments; with emphasis on data from foreset sediments along the Dronning Maud Land coast. Decipher vertical and lateral character of major stratigraphic units and interpret record of ice sheet/ice shelf activity over the continental shelf. Combine these data with adjacent deep sea data sets. This program will require acquisition of detailed seismic, bathymetric and side scan data, and the use of shallow drilling technology to verify seismic interpretations.
- Investigate the Mesozoic origin and evolution of the Weddell, Lazarev, and Riiser Larsen basins; with emphasis on the relationship between Gondwana break-up and basin formation and evolution, changing paleoceanography (current circulation, geochemistry, paleontology, opening and closing of gateways, black shale genesis, basin ventilation, and transition from "warm" Cretaceous to "cold" Cenozoic climate regimes). These objectives are detailed in ODP proposal #503. Additional sampling can be executed via dredging and shallow drilling. Sampling sites and areas include, northeast Antarctic Peninsula shelf, Larsen shelf, Ronne Trough, Filchner Trough, Explora Escarpment, Astrid Ridge, and Gunnerus Ridge. Further pre-drilling/sampling surveys should include, aeromagnetic and aerogravity, seismic, and bathymetric data. The aero-geophysical program (EMAGE) was commenced in 1996-97. A Polarstern cruise is scheduled for 2000 to acquire additional seismic and bathymetric data in the Lazarev and Riiser Larsen seas.

Prydz Bay Region: The Prydz Bay region is key to understanding the early history of break-up between Antarctica and Greater India and the development of the Indian Ocean. The major crustal and tectonic feature of this region is the prominent north-east south-west trending rift system, the Lambert Graben, which crosses the continental margin obliquely and extends into the continent toward the south. Two parallel rift grabens, divided by a crystalline basin high occur within the shelf, continental slope and Prydz Bay, representing a typical "Double Rift" system, with intracontinental and pericontinental branches The pericontinental rift branch exhibits transfer faults with an offset of up to 100 km. Prydz Bay was probably one of the first Antarctic basins to receive Cenozoic sediments and these are known to crop out on the sea floor. At the present time about 20% of the East Antarctic ice Sheet drains through the Lambert Graben into Prydz Bay and it was likely to have acted as a major trunk drainage system throughout the Cenozoic. Included in this catchment are the Gamburtsev Subglacial Mountains, a possible initial ice accumulation region within East Antarctica.

The Mac.Robertson Shelf west of Prydz Bay also contains a record of the rifting history of this margin. It is a scalped shelf with Precambrian basement, Mesozoic and pre-glacial Cenozoic sediments cropping out at the seafloor. The inner shelf half graben is filled with Cretaceous sediments. Gently dipping Jurassic, Paleocene and Eocene sediments underlie the outer shelf. The Paleocene and Eocene sediments are clearly post-rift but the it is not clear how the Jurassic sediments fit into the tectonic history of the margin. The Cretaceous age of the syn-rift sediments is at odds with the interpretations of rifting of India from Gondwana based on evidence from the Jurassic age of oceanic crust off Western Australia. (O'Brien and Leitchenkov, Appendix 7.16, this report).

Priorities and goals:

- Obtain additional seismic, sidescan and multibeam mapping data to refine drillhole site selection in Prydz Bay and on the Mac.Robertson Shelf; with emphasis on trough mouth fan and continental drift deposits.
- Conduct ODP drilling (ODP proposal # 490 submitted)(Fig. 5) and shallow drilling campaigns, and piston core programs in Prydz Bay and Mac.Robertson Shelf.

- Investigate pre-glacial, transitional and glacial phases of deposition in Prydz Bay and the Mac.Robertson Shelf; characterizing Cretaceous, Paleocene and Eocene successions.
- Investigate the Pliocene-Pleistocene history of Prydz Bay, documenting the frequency and timing of glacial advances and retreats by the Amery Glacier to the shelf edge, and interaction of these events with adjacent deep sea regions. The Lambert Glacier-Amery Ice Shelf has drained much of the East Antarctic Ice Sheet for millions of years and so proposed shelf sampling sites provide controls on ice sheet behavior. It is believed that the Prydz Channel ice stream of Lambert Glacier built a major trough mouth fan in the early Pliocene and successions are relatively undisturbed by slumping and reworking. Trough mouth fan and drifts on the continental rise probably preserve interglacial biogenic sediments and may therefore preserve a near continuous record for the last 4 million years.
- Investigate the paleoclimate record of Beaver Lake, a site that probably preserves a good Quaternary record. Drilling from this ice-covered lake is proposed, preceded by completion of a 25 km line of through-ice soundings, together with 3.5 kHz surveys and gravity coring.
- Continue a program of investigation of the late Cenozoic Pagadroma Group in the Prince Charles Mountains, with emphasis on marine and terrestrial stratigraphy, sedimentology , paleontology and biostratigraphy. Results from this program would enhance understanding of the late Cenozoic history of the region and possibly allow correlation with similar age sediments in Prydz Bay.

Wilkes Land Margin: The Wilkes Land margin is a key area by which to reconstruct the evolution of the Wilkes Land continental margin and Indian Ocean region during the last 130 m.y. This area provides one of the few locations along the margin of East Antarctica where Mesozoic rocks are exposed at the seafloor. The area lies at the northern limit of the Wilkes Subglacial Basin, a major intracontinental depression that extends ~1500 km towards the South Pole inland of the Transantarctic Mountains, and is ~500 km wide in places. This basin may be the repository of a Paleogene-Neogene marine and terrestrial record, one that preserves pre-glacial, transitional and glacial sediments. Basins on the Wilkes Land margin have probably retained the northernmost portion of this record. During Paleogene-Neogene glacial phases the Polar Front probably came close to this margin of Antarctica and so there is the potential of strong deep sea paloceanographic influences in basins along the margin. Deep inner shelf basins contain an ultra high resolution Quaternary-Holocene record that has the potential of recording ice margin fluctuations (Escutia, Appendix 7.17, this report).

Priorities and goals:

- Investigate the onset of glaciation at the Wilkes Land continental margin, and indirectly in the Wilkes Subglacial Basin based on deep (ODP proposal 482 submitted)(Fig. 5) and shallow sampling across the continental shelf.
- Conduct intermediate to high resolution seismic surveys to define potential drill site locations; to concentrate these efforts in inner continental shelf troughs, outer continental shelf trough mouth fans and continental rise drifts; to strengthen portrayal of seismic facies architectures; to improve bathymetric mapping, and to correlate these data with those obtained from drilling campaigns.
- Link late Neogene and older seismic and drillhole stratigraphy on transects across the continental shelf (ice proximal) and on continental slope (drifts), to better understand glacial-deglacial cycle history and depositional systems.
- To investigate subglacial basin and ice drainage system evolution, to estimate sediment volume transport between terrestrial and marine environments through time, and relate these data to offshore depocenters.
- Investigate Hakurei seamount and Seamount B, to determine composition of these subbottom highs, and to use these data to determine the time and processes involved with separation of Australia from Antarctica in this region.

Ross Sea: The Ross Sea lies along the Pacific margin of the Jurassic rift that is delineated by the extensive dolerite sills of the Ferrar Group of the Transantarctic Mountains, and coincides in part with the active Cenozoic West Antarctic Rift System. The Transantarctic Mountains, one of the world's great mountain chains, forms, for a large part of its length, the rift shoulder of the West Antarctic Rift System. It is over 4,000 km long, reaches elevations of over 4,000 m, and is block-faulted and back-tilted towards the East Antarctic craton. The complementary rift shoulder in the Edward VII Peninsula and western Marie Byrd Land is far more subdued and has more of a horst and graben (basin and range) style of morphology that is mostly ice covered and extends about 1000 m above and below sea level.

The Ross Sea and its southern continuation under the Ross Ice Shelf forms the Ross Embayment, which is about 500 m deep and generally has a gentle ridge and valley morphology with a maximum depth (1200 m) along the western margin, adjacent to the Transantarctic Mountains. The sedimentary basins in the Ross Sea were probably formed largely by rifting processes during and since break-up of this part of Gondwanaland in the Late Cretaceous. There were two phases of basin formation. An initial regional extension phase related to the Gondwana break-up episode, and a possibly mid-Cenozoic phase, which was localized to the western Ross

Sea. Uplift of the Transantarctic Mountains appears to have occurred in several phases commencing at about 115 Ma. The structural and deposition framework of the Ross Sea is formed by four principal depocenters, the Victoria Land basin, the Northern basin, the Central Trough and the Eastern basin. Seismic data linked to drillhole information has shown that some thousands of meters of sediments are present in the deepest part of the Ross depocenters. The oldest sediments probably range back into the Paleocene, Cretaceous, and possibly the early Mesozoic. The presence of Eocene and Oligocene sediments have been confirmed in drillholes and appear to be widespread in the western and central Ross Sea. Neogene sediments also appear to be very widespread, having been documented in drillholes in the Ross Sea, at its western margins, and within the trunk valley fjordal systems that traverse the Transantarctic Mountains.

Late Neogene terrestrial glacial successions in the Transantarctic Mountain highlands provide potential for future linking of cratonic and rift basin stratigraphy, investigation of sediment transport budgets between terrestrial and marine regions, tectonic history, paleotopography and glacial history.

The Ross Sea region has several other unique attributes for Antarctica. It is the largest and most accessible southern high latitude continental shelf. In terms of global comparisons it is one of the largest rift mountain-basin structures, with extensive linear volcanic provinces (<40 Ma) along the western Ross Sea and Marie Byrd Land rift margins. Shelf basins have been long-lived catchments for ice and sediment for parts of both the East and West Antarctic ice sheets. The ice sheet, ice shelf, and open marine interfaces have interacted and fluctuated over at least 40 m.y., resulting in a variety of proximal and distal glacigene facies. Paleocoastlines are known with reasonable certainty. The proximity of volcanic provinces provides an opportunity to develop a sound chronostratigraphy via dating of rock and tephra-based techniques. Given the wealth of information on craton margin and rift basin multi-unit stratigraphy, widespread unconformities, lithofacies trends and relationships, biostratigraphy, and environmental interpretations, future research in the Ross Sea region is likely to evolve toward detailed interpretations of the respective roles of tectonic, paleoclimate and eustatic factors in the determining the histories of the extensive continental shelf basins in this part of Antarctica (Davey, Appendix 7.18, this report).

Priorities and goals:

- Conduct a ship-based deep drilling program (ODP Proposal 489 submitted (Fig. 5), currently under ODP consideration and peer review), fast-ice deep drilling program (Cape Roberts Project, currently underway, 1997-2000), ship-based shallow drilling program (in planning stages), and ice shelf-based shallow program (in discussion stages), all directed toward the thematic targets enumerated below.
- Conduct further seismic surveys directed toward providing complete site surveys for drilling programs aimed at recovering geological materials associated with thematic targets enumerated below; and also associated with refining ground truth for the existing seismic data base in the Ross Sea region.
- Initiate a program of high resolution seismic investigation aimed toward characterizing discrete seismic facies and linking these with rock stratigraphy and interpreted lithofacies recovered from drilling campaigns.
- Elucidate past climate and glacial history, especially in regard to the origins and subsequent history of Antarctic sheets, including the frequency and rate of major phases of ice build-up and ice-decline; and contribute these data to forecasting rates and scale of future climate change.
- Synthesize and extend Cenozoic terrestrial glacial geological records, relate these data to vertical tectonic histories along the rift margins, and to evolving paleotopography and associated phases of upland denudation; and couple these studies with concomitant rift basin subsidence studies.
- Relate continental shelf geological and geophysical data bases with those of adjacent areas of the deep Southern Ocean; with emphasis on stratigraphic and biostratigraphic correlations and seismic stratigraphy.
- Decipher in both the terrestrial and marine records, potential earth system linkages with significant global, hemispheric and Southern Ocean trends, phases, and events, e.g. tectonically induced changes of intracratonic and intercratonic ocean distribution and circulation, eustatic oscillation thresholds, major thresholds in physical paleoceanography, and associated faunal overturns and restructuring of biogeography.
- Design and execute a long-range program directed toward developing a high resolution chronostratigraphy for the Ross Sea, directing emphasis towards the application of geochronology, magnetostratigraphy, biostratigraphy, and biogeochronology; and link this temporal scheme with those developed for other regions of Antarctica; and attempt correlation with established schemes developed for the Southern Ocean, southern temperate latitudes, and the global standard scheme. This priority and goal is central to the entire ANTOSTRAT enterprise, and highlights the Ross Sea-Transantarctic Rift System as possessing one of the most complete basin successions in Antarctica. This program will entail a major international collaborative effort in synthesizing existing data, obtaining new data by drilling, coordinated geophysics and geological programs, and the assembly of designated Ross Sea Standard Sections into a Ross Sea Composite Section, and Ross Sea Chronostratigraphy, for the Late Cretaceous and Cenozoic.

ACKNOWLEDGEMENTS

We acknowledge travel assistance grants from the Scientific Committee On Antarctic Research and the national Antarctic programs of the workshop participant's countries.

Dr Ian Goodwin of the SCAR Global Change Program office at Hobart arranged the amenities used during the meeting and offered many forms of assistance during the pre-workshop planning phase. We thank the Cooperative Research Centre, University of Hobart for providing the workshop meeting facilities. The compilers also extend thanks to all authors for their extensive contributions to the workshop and report, and to the many reviewers within the SCAR Geology and Solid Earth Working Groups and earth science community who provided comments.

Peter-Noel Webb and Alan K. Cooper
Workshop Conveners

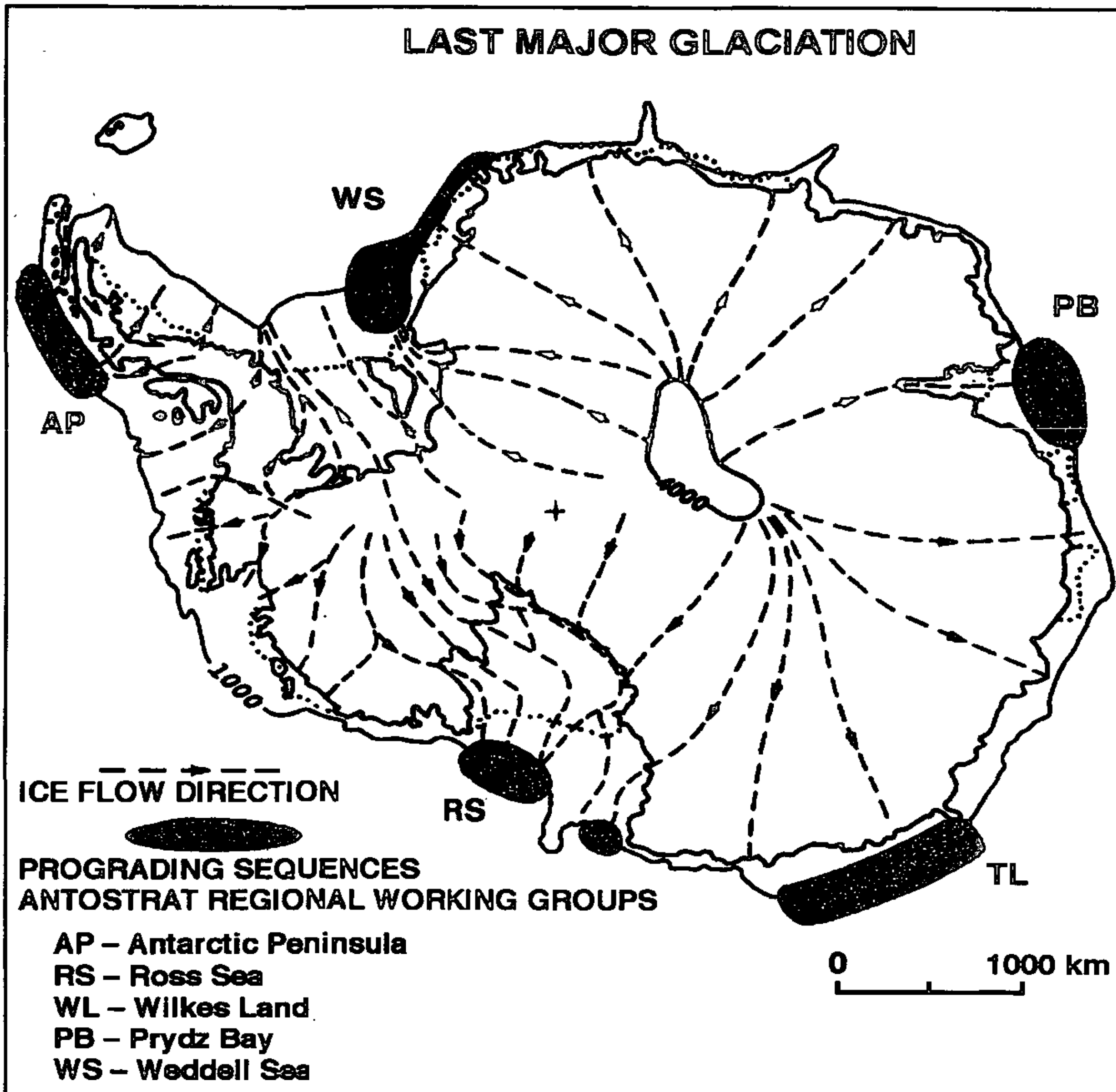

Figure 1. Map of Antarctica showing locations of major Cenozoic prograding sedimentary sequences, for the five areas around Antarctica that have been studied by the ANTOSTRAT project. These sequences lie at the seaward end of inferred former ice streams (Cooper and Webb, 1994).

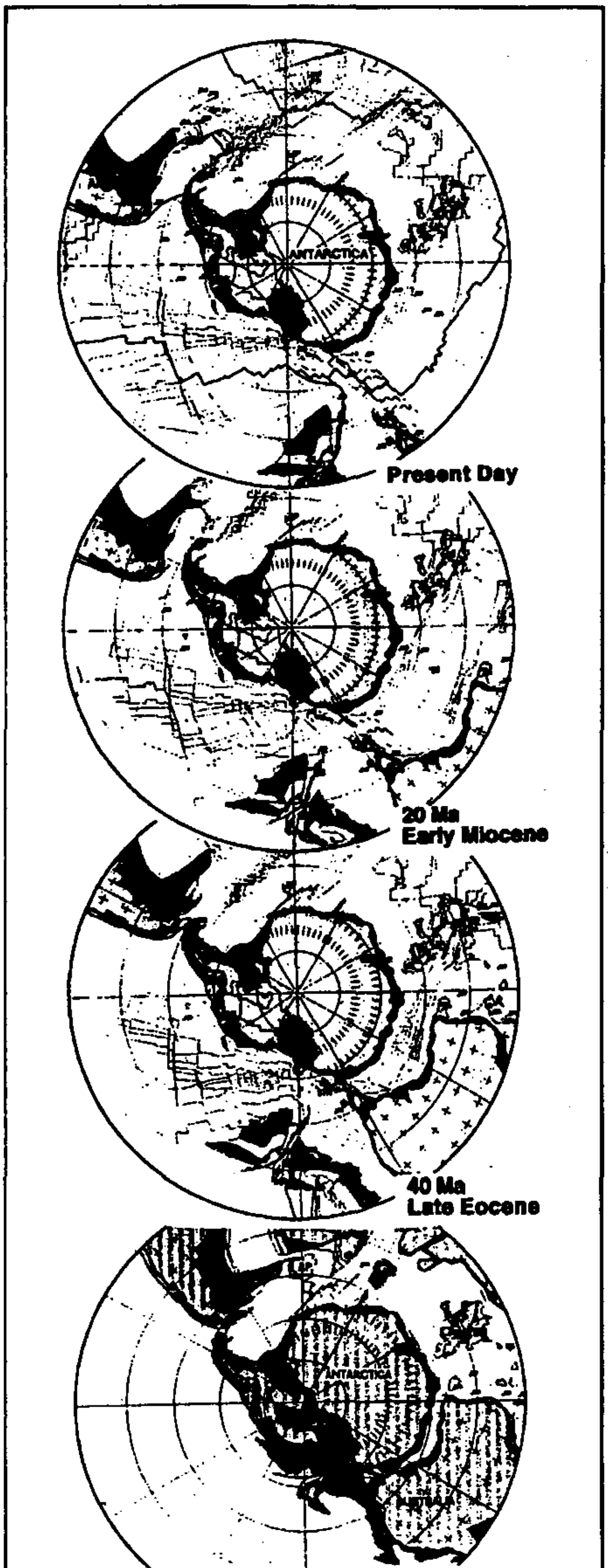

Figure 2. Fragmentation of parts of Gondwana super-continent and evolution of Antarctic Plate, during the Cretaceous and Cenozoic (Modified after Lawver, Gahagan and Coffin, 1992).

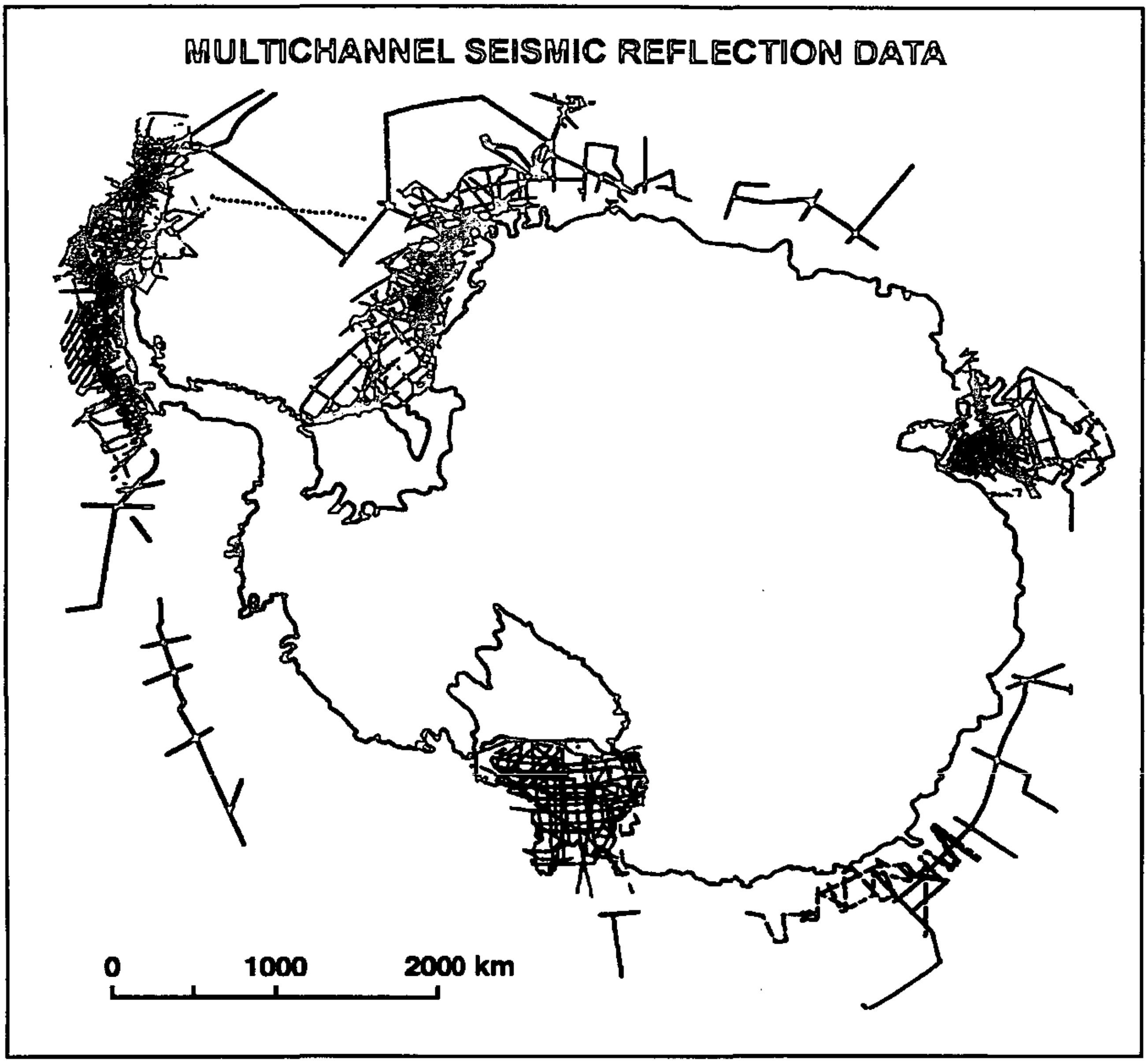

Figure 3. Map showing location of multichannel seismic reflection profiles from theAntarctic continental margin (Cooper and Webb, 1992; modified from Behrendt, 1990).

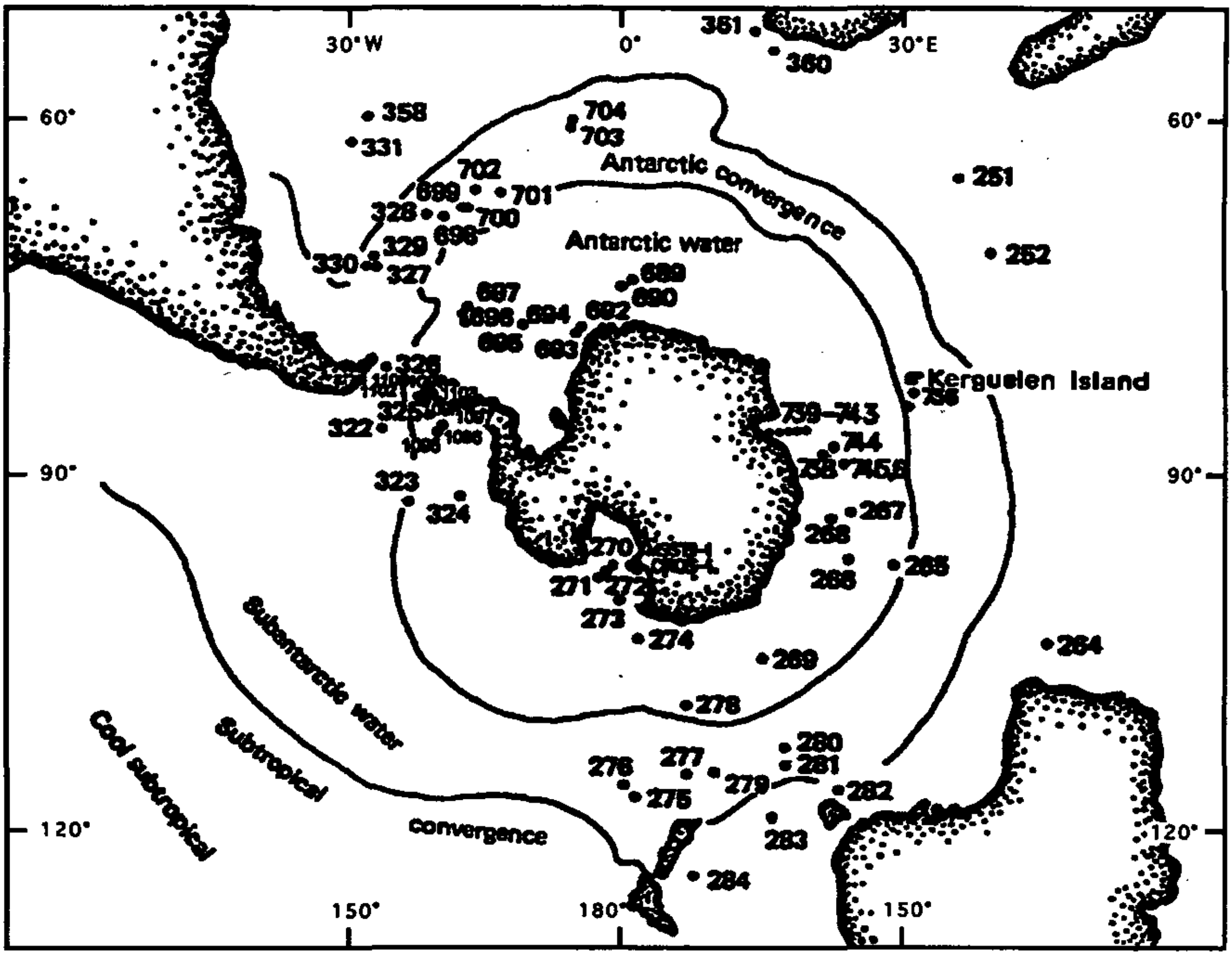

Figure 4
Deep Sea Drilling Project and Ocean Drilling Program sites completed in the southern Atlantic, Indian and Pacific oceans since 1972. ODP drillsites around the Antarctic Peninsula (in small type) were completed in early 1998 as part of Leg 178. These sites were proposed by the ANTOSTRAT Antarctic Peninsula regional working group.

Opposite page:

Figure 5
Proposed locations of Ocean Drilling Program drillsites, as proposed by the Weddell Sea, Prydz Bay, Wilkes Land margin and Ross Sea ANTOSTRAT regional working groups. Proposals for these sites are currently in review.

Figure 6
Generalized cross section of the Antarctic continental margin showing the geometry and distribution of preglacial and glacial sedimentary sections for areas where the continental shelf has been extensively prograded and aggraded (Cooper and Webb, 1994, modified from Cooper *et al.*, 1993).

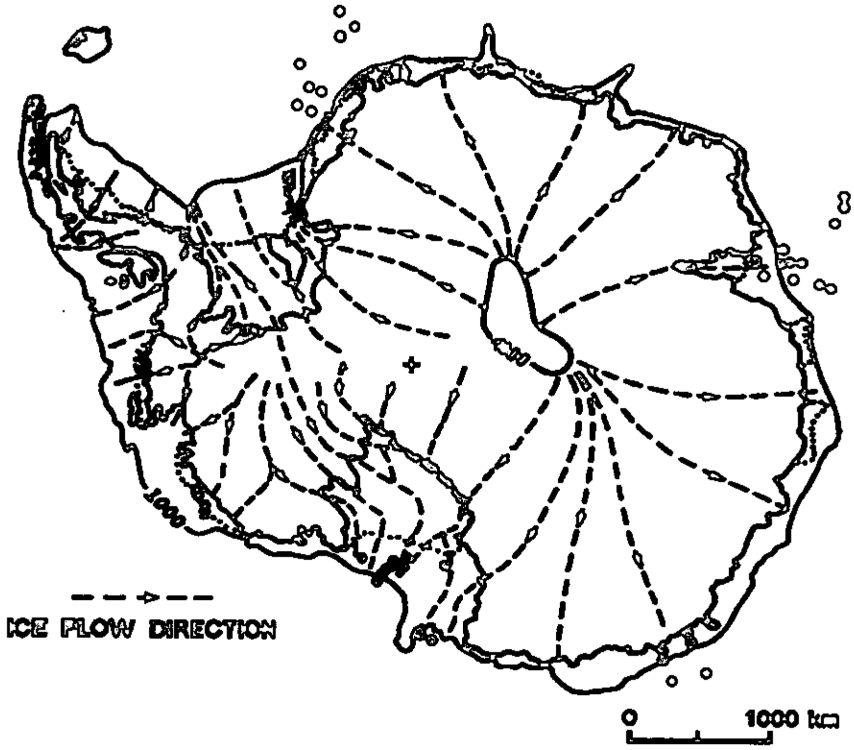

Figure 5.

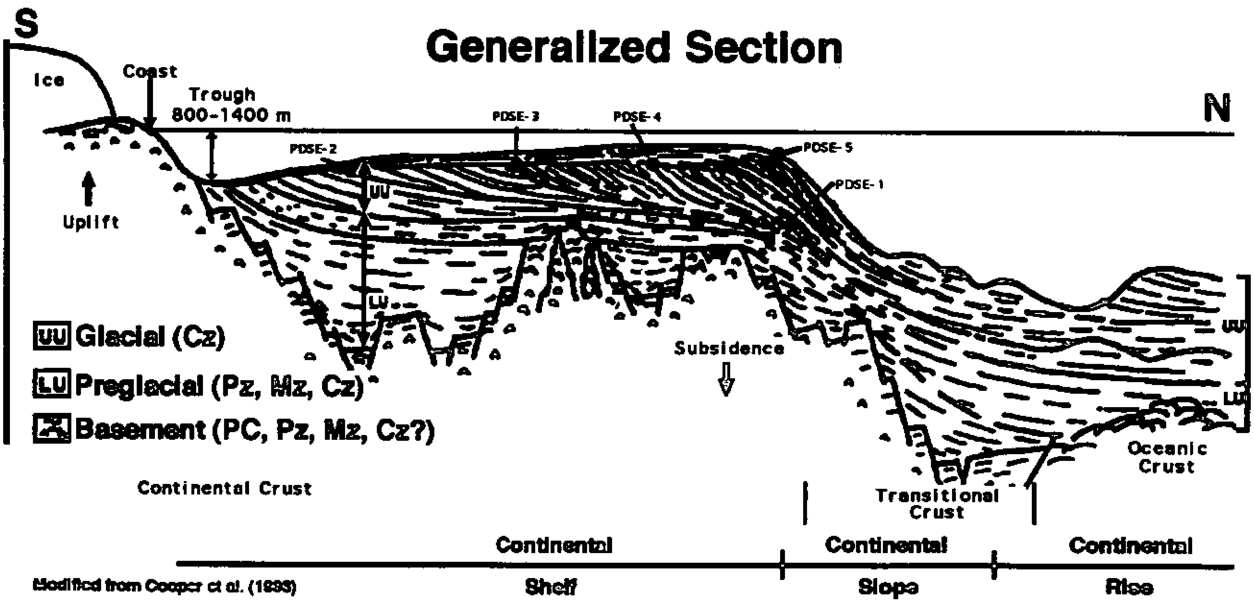

Figure 6.

APPENDICES

The following appendices contain detailed information regarding the workshop background, participants, agenda, and initial workshop report (EOS, 1998). Most figures that were provided with background papers have not been included due to the great length of the report and the technical difficulties in distributing these figures in the electronic version of the report. Also, some information is provided in tables, created using Microsoft Word for Windows 7.0, that may not appear correctly in some electronic versions, even with the "universal" Rich Text Format (RTF) that will be used to distribute the report initially.

Appendix 1: ANTOSTRAT Steering Committee (up to July 1998)

Alan Cooper (Chairman)
Peter Barker
Peter Barrett
Giuliano Brancolini
Philip O'Brien
Anders Solheim
Manabu Tanahashi
Peter Webb

Appendix 2: Workshop Participants

Australia	Phil O'Brien Neville Exon Pat Quilty Ken Woolfe
Germany	Dieter Fuetterer Rainer Gersonde Wilfried Jokat
Italy	Angelo Camerlinghi Laura De Santis
Japan	Manabu Tanahashi
New Zealand	Peter Barrett Nerida Bleakley Fred Davies Paul Fitzgerald Alex Pyne Gary Wilson
Norway	Yngve Kristoffersen Anders Solheim
Poland	Andrzej Gazdzicki
Russia	Garrik Grikurov German Leitchenkov
Spain	Miguel Canals
United Kingdom	Peter Barker
United States	Janel Anderson John Anderson Alan Cooper Carlotta Escutia David Harwood Robert (Bob) Oglesby Sandra Passchier Ross Powell David Elliot Peter Webb Sherwood (Woody) Wise

Appendix 3: Selected References

The literature cited below provides basic references to the post-1987 work of the SCAR Group of Specialists on Cenozoic Paleoenvironments, ANTOSTRAT (Antarctic Offshore Stratigraphy Program), and reviews and syntheses of long time scale global change research. All publications provide additional bibliographic detail on these categories of Antarctic activities during the past decade.

Barker, P.F., 1998. Ocean Drilling Program, 1998. Leg 178 (Antarctic Peninsula)

Barker, P.F. and Cooper, A.K., (editors), 1997. *Geology And Stratigraphy Of The Antarctic Margin* 2. American Geophysical Union, Washington, D.C., Antarctic Research Series, 71, 187pp.

Barrett, P.J., 1992. Antarctica and global change: a geological perspective. *In*, C.M Harris and B. Stonehouse (editors), *Antarctic and Global Change*, London, Belhaven Press, pp. 35-50.

Barrett, P.J. 1996. Antarctic paleoenvirornment through Cenozoic times – A review. *Terra Antartica*, 3(2), 103-119.

Cape Roberts Project Science Team, 1998. Initial Report on CRP-1, Cape Roberts Project, Antarctica. *Terra Antartica*, 5(1), 187pp.

Cooper, A.K. (editor), 1991-93. "ANTOSTRAT News" (No.1, July 1991; No.2, November 1991; No.3, March 1992; No.4, July, 1992; No.5, November; No.6, March, 1993; No.7, August 1993; No.8, December 1993).

Cooper, A.K. and ANTOSTRAT Steering Committee, 1992. A SCAR Seismic Data Library System for cooperative research: Summary Report Of The International Workshop On Antarctic Seismic Data. *SCAR Report*, 8, 15pp.

Cooper, A.K. *et alia* (editors), 1995. *Geology And Seismic Statigraphy Of The Antarctic Margin* 1. American Geophysical Union, Washington, D.C., Antarctic Research Series, 68, 302pp.

Cooper, A.K. and Webb, P.-N., 1990. International workshop on Antarctic offshore seismic stratigraphy (ANTOSTRAT). U.S. Geological Survey, Open File Report, 90-309, 290pp.

Cooper, A.K. and Webb, P.-N., 1992. International offshore studies on Antarctic Cenozoic history, glaciation, and sea-level change: The ANTOSTRAT Project. *In*, Yoshida, Y., Kaminuma, K., Shiraishi, editors, *Recent Progress in Antarctic Earth Science*, Terra Scientific Publishing Company (TERRAPUB), Tokyo, 655-659.

Cooper, A.K., Barker, P.F., Webb, P.-N., and Brancolini, G., (editors), 1994. The Antarctic Continental Margin: Geophysical and Geological Stratigraphic Records Of Cenozoic Glaciation, Paleoenvironments, and Sea-Level Change, The Antarctic Offshore Acoustic Stratigraphy Project (ANTOSTRAT) Symposium. *Terra Antartica*, 1(2), 480pp.

Cooper, A.K., Webb, P.-N., and Brancolini, G., 1995. Strides made in understanding Antarctic stratigraphy and Cenozoic history. *EOS, Transactions, American Geophysical Union*, 76(10):100-101.

Kennett, J.P. and Warnke, D.A. (editors), 1992. *The Antarctic Paleoenvironment: A Perspective on Global Change*. American Geophysical Union, Washington, D.C., Antarctic Research Series, 56, 384pp.

Kennett, J.P. and Warnke, D.A. (editors), 1993. *The Antarctic Paleoenvironment: A Perspective on Global Change*. American Geophysical Union, Washington, D.C., Antarctic Research Series, 60, 272pp.

SCAR, 1997. Working Group on Geology. *In*, Summary Reports to XXIV SCAR, Cambridge, United Kingdom, 12-16 August, 1996. *SCAR Bulletin*, 126, 5-7.

SCAR, 1997. Working Groups on Geology and Solid-Earth Geophysics. *In*, Summary Reports to XXIV SCAR, Cambridge, United Kingdom, 12-16 August, 1996. *SCAR Bulletin*, 126, 18-20.

SCAR, 1997. Working Group on Solid-Earth Geophysics. *In*, Summary Reports to XXIV SCAR, Cambridge, United Kingdom, 12-16 August, 1996. *SCAR Bulletin*, 126, 16-18.

Webb, P.-N., 1990. The Cenozoic history of Antarctica and its global impact. *Antarctic Science*, 2(1), pp. 3-21.

Webb, P.-N. and and Cooper, A.K., 1998, Antarctica's Role in Global Change Examined. *EOS, Transactions of the American Geological Union*, January 6th, 1998, 79(1), 3-5.

Webb, P.-N. and Wilson, G.S. (editors), 1995. The Cape Roberts Project, Antarctic Stratigraphic Drilling. Proceedings of the U.S. Planning Workshop Science Objectives and Requirements Meeting, 6-7 March 1994. *Byrd Polar Research Report*, 10, 117pp.

Wise, S.W. and Janecek, T.R. and Shaldrill Committee, 1998. Workshop Report on shallow drilling systems for U.S. Antarctic Drilling Program vessels. Internal Report, Office of Polar Programs, U.S. National Science Foundation, 15pp.

Appendix 4: ANTOSTRAT Workshop Program: Agenda and Format

I. AGENDA

Sunday 6th July

Morning: Joint session for ANTIME and ANTOSTRAT Workshops

- ANTIME and GLOCHANT/PAGES science (Ian Goodwin)
- ANTOSTRAT objectives and science agenda (Alan Cooper)
- "Late Phanerozoic Antarctica, global change challenges at micro-, meso-, and macrotemporal scales" (Peter Webb)
- Late Quaternary Antarctica, the key issues" (John Anderson)
- Sedimentary processes, events and stratigraphy (Ross Powell)

Afternoon: ANTOSTRAT Session 1

Data bases, current and planned projects, and technology for 1998-2008

- The ANTOSTRAT Seismic Data Library System (SDLS) (Giuliano Brancolini/Alan Cooper)
- ANTOSTRAT Antarctic margin Ocean Drilling Program initiatives (Peter Barker)
- Cape Roberts Project, southwest Ross Sea region (Peter Barrett)
- Shallow drilling technology and sampling of Late Phanerozoic targets (Yngve Kristoffersen)

Monday 7th July: ANTOSTRAT Session 2

Hemispheric, regional and local crustal evolution and events

- Late Phanerozoic plate tectonics and structural geological history (David Elliot)

Geological time

- Geochronology: application of absolute and relative dating systems and schemes in the Antarctic and peri-Antarctic realm (Patrick Quilty)

Late Phanerozoic marine geology

- Continental shelf sedimentary basins (Peter Barrett)
- Paleoceanography and marine biosphere history (Sherwood Wise)

Report writing

Tuesday 8th July: ANTOSTRAT Session 3

Late Phanerozoic terrestrial geology

- Terrestrial realm (Peter Webb)

Seismic stratigraphy and physical properties

- Regional seismic stratigraphy (Alan Cooper)
- Seismic characterization and physical properties (Anders Solheim)

Modeling

- Paleoclimate, modeling and hypothesis testing (Bob Oglesby)

Report writing

Wednesday 9th July: ANTOSTRAT Session 4

ANTARCTIC REGIONAL WORKING GROUPS

These groups will meet separately and consider on-going, scheduled, and potential science programs through the year 2008. The groups will consider the topical, thematic, issue, event, and technology overview-discussions of the previous three days, to outline and prioritize the key items and opportunities that can realistically be addressed in their region in the coming decade. Primary emphasis will be on activities that provide geologic "ground truth" information. Work based in deep sea, continental shelf and on-land locales will be included in these discussions.

Regional working groups will be provided with a standardized reporting template so as to facilitate inclusion in the final report. The first-mentioned person will act as the group leader for the region. Group leaders will provide summaries of their group's discussions at the final whole-workshop session. Note that all workshop participants are welcome to attend the regional meeting of their choice and to move between meetings. Attendees who have expressed specific regional interests are provided below.

It is anticipated that these discussions will be of assistance to proponents of ANTOSTRAT Ocean Drilling Program proposals as they update and reinforce their proposals during meetings on Saturday and Sunday 12-13 July (see below).

Antarctic Pen: Peter Barker, Miguel Canals, Andrzej Gazdzicki, Jose Flores, Jeronimo Lopez, de Batist, et alia

Weddell Sea: Wilfried Jokat, Yngve Kristoffersen, Sherwood Wise et alia

Prydz Bay: Philip O'Brien, German Leitchenkov, Patrick Quilty, Manabu Tanahashi, et alia

Wilkes Land: Carlota Escutia, Manabu Tanahashi, Alan Cooper, et alia

Ross Sea: Fred Davey, Peter Barrett, Giuliano Brancolini, Alan Cooper, Paul Fitzgerald, David Harwood, Gary Wilson, Peter Webb, Ken Woolfe, et alia

Summary presentations: from regional planning meetings by group leaders (Barker, Jokat, O'Brien, Escutia, Davey)

Report writing

CLOSING SESSION

Comments on the Antarctic Late Phanerozic Earth System Science initiative, reactions of the workshop's "Devil's Advocate" (Garrik Grikurov)

Review of workshop and comments on preparation of the SCAR report (Alan Cooper and Peter Webb)

Thurday 10th July

Joint ANTOSTRAT-ANTIME sessions (selected list of agenda items)

Planning:

- National and international science program planning
- Possible collaborative geological and geophysical field programs - on-land/marine
- Logistic facilities - on-land/marine
- Technological developments - on-land/marine
- Data bases
- Shared science objectives
- Future interactions
- Future symposia

Science:

- Polar geophysical and geological program objectives
- Polar seismic stratigraphy
- Polar sequence statigraphy
- Sedimentary processes
- Temporal-geological factor relationships
- Glacial cycles
- Polar geological processes and events
- Catastrophic events in polar regions and environments
- Ice sheets, ice shelves and sea ice
- Polar earth sciences and inter-hemisphere relationships
- Polar earth sciences and geosphere, atmosphere, hydrosphere relationships

Report writing (for ANTOSTRAT)

FRIDAY 11TH JULY

Field excursion with ANTIME Workshop members to Permian glacial marine sections of Tasman Peninsula

II. FORMAT

ITEM	FORMAT	SCIENTIFIC CONTENT
Overview Presentation	• Panelist gives 30 minute talk • Two "Recorders" take notes	• Science presented by Panelist • Recorders" note highlights
Plenary Discussion	• Panelist and participants coordinate discussion session • Two "Recorders" take notes	• Ideas are generated by participants • Recorders" note important points
Small Group Discussions	• Panelists and "Assistants" coordinate discussion & writing, in "Format 1" • Important points noted by Recorders" are transcribed into "Format I	• Small group provides additional objectives/topics for final report • Small group makes "first cut" at prioritizing the list of topics
Final Report	• Will have the following sections: • Executive Summary (2 pages) • Thematic Chapters (2 pg/chp.) • Regional Chapters (2 pg/chp.) • Appendices (var./chp.) • References (for all chapters	>Contents will be summarized by: >Report editors & steering committee >Panelist >Regional Working Group Panelist >Panelist & "Assistants" >Panelist & Editors
Publications	• **SCAR Report** - a critical objective of the workshop. • Workshop Report with all workshop results and sections • EOS article	>Primary function is to outline objectives and justification for a new earth science Group of Specialists >Provide additional advice for National Antarctic Programs >Inform general science community

List of Workshop Panelists and Assistants

Workshop jobs:

Panelists: will give the initial presentation and lead the follow-up discussion.

Assistants: will assist the panelist with the small group discussions and follow-up plenary presentations and discussions.

Recorders: the assistants that are noted by "*" will record the important concepts that are presented in the panelists presentations and later discussions. Recorders notes will be used as the basis for preparing template worksheets (see example) that outline the important science objectives for inclusion in the final report.

Observers: workshop participants who are not listed, and are asked to circulate among the group discussions to provide input, and to help as needed.

Sunday 6th July

Panelist	Topic/talk	Assistants
Peter Webb	Late Phanerozoic geology	Elliot*, Fitzgerald*, Grikurov
Ross Powell	Sedimentary processes	Escutia*, O'Brien*, Woolfe
Alan Cooper	Seismic Library (SDLS)	Leitchenkov*, Solheim*, Oglesby, Tanahashi
Peter Barker	ANTOSTRAT	
	ODP Initiatives	Davey*, Jokat*, Exon
Peter Barrett	Cape Roberts	Pyne*, Gazdzicki, Passchier
Yngve Kristoffersen	Shallow drilling technology	Webb*, Wise*,Quilty

Monday 7th July

Panelist	Topic/talk	Assistants
David Elliot	Late Phanerozoic plate tectonics	Barker*, Grikurov*, Fitzgerald, Yokat
Patrick Quilty	Geochronology	Gazdzicki*,Webb*, Passchier
Peter Barrett	Sedimentary basins	Exon*, Kristoffersen*, Leitchenkov,Cooper
Sherwood Wise	Paleoceanography	Escutia*, Gersonde*, Oglesby

Tuesday 8th July

Panelist	Topic/talk	Assistants
Peter Webb	Terrestrial geology	Barrett*, Fitzgerald*, Passchier
Alan Cooper	Regional seismic stratigraphy	Davey*, Exon*,Leitchenkov, Jokat
Anders Solheim	Seismic characterization	Barker*, Kristoffersen*, Escutia, Canals
Bob Oglesby	Paleoclimates	Elliot*, Wise*, Grikurov

Wednesday 9th July

Panelist	Topic/talk	Assistants
Peter Barker	AP regional working group	Camerlenghi*, Gazdzicki*
Fred Davey	RS regional working group	Barrett*, De Santis*
Carlota Escutia	WL regional working group	Tanahashi*, Cooper*
Phil O'Brien	PB regional working group	Leitchenkov*, Quilty*
Wilfried Jokat	WS regional working group	Kristoffersen*, Wise*
Garrik Grikurov	"Devils Advocate"	*Elliot, *Fitzgerald

Appendix 5: Report on Hobart Workshop published in *EOS Transactions of the American Geophysical Union*, 79(1), January 6th 1998

Antarctica's Role in Global Change Research Examined

The greatest discoveries about Antarctica's late Mesozoic and Cenozoic geologic history have been made over the past four decades since the International Geophysical Year. These discoveries were by earth scientists that conduct research in many countries under their National Antarctic Programs, which in turn follow the broad science guidelines recommended by the Scientific Committee on Antarctic Research (SCAR). SCAR has many sub-groups that address thematic issues.

One of these groups, the Antarctic Offshore Stratigraphy Project (ANTOSTRAT) was tasked by SCAR to bring together a cross-section of Antarctic earth scientists, to outline the critical thematic topics related to the last 100 m.y. of Antarctic earth history, and to recommend objectives for the coming decade of Antarctic earth science studies— to guide and promote Antarctic work. Such a group of discipline- and regional-specialists met at a recent workshop in Hobart, Tasmania (July 6-11), with participation of over forty scientists from eleven countries. A second SCAR workshop was held simultaneously by the ANTIME group, to focus on the last 20,000 years of earth history.

This report describes the ANTOSTRAT workshop. The principal outcome was the unanimous approval of a heavily debated recommendation that earth science studies in the coming decade should focus on acquiring rock samples via drilling, coring, and other techniques to help establish the onset and development of Antarctic glaciations, and link these glacial-interglacial periods to global climates of the past 100 m.y.

Many thousands of kilometers of remote-sensing geophysical data (e.g., high- and low-resolution seismic reflection, side-scan, magnetics, etc.) have been collected around the Antarctic margin over the past two decades. ANTOSTRAT scientists had compiled and analyzed these regional-survey data over the past decade, and their work was the foundation for workshop. The compilations focus on five regions of the Antarctic continental margin: Ross Sea, Wilkes Land, Prydz Bay, Weddell Sea, and Antarctic Peninsula (Cooper and Webb, 1994; Cooper et al., 1994).

Multichannel seismic-reflection (MCS) data are the principal imaging tool used to map geometries of sub-surface strata and geologic structures, and as such, have been central to the ANTOSTRAT studies. A key activity has been the implementation of the Antarctic Seismic Data Library System for Cooperative Research (SDLS) that now provides all researchers with open access to MCS data at 12 branches in 10 countries. The SDLS operates under the science aegis of SCAR and mandates of the Antarctic Treaty. The following summarizes some of the key discussion topics of the workshop.

Tectonics: Tectonics have played a key role in the evolution of Antarctica's ice sheets. Vertical tectonics in particular have formed topographic features that have dammed the movement of ice (e.g., Transantarctic Mountains), have created paleo-seaways in the Antarctic interior regions that ameliorated paleo climates (e.g., Wilkes sub-glacial basin), have provided pathways through the mountains where ice can drain seaward (e.g., Beardmore and Drygalski troughs), and have potentially controlled circum-Antarctic ocean-currents via bathymetric gateways (e.g., Scotia Arc platform).

Although the evolution of some of these features is still speculative, their influences on Antarctic isolation and segmentation, with eventual increased insolation and ice-sheet development are likely large. It was concluded that drilling into the sedimentary sections within and adjacent to these features is the only way to document their influences on Cenozoic glaciations.

Sedimentary basins: Only 2% of Antarctica's geology is exposed on the continent, with the rest covered by ice and water. Sedimentary sections are likely under the ice, but have not been seismically mapped and can only be inferred from geophysical data and limited onshore drilling in the McMurdo Sound region. Large sedimentary basins of late Mesozoic to Cenozoic age are known beneath all segments of the Antarctic continental margin, and hold up to 14 km of strata carried from the interior regions of Antarctica.

The basins' framework is reasonably well mapped seismically, but stratal ages are mostly unknown. The basinal sections are important, for documenting the different, but simultaneous events around Antarctica, such as variable movements of glaciers across the continental shelf, and coeval events in adjacent ocean basins, such as variable initiation of bottom-water currents. Because strata were deposited at different rates, basins with rapid sedimentation, such as the eastern Ross Sea, when drilled can give high-resolution records of the onshore and continental shelf events.

Shelf records can in turn be compared with those of adjacent ocean basins to help link and calibrate proxy deep-ocean-basin records. The offshore regions, where thick sedimentary sequences exist, offer the best potential sites for drilling and coring along several transects across different segments of the continental margin to decipher Antarctica's glacial history.

Seismic stratigraphy: Seismic stratigraphic studies provide the strongest evidence to date for local and regional expansions of glaciers onto the Antarctic continental shelves since Paleogene time. Thick sedimentary wedges at the continental shelf edge and strongly varied shelf sequences imaged by acoustic data attest to nearby glaciers. Numerous seismic surveys have been conducted and glacial-geology models created, yet the geologic samples collected are inadequate to "ground-truth" the surveys and to verify the models.

It is not yet possible to develop a circum-Antarctic sequence stratigraphy like that commonly applied to low-latitude continental margins (e.g., Vail model). Future Antarctic seismic studies should focus on systematically characterizing glacial seismo-stratigraphic facies and features on all segments of the Antarctic continental margin. These would be used, in conjunction with drill-core and down-hole logging data, to establish an Antarctic sequence stratigraphic model for the Cenozoic glacial era. Emphasis should be on very high-resolution seismic data, closely gridded surveys, and accurate ties of seismic horizons to drill core and logging data.

Glacial sedimentologic processes: Few comprehensive process studies have been done to precisely relate modern Antarctic environments to the varied depositional processes that may occur there, to help guide interpretation of older geological successions. The absolute definition of glacial lithofacies is still strongly debated, and reflects the large variablility in environments and processes in time and space. It was recommended that urgent attention be directed to three subjects: characterizing the sedimentology of seismic-stratigraphic units, to establish offshore "type localities"; characterizing sub-glacial and grounding-line depositional systems; and developing quantitative models as to how glacial-sedimentary sequences accumulate on the continental margin.

Linkages: The linkages between the Antarctic continental shelf and abyssal ocean basin are weak, and hinder global correlations for climates of the past 100 m.y. and longer. Significant gaps exist in circum-Antarctic paleoenvironmental histories for Late-Jurassic to Early Cretaceous, Late Cretaceous, and the Cretaceous-Tertiary boundary. Only few cores exist for these intervals, and are inadequate to derive, for example: the extent and impact of the Early Cretaceous anoxic event recorded by the "black shales" recovered in the Weddell Sea; the pan-Antarctic Late Cretaceous paleoclimates as Antarctica moved into its polar position; and the patterns of faunal changes and mass extinctions, if any, across the Cretaceous-Tertiary boundary.

Significant benthic faunal restructuring occurred in association with the oceanic Paleocene-Eocene thermal event, and there is uncertainty about the influence of this event on watermass evolution, onshore-climates and initial ice-sheet formation. Drilling in the Southern Ocean has compiled comprehensive calcareous and siliceous microfossil-based biostratigraphies, yet the impacts of onland Antarctic climatic changes on watermass characteristics and circulation patterns on these microfossil groups is poorly known. Further core samples in specific regions of the Southern Ocean are needed to resolve these uncertainties.

Onshore basins: The extensive sub-ice basins and the mountain drainage systems of onshore Antarctica may hold Mesozoic and Cenozoic strata. These areas often occur near volcanic regions, thereby providing dateable volcanic rocks. Sampling these onshore strata via drilling through the ice, would give the most direct paleoclimate record for Antarctica, for comparison with continental shelf and deep-ocean strata, but has mostly not been attempted due to difficult logistics.

Priorities outlined for onland investigations of marine-seaway and terrestrial rocks include: greater recovery of sub-ice rocks; improved chronostratigraphic control from marine biostratigraphy and volcanic debris; and mapping of sub-ice features to delineate sub-sea-level basins with likely stratigraphic sections.

Climate models: Global Climate Models (GCM) have increasingly higher temporal- and spatial-resolutions than previously, and may now help derive regional long-term paleoenvironments in and around Antarctica. In applying GCM models to Antarctica, it was noted that model accuracy is highly dependent on the quality of boundary condition data. For useful regional GCMs of Antarctica, geologists must provide detailed information on such things as topography, vegetation cover, geological data on local climates, and accurate times for these conditions. It was proposed that GCM models be constructed for ten critical periods ("time slices") in the evolution of the Antarctic Ice Sheet, to improve the understanding of Antarctica's long-term role in the global climate system. "Time slices" of 1-2 my duration will be undertaken for periods from Late Cretaceous time to the Present, and include mid-Campanian cooling (~75 m.y.), late Paleocene-Eocene thermal boundary (~52 m.y.), early to mid-Pliocene warmings (~4.3 and 2.5 m.y.) and others.

Future drilling and coring: Like the past, the greatest future advances in deciphering Antarctic glacial history are likely to come from drilling and coring of the extensive sedimentary deposits that underlie Antarctica and its continental margin (Webb, 1990; Barrett, 1996). Prior drilling by the Deep Sea Drilling Program (DSDP) and the Ocean Drilling Program (ODP) provided the information on which many prevailing models are built. Yet the drilling information is fragmentary and incomplete, and was last done a decade ago.

Over the past three years, ANTOSTRAT has laid the groundwork in planning and developing proposals to ODP for future circum-Antarctic drilling in areas where extensive prior surveys were done and thick sedimentary sections are known. ODP Leg 178 is scheduled to be drilled in one of these regions, the Antarctic Peninsula, in February 1998. Hopefully, other ODP drilling legs will follow on other parts of the margin.

Efforts by other groups are in progress to develop offshore high-speed diamond drilling systems that can be mounted on ships of opportunity, or on sea-ice, to drill up to 200 m into strata of the continental shelf. Such systems may "come on line" within the next decade, and must be capable of penetrating the ubiquitous meters-thick hard diamictite that lies near the sea floor around Antarctica, and has defended underlying strata from nearly all ship-board free-fall coring devices. Deeper drilling than 200 m sub-surface, will only be possible from dedicated drilling ships like ODP and sea-ice-rigs like that be undertaken at Cape Roberts in the southwest Ross Sea. Use of these systems requires years of planning and large budgets – but is the only way to get the needed information.

Reality check: The dreams of Antarctic geoscientists must be balanced by the reality of logistics and costs, as the workshop was sagely admonished by a 40-yr Antarctic veteran in field work and program development, and assigned as workshop contrarian. Yet, he noted, we should strive for several critical objectives: to improve fundamental definitions; seek temporal- and spatial-resolutions at the scale of the processes and events being studied (resolution is seemingly inversely proportional to cost); cherish ODP and other drilling; seek to explain paleoenvironmental impacts of non-uniform periodicities in the geologic record; and seek solutions to seemingly impossible "logistic" problems in Antarctica.

Workshop recommendations: The consensus of the workshop, after long debate, was that Antarctic earth science research of the next decade (1998-2008) should focus on acquiring geologic samples via drilling and coring, to provide "ground truth" information for our existing remote-sensing surveys and geologic models. Also was decided that SCAR should establish an advisory group (Group of Specialists) to promote and coordinate a range of programs directed toward investigating the onset and development of glaciation in Antarctica since late Mesozoic times. Specific tasks would include gathering geoscience data for working with climate and ice sheet modellers to prepare ice- and climate-scenario maps of Antarctica at selected time intervals; promoting and coordinating ODP proposals; and promoting the use of existing sampling systems and development of new shallow-drilling systems.

It was clear that future major advances in Antarctic earth science will require access to geologic samples from many "time slices" to adequately "ground-truth" the extensive remote-sensing data and the multifarious paleoenvironmental models.

References

Barrett, P. J., Antarctic paleoenvironment through Cenozoic times - A review, *Terra Antarctica, 3*, 2, 103-119, 1996.

Cooper, A.K. and Webb, P.-N., The ANTOSTRAT Project: An International Effort to Investigate Cenozoic Antarctic Glacial History, Climates, and Sea-level Changes, *Terra Antarctica, 1*, 239-242, 1994.

Cooper, A.K., Barker, P.F., Webb, P.-N., Brancolini, G. (Eds.), The Antarctic Continental Margin: Geophysical and Geological Stratigraphic Records of Cenozoic Glaciation, Paleoenvironments, and Sea-Level Change, *Terra Antarctica, 1*, 2, 236-480, 1994

Webb, P.-N., The Cenozoic history of Antarctica and its global impact, *Antarctic Science, 2*, 1,3-21, 1990.

Peter-Noel Webb, Department of Geological Sciences and Byrd Polar Research Center, The Ohio State University, Columbus, Ohio 43210, and Alan K. Cooper, U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025

Appendix 6: Three documents related to the evolution and implementation of the ANTOSTRAT subcommittee - July 1997 to July 1998.

6A. Response to Consensus Statement on Hobart Workshop, Forwarded to SCAR Executive Committee Meeting, Capetown, 25-29 August, 1997

Message to SCAR Executive: Following the Hobart Workshop, ANTOSTRAT committee chairman Alan Cooper forwarded a message (8th August 1997) to Peter Clarkson, Executive Secretary, SCAR, which provided a brief summary of proceedings and contained a copy of the consensus statement prepared at the concluding plenary session of the Hobart Workshop (see above). The issue was discussed at the SCAR Executive meeting in Capetown in August 1997.

Reply and response to the ANTOSTRAT committee consensus statement (see above): Text of a message received by Alan Cooper from Peter Clarkson, Executive Secretary, Scientific Committee on Antarctic Research, Cambridge, United Kingdom (26th September 1997).

"Thank you for your letter reporting on the ANTOSTRAT Workshop on Late Phanerozoic Earth System Science, held in Hobart during July this year, and the accompanying statement developed at the workshop on Group of Specialists or Coordinating Committee On Antarctic Glaciation – Onset and Development.

The SCAR Executive Committee read the report with great interest and appreciate the work which went into successfully running the workshop. The Executive looks forward to receiving the full report in due course.

The Executive appreciates the importance of the science discussed and the value of the proposed work program in supporting the science. It also noted your request for comment and response on the proposals contained in the letter and the statement. On the basis of the tasks outlined in the statement it considers that a Coordinating Committee under the Working Groups, rather than a Group of Specialists, may be the best mechanism to provide the coordination sought.

SCAR Executive would expect these documents and any workshop report to be referred to the Working Groups on Geology and on Solid-Earth Geophysics. This is the appropriate route for any proposal for a Coordinating Committee or Group of Specialists, and it is the responsibility of the Working Groups to put forward the appropriate proposals to the SCAR delegates when they meet. The delegates will decide on the preferred option to any proposal put forward by the Working Groups."

6B. Recommendations taken to SCAR XXV Meeting (Concepción, Chile; July, 1998)

The ANTOSTRAT Steering Committee requests that the Working Group on Geology and Working Group on Solid-Earth Geophysics consider the following recommendations. Recommendations 1 and 2 are based solely on the consensus statement from the ANTOSTRAT Hobart workshop. Recommendation 3 is a refinement based on Steering Committee discussions at the ANTOSTRAT Workshop on Antarctic drilling (Siena, Italy; May 10-14, 1998).

Recommendation 1:

Mindful that the Antarctic region has profoundly affected Earth's climate over the past 130 m.y. (i.e., since Early Cretaceous time), and the region is highly sensitive to climate variations on account of it polar position, and

Being aware that planetary climate has cooled by more than 6 degrees Celsius since Cretaceous time, and that currently-increasing CO^2 levels may raise global temperature by an equivalent amount over the next few Centuries, and

Acknowledging the progress made by the SCAR Group of Specialists on Cenozoic Paleo-environments ANTOSTRAT Project in providing a solid basis for Antarctic glacial history through seismic-stratigraphic investigations and circum-Antarctic drilling initiatives,

The Working Groups on Geology and on Solid-Earth Geophsics recommend that SCAR approve implementation of a Coordinating Committee under the joint working groups on Solid Earth Geophysics and Geology, to ensure continued coordination of current investigations, and initiate new studies to advance understanding of changes in climate of the Antarctic region over the past 130 million years as a guide to possible anticipated changes to the Antarctic region from future planetary climate changes.

Recommendation 2

The Working Groups on Geology and on Solid-Earth Geophsics recommend that the Coordinating Committee be asked to take on the following responsibilities

Promote and expedite science programs for gathering geoscience data on the following

1) inception of Antarctic glaciation since Cretaceous time, and geologic- and climate-processes related to variations in frequency and amplitude of these glaciations on time scales from millenia to millions of years
2) modeling past Antarctic climate and ice cover, taking into account different landscapes of the past, and linking these changes with global-climate- and seal-level-oscillations, as indicated by data from other regions

Promote workshops to discuss the use, acquisition, development and scheduling of new sediment sampling systems to acquire needed geologic "ground-truth" data, and encourage geophysical surveys to support the use of the sampling systems.

Organize symposia over the coming decade to facilitate presentation of new scientific findings, encourage new science programs, and monitor the directions of the overall Program.

Recommendation 3

Recognizing that ANTOSTRAT has over the past nine years, successfully promoted and coordinated geophysical and geological studies of the Antarctic continental margin directed toward understanding Cenozoic Antarctic glacial history, and

Being aware that the earth science community, including the international Ocean Drilling Program, recognize the name of, and understand the science goals of, ANTOSTRAT, and

Mindful that "name recognition" is important for maintaining the momentum of ongoing science activities of the former ANTOSTRAT project,

The Working Groups on Geology and on Solid-Earth Geophsics recommend that the new group be called the ANTOSTRAT Coordinating Committee, to include some members of the former ANTOSTRAT Steering Committee (for continuity of needed expertise) and some new members (to provide expertise in new disciplines).

6C. Recommendation Approved by SCAR Delegates At SCAR XXV (Concepción, Chile; July, 1998)

The following is the verbatim text of the recommendation developed by the Joint Working Groups of Geology and Solid Earth Geophysics and presented to SCAR delegates at SCAR XXV. The recommendation was approved, thereby establishing the ANTOSTRAT Subcommittee.

ANTOSTRAT Subcommittee on Late Phanerozoic Glacial History

Under the Joint Working Groups of Geology and Solid Earth Geophysics

Objectives

Recognizing that the Antarctic cryosphere has evolved in a complex non-linear fashion during Late Phanerozoic time (Cretaceous to the present), and that the history of the Antarctic Ice Sheet can only adequately be documented with geologic samples and regional geophysical surveys (seismic), the joint working groups propose to establish a subcomittee to promote and coordinate efforts with ANTIME to acquire stratigraphic data via coring and drilling operations in conjunction with needed geophysical surveys to document ice sheet evolution during Late Phanerozoic.

Recognizing also that ANTOSTRAT (Antarctic Stratigraphy) and ANTIME (Antarctic Ice Margin) have different and complementary objectives (see Addendum I), the subcommittee shall:

I. Coordinate field activities, data, and technology

- Promote and coordinate proposals to the Ocean Drilling Program for Antarctic margin drilling;
- Oversee the Antarctic Seismic Data Library System (SDLS) in support of Antarctic coring and drilling operations;
- Encourage development and use of shallow drilling systems to acquire needed stratigraphic samples from Antarctica;

II. Synthesize glacial history

- Encourage the use of stratigraphic samples to constrain models for the onset and evolution of the ice sheet during the Late Phanerozoic;
- Integrate the results of their studies with those of the ANTIME Project; and
- Conduct workshops and symposia to report science results and facilitate cooperative research projects.

Membership

There would be a maximum of 9 members, with new members recommended by vote of the subcommittee and approved by the joint Working Group. Five members of the prior ANTOSTRAT Steering Committee would be retained on the subcommittee for a 2-year term to provide needed continuity and momentum for ongoing projects (e.g., ODP). Four new members would be added following compilation of a short list of candidates, selection by the subcommittee and approval by the joint Working Group.

With the likely ending of ODP drilling operations around Antarctica in early 2002, the work of the subcommittee would be reviewed and evaluated by the joint Working Group at the SCAR XXVII meeting in 2002.

The Subcommittee would initially be:

Discipline	Name	Comment
Geophysics/ANTOSTRAT	A. Cooper*	
Geophysics/ODP	P. Barker*	
Geophysics/ODP/ANTIME	P. O'Brien*	
Geology/fast-ice drilling	P. Barrett*	
Climate modeler	** 1	(new position)
Shallow drilling systems	** 2	(new position)
Geology/ANTIME	** 3	(new position)
Ice-sheet modeler	**	(new position)
SDLS Coordinator	G. Brancolini*	

* Denotes prior member of the ANTOSTRAT steering committee.
** Short list of names being compiled.
[12/98 postcript: Robert Oglesby (1), Yngve Kristoffersen (2), and Ian Goodwin (3) have been selected for the new positions on the steering committee. One position remains open.]

Projected meetings

The ANTOSTRAT Subcommittee expects to organize workshops and symposia to facilitate most of its activities. Occasionally, members will attend important outside meetings to formally assure representation of Antarctic coring/drilling interests. For the coming few years, activities at the following meetings are planned.

Year	Meeting
1999	International Conference on Scientific Drilling (May 26-29; Vancouver, Canada) (Attend to assure Antarctica's involvement in future Ocean Drilling Plans)
1999	Cape Robert's Workshop on Ross Sea Drilling, in conjunction with ISAES (July 1999; New Zealand) (No funds requested)
1999	Subcommittee planning meeting and Workshop on drilling priorities and SDLS future operations, in conjunction with ISAES (July 1999; New Zealand)
2000	Workshop on Antarctic shallow drilling technologies (Spring 2000; UK likely venue)
2000	Workshop on Antarctic margin drilling results—ODP, Cape Roberts, and others (Summer 2000; Pacific Grove, USA likely venue)
2001	Regional working group meetings for Antarctic coring and drilling (Several locations)
2002	International ANTOSTRAT Symposium (Italy)

Addendum I. Comparison of ANTOSTRAT and ANTIME

	ANTOSTRAT (Antarctic Offshore Stratigraphy)	*ANTIME* (Antarctic Ice Margin)
Objectives	• Long-term thresholds in Pre-Pleistocene ice sheets (*e.g. Onset, First major expansion, Transition from Pliocene to Pleistocene conditions)* • 10,000 years to 1 Million years environmental change	• Short-term changes in Pleistocene-Modern ice sheets • Annual/Decadal environmental change
Geologic age range	200,000 years to 130 Million years	0 to 200,000 years
Methods	• Deep drilling • Deep seismic • Paleomagnetic dating • Biostratigraphy • Sequence stratigraphy • Ice cores not available yet	• Shallow coring • Shallow seismic • ^{14}C, ^{210}Pb dating • Paleobiology • Geomorphology • Ice core correlation

Appendix 7: Working papers prepared for the Hobart Workshop on data bases, current and planned projects, technologies, thematic and regional earth science issues.

ANTOSTRAT Pre-Workshop Draft Report

ANTARCTIC LATE PHANEROZOIC EARTH SYSTEM SCIENCE

Hobart, Tasmania
July 6-11, 1997

Draft report compiled in June 1997
from papers submitted by theme and regional workshop coordinators

With few exceptions (Cooper, Elliot, Oglesby), the text of the following reports have not been significantly modified from those submitted prior to the workshop. For papers dealing with proposed drilling (e.g., ODP, Cape Roberts), there have, in some cases, been significant changes in anticipated drilling operations and specific strategies, as of the time of distribution of this report (1/99). The general science directions have not changed significantly. For information, contact the senior authors of the papers.

LATE PHANEROZOIC ANTARCTICA: GLOBAL CHANGE CHALLENGES AT MACRO-, MESO- AND MICRO-TEMPORAL SCALES

Peter-N. Webb
Department of Geological Sciences & Byrd Polar Research Center, The Ohio State University, Columbus, Ohio, 43210, USA

The last 100 m.y of the Phanerozoic Eon (Cretaceous-Cenozoic) was marked by major latitudinal and longitudinal transport of continents, significant interactions between plates, active sea floor spreading and formation of the modern oceans, ever-evolving current circulation systems, major biotic appearances and terminations, rapid organic evolution, dynamic adjustments of biogeographic province demarcation, and a transition from a generally warm hothouse Earth to a bipolar icehouse Earth. At the global level, Cretaceous and Cenozoic earth sciences are reasonably well understood and integrated, and major events well constrained in time. While it is generally agreed that the Paleoaustral Region (late Phanerozoic terrestrial Antarctica and the surrounding oceans) played a significant role in late Phanerozoic events, particularly in the last ~50 m.y., most data bases are at the reconnaissance level, and the southern high latitudes are still omitted from many global climate modeling experiments. In other words, we still can only speculate on the role of many of the earth system linkages between the Paleoaustral Region and other parts of Earth.

Late Phanerozoic studies in the Paleoaustral Region over the last four decades exhibit several interesting trends. Chronostratigraphy (or the record of time represented by a sedimentary or igneous rock record) has improved steadily, but remains inadequate by modern standards. As the complexity of Paleoaustral geological history and processes has become more fully understood, the number of discrete events, episodes, transitions, etc., recognized, has multiplied, and the need to invoke more geological time to accommodate these events has been accepted. Take an extreme example. Geological histories for post-Jurassic Antarctica were often compacted into the Quaternary in the 1960's, but now, forty years later, are thought to span long intervals of Cenozoic and even late Mesozoic time. In some instances our control of the geological time factor is reasonably accurate. More often than not it is crudely relative, highly subjective, and possibly in error by ten or more million years.

It is time, then, to reassess our understanding of all Paleoaustral/polar earth system processes, the rates of processes, the relationships between processes, the changing role and priority of the major forcing factors over time, and our mastery of geological time itself. Having taken care of infra-Paleoaustral affairs we will better positioned to deal with complex extra-Antarctic earth system linkages.

Late Phanerozoic Global Earth Systems

The transition from so-called global hothouse to icehouse worlds during the late Phanerozoic has been explained in terms of extra-terrestrial and terrestrial (Earth) factors or phenomena, operating at a variety of temporal scales (Crowley and North, 1991, *Paleoclimatology*, Oxford University Press). Marine and terrestrial geosphere/biosphere data bases from the low and middle latitudes have been successfully used to recognise late Phanerozoic global paleoclimate and paleoenvironment periodicity, trends, phases, thresholds, and events, of various frequencies and amplitude. Some low-middle latitude data have even been employed to argue proxy interpretations of paleoclimate/cryosphere history and trends in the Paleoaustral Region, including East and West Antarctica.

If the low-middle and high latitude hydrosphere, cryosphere, and atmosphere formed a closely coupled interactive system during the late Phanerozoic, as has been proposed, useful isochronous, diachronous and other datums of various temporal resolution should be decipherable in tropical/temperate and polar data sets. It is, then, simply a matter of identifying these interactive systems and interpreting global change patterns apparent in the collective data bases. For example, it should be possible to couple third order global eustatic cycles, polar glacial-deglacial cycles, and high resolution stable isotope oscillation patterns in deep sea data bases in a well constrained global framework. We are well aware that this is not the situation and this and other equally vexing problems remain unresolved.

Characterization of Late Phanerozoic Paleoaustral Phenomena and Events

Our immediate charge is to prepare Paleoaustral data bases for eventual integration into a variety of global studies, including time-series and time-slice paleoclimate modeling. Are Paleoaustral geosphere-biosphere data sets complete, understood, and organized in ways that facilitate comparisons, correlations, modeling of data, and earth system analysis and synthesis? I suspect not.

The formulation of earth system circuitry at various scales is a highly subjective undertaking. That is, we all apply varying weights to the importance of time, processes, events, periodicity, etc, in the geosphere, hydropshere, cryosphere, atmosphere and biosphere. In many instances our views of Phanerozoic history and the hypotheses and interpretations we erect are strongly influenced by individual attitudes to uniformitarianism or actualism.

The Paleoaustral earth system scientist might be advised to return to basics, focus on the details of observational data, consider relationships between diverse data bases, and rank types of data and the problems they might be used to solve. In other words, there should be a clearer understanding as to how different types of data might be applied to solving different types of problems, and problems of different magnitude. If we do not characterize our enormous polar data bases in some logical way we cannot hope to participate in future long-time-scale global change experiments and syntheses.

One of my primary recommendations for this workshop is that we compile an inventory of Paleoaustral topics, themes, processes, events, phenomena, etc, and organize these against the best time schemes we can muster. This should provide us with some understanding of what we have to work with, where our data are strong, weak, or totally lacking, and importantly, where we should invest future field, laboratory, technical and logistic effort and resources. To initiate this proposed phase of (re)evaluation, I propose that we characterize all existing and new geological and geophysical data at three levels of temporal resolution. Here is an example of what I have in mind.

- ~5 to 10 m.y. (Macro-temporal phenomena & events) - Examples include: phases of seafloor spreading and ocean floor development, opening of oceanic gateways, basin subsidence episodes, and uplift phases of discrete crustal blocks; major episodes of terrestrial erosion and coeval transport to marine and terrestrial basin depocenters; episodes of accelerated crustal (isostatic) adjustment; eustatic supercycles; stratigraphic supergroups/groups; major basin deformation events; widespread angular unconformities; major paleobiological overturns; and geographically widespread acoustic facies, and regional acoustic interfaces (reflectors).
- ~0.1 m.y. to 1 m.y. (Meso-temporal phenomena & events) - Examples include: stratigraphic formations; disconformities; significant fault displacements; glacial-interglacial cycles with significant ice advance and retreat, glacio-isostatic adjustments, and periodic ice shelf grounding; third order eustatic cycles; and first and last appearance datums in microfossil records.
- 1 yr to 10,000 yrs (Micro-temporal events and phenomena) - Examples include, annual lacustrine cycles, annual autumnal leaf fall (*Nothofagus beardmorensis*) in the Sirius Group; multi-season tree rings (*N. beardmorensis*), and soil horizons, also in the Sirius Group; volcanic extrusives and tephra showers; stratigraphic members, beds, laminae; hiatuses; ice rafting events, ice loading events, and bottom scouring events; and glacio-isostatic adjustment (uplift) during deglacial phases. In some instances the marine and terrestrial record has the potential to provide details of sudden "catastrophic" events such as floods, wind, disease, and drought etc. This category of events and phenomena has much in common with the ANTIME agenda.

The Ideal Paleoaustral Region Data Base

For late Phanerozoic Paleoaustral Region data and datums to be useful in a variety of global exercises they should have a temporal resolution value of at least 2 million years, and the many significant datums should be distributed through all 100 million years. Let's examine the status of our data. Documented Paleoaustral processes, phenomena, and events, characterized at the three temporal levels suggested above, should now plotted against the 100 m.y. late Phanerozoic time scale. I would be surprised if the existing Paleoaustral data based survived the 2 million year resolution test of applicability, although some short spans of the record might.

What do we learn from this exercise? The terrestrial record is very incomplete. The marine record is significantly better, but one has to develop a composite record from widely scattered areas of the Paleoaustral Region. It is almost impossible to relate late Phanerozoic terrestrial and marine histories within the Paleoaustral Region at a level of accuracy found in other parts of Earth.

Specific Late Phanerozoic Global Change Thematic and Topic Objectives: A major goal for the next decade should be an improvement in our understanding of earth system linkages within the Paleoaustral Region; and between the Paleoaustral Region and lower latitude deep ocean, continental shelves and terrestrial environments. Examples of global, hemispheric and regional themes and topics will be introduced and discussed at the workshop, and include macro-, meso- and micro-temporal phenomena. A few examples of these include:

- Major drainage systems and volume estimates of continent to continental shelf and deep sea sediment transport versus time
- Episodes of widespread cratonic weathering and erosion versus time
- Cryosphere-hydrosphere relationships: ice sheets, glacial history and sea level
- Potential presence of trans-Antarctic seaways, and recognition of shallow and deep water circulation patterns
- Development of surface and deep water circulation around Antarctica in response to plate tectonic evolution; and bottom water origin and circulation history
- Marine and terrestrial thermal thresholds - Mid Cretaceous thermal maximum (90-120 Ma), Eocene thermal maximum (50-55 Ma), Mid Tertiary (Oligocene) thermal transition (25-35 Ma), Miocene-Pliocene transition (5-6 Ma) and the Messinian salinity crisis, Early Pliocene (~4 Ma) warm period, and Late Pliocene and Pleistocene cooling
- The hothouse to icehouse transition in the Paleoaustral Region; can it be recognized, and is it coeval with transitions identified in other parts of Earth
- The Paleoaustral Biotic Realm to Polar Biotic Realm transition: Evolution of the modern Antarctic benthic biota during the Neogene
- Late Neogene biotal distributions and climate change, migration, refugia, and extinction

ANTARCTIC SEISMIC DATA LIBRARY SYSTEM FOR COOPERATIVE RESEARCH (SDLS)

Alan Cooper
U.S. Geological Survey, Menlo Park, CA, USA
and
Giuliano Brancolini
Osservatoroi Geofisico Sperimentale, Trieste, Italy

I. What is the SDLS?

Purpose

The Antarctic Seismic Data Library System provides open access to multichannel seismic reflection data collected by all countries in Antarctica, to facilitate large-scale cooperative research projects.

How started

- The SDLS was designed in April 1991 by consensus of all countries that collected seismic data in Antarctica, to establish that seismic data were not being concealed for use in the exploitation of Antarctica's resources.
- In late 1991, the SDLS was formally implemented under Antarctic Treaty Consultative Meeting (ATCM) Recommendation XVI-12.

Where located

- The SDLS has 11 library branches that are located in 10 countries worldwide.
- Researchers may go to any library branch to inspect Antarctic multichannel seismic reflection data.

Benefits of SDLS

Education

- SDLS helps to preserve our privilege to collect seismic data and conduct geoscience studies in Antarctica, by educating the public and Environmental Protection Groups about the benefits of Antarctic seismic research.

Data access

- SDLS facilitates large-scale cooperative research projects by providing quick and easy access to digital seismic data.

Data protection

- SDLS protects the intellectual property rights of data collectors while stimulating new cooperative research projects.

Data storage

- SDLS has many sites for long-term access to Antarctic seismic data, but the SDLS is not a data bank.

II. How does the SDLS function?

How managed

- The SDLS operates under the general auspices of the Scientific Committee on Antarctic Research, and is currently overseen by the ANTOSTRAT Project.
- The SDLS is directed by the ANTOSTRAT Steering committee and the SDLS Coordinator, and operates under guidelines outline in SCAR Report #9 (1992).

How supported

- The SDLS does not receive money from SCAR.
- Overall management costs are currently underwritten by the U.S. National Science Foundation, U.S. Geological Survey and Osservatorio Geofisico Sperimentale (Italy).
- Costs for production of each CD-ROM (used for data distribution), is to be paid by the National Antarctic Program Manager of that country that collected the MCS data, with a subsidy now from the Italian National Research Program. Previously, all production costs had been paid by U.S. Geological Survey.
- The operational costs for SDLS branches are paid by the host organization.

How data are handled and used

Data submission

- MCS users are required to submit their digital processed seismic data (stack sections) to the SDLS within 4 years of data collection.
- Data are submitted on magnetic tapes to Dr. Giuliano Brancolini at OGS in Trieste, Italy.

Data distribution inside SDLS

- MCS data are transferred to CD-ROMs, with special display software, ancillary data sets, and text information.
- The CD-ROMs are mailed to SDLS library branches, where their safety and proper use is overseen by a senior Antarctic researcher.

Data access, use and restrictions

- Researchers may visit any SDLS branch to view the MCS data.
- Library branches must provide a large computer display for the CD-ROM data, and some branches may have paper copies of the data for examination.

- SDLS branches are not allowed to provide copies of data.
- For the first 8 years from time of data collection, there are restrictions on the use of the MCS data – data may only be used in cooperative projects with the data collector, or otherwise only with their permission.
- Thereafter, there are no restrictions on the use of the MCS data.

Data distribution outside SDLS

- After 8 years from time of data collection, CD-ROMs held by the SDLS (other than those at current SDLS branches) are sent to the World Data Center for unrestricted distribution to the public.
- CD-ROMs at SDLS branches stay there indefinitely.

III. What is the future of the SDLS?

What is its function

- The SDLS is mandated by the Antarctic Treaty, but its future usefulness (like its past success) depends on people's interest in large-scale Antarctic science and solving global problems, for which cooperation is essential.
- The SDLS has many benefits, the most important of which is helping to protect our privilege to conduct geoscience research in Antarctica, by setting an example of giving open access to highly scientifically valued MCS data.

Who will oversee the SDLS

- The general Treaty-mandate and SCAR-oversight will continue.
- Until the end of 1998, SDLS will function under ANTOSTRAT. Thereafter, the SDLS will be under either a new SCAR activity or the SCAR Working Group on Solid Earth Geophysics.
- Day-to-day activities will be coordinated, until January 1, 2000, under a joint working agreement between U.S. Geological Survey and Osservatorio Geofisico Sperimentale, and under the overall guideance of the ANTOSTRAT Steering committee, or equivalent after 1998.

How can the SDLS be more useful

New technologies for data access

- World Wide Web: Many new possibilities that include
  - interactive maps,
  - display of data over the web,
  - download of data over the web,
  - cross-links to other Antarctic geoscience data bases (e.g., geologic samples, -physical oceanography, glaciology, etc),
- High-density CD-ROMs: Access to data may be possible via high-density CD-ROMs, made as needed on demand.
- New software included on the CD-ROMs for more varied interactive display and printing of data
- Other?

New data added to library system

- Add land MCS data
- Add all digital Antarctic seismic data
- Add other digital geophysical data (e.g., bathymetry, gravity, magnetics, etc.)
- Other?

New ways to use old data

- Libraries might loan out CD-ROMs for data older than 8 years
- Prior publications and maps might be included with the data on CD-ROM, such as was done with AGU ARS V.68
- Other?

Different way to assure data submissions

- On-time submission of data is a common problem (readily overcome by resetting personal and institutional priorities)
- Positive: Provide incentives (e.g., leadership positions, awards, etc.) for individuals who submit data on time and facilitate cooperative projects.
- Negative: Post names of delinquent PI's and institution names on Web site.

IV. Issues and questions

Science

Data sharing and use

- What are the advantages and disadvantages of applying the "restricted-open-access" philosophy of the SDLS to other types of data that are commonly needed/collected in large-scale cooperative research projects?
- Would such a worldwide library system for these data encourage and facilitate future cooperative research?
- Or, are there other ways to encourage and assure sharing of geoscience data within "reasonable" time limits, to honor the spirit of the Antarctic Treaty?

Value of old data

- Is access to prior data sets of value to planning new cruises and preparing research reports?
- Or, are the prior research reports based on the prior data sets adequate for these purposes?

Administrative

Data submission

- Should new guidelines and requirements be implemented and forwarded to the ATCM to assure timely submission of data to the SDLS?

- Should all data collectors be held to the same standards of data submission and payments, regardless of inequalities in economic conditions of different Nations?
- How should the SDLS deal with common statements by data collectors of "inadequately processed and unprocessed data" and "inadequate technical help to provide data", as reasons for not submitting data on time?

Data Security

- Are current guidelines adequate to protect the intellectual property rights of data collectors while data are in the SDLS (and within 8 years of data collection)?
- Have there been any problems to date?

Finances

- What, if anything, should now be done to help data collectors principally (and SDLS staff, secondarily) to assure that each National Antarctic Program manager pays for the costs of CD-ROM production ($5000/CD) for data collected by their country? (or that equivalent moneys are provided to SDLS by that country for oversight and technical operation – e.g., U.S. and Italy)?
- Should a "finance sub-committee" with members from each country be instituted to assist in assuring that funds are forthcoming to the SDLS?

Other?

- What are the other issues that should be addressed now?

V. Recommendations

- SDLS workshop - A workshop should be held, with participation of the entire MCS data collection community, to review the SDLS operating guidelines and technologies to be used in the coming decade.
- Technical committee - An ad-hoc committee be established to work on technical issues of updating and upgrading the SDLS
- Data submission and payments - Procedures should be clearly outlined and steadfastly implemented to assure uniform application to all data collectors, and timely submission of data and payments to the SDLS.

ANTOSTRAT ANTARCTIC MARGIN ODP INITIATIVE

Peter Barker
British Antarctic Survey
Cambridge, UK

The current ANTOSTRAT involvement with ODP has developed slowly over the past 3-4 years, and seems likely to last for a further 3-4 years. In this paper I set it in context, outlining both the science and what might be called the politics of the enterprise.

The Science

We now understand the essentials of sediment transport and deposition under a fully-fledged glacial regime, as seen on Antarctica. The Antarctic continental shelf is over-deepened and generally inward-sloping because of the erosive action of a grounded ice sheet. The ice sheet "drains" largely through ice streams, whose rapid flow is enabled by the presence of a basal layer of deforming till. The ice sheet appears to have been grounded to the continental shelf edge during most glacial maxima, and extensive progradational wedges at the continental margins of Antarctica have largely been created from this deforming till. In the simplest model, till is deposited on the upper continental slope during maxima, and on the shelf whenever a grounding line retreats and/or the ice base lifts. Pelagic and hemipelagic interbeds are deposited on shelf and slope during interglacials, when the grounding line is inshore. Ice sheet re-advance can lead to erosion of shelf deposits.

To some extent, the essentially unsorted glacial sediments deposited on the upper continental slope directly ahead of the grounding line are unstable, giving rise to debris flows and turbidity currents that cross the lower slope and rise. These processes involve gravitational sorting and, with the ambient bottom current regime, can lead to the development of sediment drifts on the continental rise. Some of these incorporate turbidites transported directly from the upper slope, whereas in other cases direct turbidity current flow by-passes the drifts, which comprise only the fine-grained component, entrained in a nepheloid layer of the ambient bottom currents and deposited down-current.

It is now clear that a record of ice sheet history is preserved within all three depositional environments: shelf topsets and slope foresets of the prograding wedge, and sediment drifts of the continental rise. The foreset record is direct, and the accessibility of the continental shelf during the present interglacial has focussed the greatest amount of attention onto its upper surface, but over geological time it is discontinuous because of erosion. Slope foresets provide a more continuous record, but both topsets and upper slope foresets are largely unsorted, which can present problems of sediment recovery during sampling. The continental slope has received comparatively little attention. The record of glaciation contained in drifts on the continental rise is less direct, being dependent additionally on non-glacial processes (slope instability, bottom currents), but may be easier to extract because the sorted sediments are more easily sampled.

Much of the development of this understanding has taken place within the period of ANTOSTRAT activity, and has owed much to the research environment created, in which seismic data held by several groups could be freely exchanged and communally interpreted, and sediment sampling by piston coring has in some cases successfully built on the seismic interpretations. The rapid progress made in understanding the modern Antarctic offshore environment, compared with relatively slow progress in the Northern Hemisphere despite much longer and more intensive study, may be attributed to the relative simplicity and accessibility of the Antarctic environment: an approximate radial symmetry, a fully glacial regime without significant fluvio-glacial activity, the absence of political barriers to collaboration, the fortuitous coincidence of national bases (and thus ship tracks and seismic data) in sheltered indentations in the coastline with the major ice drainage channels and thence prograded wedges.

Drilling Proposals

It became clear that the ANTOSTRAT data set could support a co-ordinated examination of Antarctic glacial history, by means of ODP drilling. Glacial history is of global importance, because of ice sheet interaction with ocean and atmospheric circulation, and its effects on sea level and oxygen isotopic determination of palaeotemperatures. The margin sediment record is crucial because existing low-latitude proxy estimates of ice sheet history are, and will remain, ambiguous and conflicting.

When the plan was first discussed at the August 1994 ANTOSTRAT Symposium in Siena there was only one ODP proposal for margin drilling extant, for the Antarctic Peninsula margin. However, four additional Letters of Intent were submitted to ODP for the end-December 1994 ODP proposal deadline, and tied together by a Summary Document. By end-1995, after a second meeting in Siena in September 1995, we had 5 full-blown proposals and a revised Summary. These were:

- Antarctic Peninsula Pacific Margin. Barker et al. Proposal 452-REV2.
- Glacial history and Palaeoceanography: Prydz Bay-Cooperation Sea, Antarctica. O'Brien et al. Proposal 490.
- The Wilkes Land Margin. Escutia et al. Proposal 482.
- The Ross Sea Continental Shelf. Davey et al. Proposal 489.
- Linking changes in Southern Ocean deep circulation and terrestrial events in East Antarctica - the Weddell Sea Record. Kristoffersen et al. Proposal 488.

The results of these proposals can be combined to produce a complete glacial history, by use of numerical models of ice sheet development. Drilling on 3 or 4 margins would provide the complete story.

The ODP is an independent organisation with its own review procedures and considerable pressures upon and within it for drilling all over the world, to examine a wide range of problems in geoscience. The ANTOSTRAT proposals have undergone several stages of thematic review, and at times it has not been easy to detect progress. However, in May 1996 ODP set up an Antarctic Detailed Planning Group (ADPG) to examine and rank a range of proposals related to Antarctic margins. It recommended an investigation of Antarctic glacial sediments by means of a co-ordinated and prioritised suite of drilling campaigns around the continental margin. It recognised that more than one leg would be required to achieve the objective, and it provided a leg priority listing within a multi-leg plan. Its conclusions were very close to those of ANTOSTRAT. Antarctic Peninsula drilling had the additional role of helping understand the relationships between depositional environments so that drilling strategy on subsequent legs could be refined.

This step was extremely important: the ADPG membership included members of ODP Panels, and its recommendations were accepted by the Planning Committee, the dominant ODP science committee at the time. The ADPG is disbanded, and ODP has since been re-organized, but it is committed to those recommendations in theory and (so far as we know) in practice. One of the central reasons for continued formal SCAR recognition of ANTOSTRAT beyond the demise of its parent Group of Specialists last year was to assist interaction with ODP to maintain this commitment.

All is not plain sailing. One leg has been scheduled so far: the Antarctic Peninsula margin will be drilled during Leg 178 in February to April 1998. An ice support ship will be chartered for this leg, and is an additional expense for ODP, which has said it cannot afford that expense every year. In fact, drilling on the Kerguelen Plateau has been scheduled for early 1999, in the Antarctic margin's ice and weather window. We have received an undertaking that there will be no procedural barriers to consideration of EITHER a revised Prydz Bay proposal OR a revised Wilkes Land/Ross Sea proposal pair, for drilling in the ice and weather window in early 2000. However, it is up to us to ensure that the science quality of those proposals is sufficiently high to merit drilling. The next deadline for proposal submission is 1st September 1997, and at the end of this week (12 and 13 July) we shall be spending time specifically in helping improve the existing proposals.

Drilling in a particular region is dependent on the existence of other highly-ranked proposals in the vicinity: there is a limit to the extent to which a single highly-ranked proposal can direct drill-ship movement, but "proposal pressure" is a reality. It seems most likely that Prydz Bay and the Wilkes Land/Ross Sea pair will be within reach of the drill ship in early 2000. However, we cannot guess the future movements of the drill ship and would be advised to ensure that the Weddell Sea proposal (now combined with a proposal to drill Mesozoic black shale and basement targets) is optimal also.

The Future

I see the future as a continuation of present strategies for a limited time, but no less difficult than the recent past, and needing continued care and effort.

In science terms, the central goal of this initiative should remain the elucidation of Antarctic glacial history. If it succeeds this will be a tremendous achievement, the solution of a difficult problem of long standing and of global significance. I think the strategy is right, and we stand a good chance of success.

The main difficulty most probably lies in maintaining ODP interest and enthusiasm. In essence, 90-95% of the ODP community would rather the ship was elsewhere. Some of those interested in the problem doubt our ability to produce a solution. To a large extent, Antarctic Peninsula drilling is a test of viability, particularly in the matter of recovery in tills, and there are those who are unhappy at sanctioning further drilling until viability is demonstrated. However, time is short, because of the pressure for the drill ship to head for other, more distant parts of the world. Our immediate aim is to work towards scheduling an ANTOSTRAT leg or legs for drilling in early 2000, and ensuring that leg is adequately supported (for example, with site survey data matching ODP regulations). Beyond that we should consider how to bring things to a satisfactory conclusion. What can the Antarctic community do to help things along? How do we ensure that those members of the ANTOSTRAT community NOT from ODP subscriber countries remain involved in the enterprise? What will be the likely contributions to the elucidation of glacial history from operations OTHER THAN ODP (Cape Roberts drilling, shallow shipboard drilling) that will be active within the same period?

It will be useful, in the context of this Workshop, to consider the possibility of any additional, future use of ODP drilling capability, in pursuit of objectives other than Antarctic glacial history. My views on this are twofold:

- first, we should not risk the current exercise by appearing, as the Antarctic geoscience community or a subset of it, to change our view of what is the best science for ODP to be examining on the Antarctic margin. To my mind, Antarctic glacial history IS the most important, and the most tractable problem for ODP to tackle. Moreover, this specified objective, embodied in the report of the ADPG, is our only claim upon current ODP resources: change the objective, and we start again in the proposal writing and review process.
- second, the current involvement with ODP will take longer than I (for one) thought: we really need an additional leg, post-early 2000, to see the problem through. To get this far has taken 4 years, and we were helped by proposal pressure that brought the drill ship into the South Atlantic and Southern Ocean. It will be difficult to do this again, quickly, and impossible to attempt it with any guarantee that it will happen.

In short, it is unrealistic to make plans that involve the use of ODP resources to tackle other problems, in the short and medium term. For the next 5 to 10 years, we must work with what we in the Antarctic community can create ourselves.

These comments are not intended to eliminate ALL possible changes to existing proposals. The community within global marine geoscience that is interested in the high-resolution record of Holocene climate change (and correlation with the continental record in ice cores) has very successfully adopted the strategy of piggy-back studies on planned ODP legs. Recent examples include sites in Saanich Inlet and the Santa Barbara and Cariaco Basins. In particular, a proposal (#502) headed by Eugene Domack to sample a 70m ultra-high-resolution Holocene record in the Palmer Deep on the inner shelf of the Antarctic Peninsula just south of Anvers Island, will occupy 1-2 days of Leg 178. It will provide an interesting complement to the principal objectives and depositional environments of the leg, and we may learn much from it that will inform our interpretation of older sediments. The overdeepened shelf elsewhere around Antarctica may preserve similar records, and their sampling could be a legitimate target of an ANTOSTRAT drilling leg. The relevant community is meeting in the ANTIME Workshop, nearby.

DEEP STRATIGRAPHIC DRILLING IN THE ANTARCTIC OUTSIDE ODP

P. J. Barrett,
School of Earth Sciences, Victoria University of Wellington,
P O Box 600, Wellington

Deep stratigraphic drilling (>25 m) is an essential means of sampling strata if we are to build up a historical record of climatic and tectonic events over the last 100 million years from the Antarctic region. It is expensive in time, money and logistic effort but provides data and as a consequence insights that can be obtained in no other way. The value of continuously coring stratigraphic sequences has been widely appreciated through knowledge gained from the deep ocean basins and continental margins since the inception of the Deep Sea Drilling Project in 1968. The Antarctic margin has benefitted from two DSDP/ODP campaigns (1972-73, and 1987-88), but the small number of holes (8 in total) and the poor core recovery from strata drilled on the continental shelf persuaded Antarctic scientists to look for other ways of sampling the Antarctic stratigraphic record, which it was acknowledged contained the most direct record of the term history of the ice sheet. As a consequence Antarctic scientists and operators have developed experience in cold climate stratigraphic drilling both onshore and offshore to depths of several hundred metres.

The first deep drilling project on the Antarctic continent was the Dry Valley Drilling Project, a joint project by Japan, NZ and USA, between 1970-75. The project used a land-based Longyear 44 wireline diamond drilling system to core continuously to depths of over 300 m in valley fill (e.g. Taylor Valley), in volcanic flows and hyaloclastites (e.g. at McMurdo Station) and in basement granite (e.g. Lake Vida, Victoria Dry Valley). The project showed how it was possible to core through permafrost with almost 100% recovery (but not how to continue beneath the permafrost), and also tested the feasibility of using the same rig to drill offshore from a sea ice platform for drilling strata to date the beginning of Antarctic glaciation in the Ross Sea region.

Several further attempts were made by the NZ Antarctic Programme to drill deep enough to recover pre-glacial strata, the most successful being the CIROS-1 drill hole, which reached a depth of 702 m in 1986 with 98% core recovery. The history from the core is now known to span the period from around 20 to 35 Ma ago with glacier ice calving at sea level in the oldest cores, but grounded ice probably no older than 30 Ma. In the next two field seasons a similar drilling system will be used for the Cape Roberts Project to sample the same sequence 70 km north and continue into another 1000 m into older strata, seeking the extend back the climatic and tectonic history of the region to the Cretaceous.

The CIROS-1 drill hole showed that deep core could be recovered not only from offshore but also onshore sites under the climatic constraints of Antarctic conditions. The Cape Roberts Project will take deep drilling a stage further, by attempting to drill in water over twice as deep (400+ m), and by developing a portable rig, camp and laboratories. The main components are built in and around standard shipping (ISO) containers, and can be shipped, off-loaded and sledged (but not flown) into place. The cost of the planned 3 holes yielding 1500 m of core in two seasons is $US 4.3 million for all aspects of the logistics, the drilling system and core recovery. Scientific work on the core is expected to cost another $2 million.

Once the Cape Roberts Project is completed, hopefully in 1999, then the camp and drilling system will be available for other tasks. Past experience indicates roughly the following times for planning such projects. (lead time is 4-7 years from conception to drilling):

1-2 years: Site surveys. Although some preliminary seismic, gravity and magnetic surveys may have been carried out to define drilling targets with reasonable confidence, site specific surveys will be needed.

2-3 years: Organisational development. Getting core scientific and logistic team to agree on both science goals and operational approach, to secure funding required, and organise comprehensive environmental evaluation. This could run in parallel with the site surveys.

2 years: Assembly of drilling system and shipping to a location close to drill site area

1-2 years: Drilling activity and scientific study. If on sea-ice then the risk of delay due to ice conditions

1 year: Site clean up

Sequences worth considering for coring with a drilling system of this type include the following, but there are certain to be many others:

- Deep sampling of Neogene strata beneath Ross Island
  Goals: Most complete Neogene record in Victoria Land basin for climate history of region.
  Task/Location: Coring to depth of 4000 m at McMurdo Station (first 1000 m would be volcanics).
  Needs: Group of scientists to review data and write proposal.
  Note: Magnetic and seismic surveys already done.

- Sampling the remote deeps from shelf and sea ice in the Ross Sea sector
  Goal: Core most complete proximal sedimentary record of the last 200,000 years
  Task/locations: Use Cape Roberts system from fast ice in several deep basins along TAM front e.g. off Beardmore and Byrd Glaciers, off Drygalski Ice Tongue. Involves coring up to 200 m with a hydraulic piston coring system in up to 1000 m of water.
  Needs: Group to review possible sites for ice conditions and thickness of subseafloor sediment. Maybe piston cores to estimate modern sedimentation rate to gauge likely time range of sediment to be cored.
- Sampling Neogene strata in Lambert Graben
  Goals: Neogene record of glaciation to gauge stability of AIS in this sector.
  (Link Pagadroma Tillite with lake/nearshore sediment and drifts on rise for same time period.) Task/ Location: Coring on fast ice to depths of ?500 m in Beaver Lake area.
  Needs: Group of scientists to review existing data Geophysical surveys for sediment thickness and velocity profiles for various parts of graben.

APPROACHES TO MARINE SHALLOW DRILLING ON THE ANTARCTIC SHELF

Yngve Kristoffersen,
University of Bergen, Norway.

Shelf sediments which document past glacial advances are often represented by relatively coarse material compacted by the iceload and therefore difficult to penetrate by conventional sediment sampling devices lowered from a vessel. Penetration more than a meter or so in overconsolidated material can only be obtained by drilling. On the positive side is that glacial erosion of inclined strata on a prograding shelf often expose truncated sediment sequences at the sea floor and provide access to a geological record which range from the young sediments at the shelf edge to succesively older strata towards land or the front of an ice shelf. Important information can therefore be obtained by shallow drilling (say less than 100 m sub-bottom).

Goal:
To obtain undisturbed sediment cores +50 m long in water depths up to 1000 m for geological ground truth and interpretation of past glacial environments.

Approaches:
- Drilling from landfast ice
- Ice strengthened dedicated drilling vessels;
- Mobile systems adapted to existing Antarctic research and support vessels;

Drilling from landfast sea ice platforms has successfully been carried out in the Ross Sea with great scientific reward during the MSSTS, CIROS projects and currently at Cape Roberts as international cooperative efforts. Holes have been drilled down to over 700 m below the seabed with good recovery using conventional offshore drilling technology. The sediment cores document the earliest glaciation in the Ross Embayment during the Oligocene. Choice of drill sites are however, constrained by the presence of suitable fast-ice. Unexpected changes in the ice situation from one year to another represent a challenge, and relocation on short notice is difficult.

Very few ice-strengthened geotechnical drilling vessels are commercially available, and rates are more than \$ 50k/day. Mobile systems based on standard offshore drilling technology using heavy API pipe also require a substantial size of the rig and relatively large mobilisation costs. They require a moon pool of a size that is not available in the current Antarctic fleet of research vessels, and therefore a dedicated vessel.

Small mobile systems which can be lowered to the seafloor and remotely operated from a research vessel have been built and successfully used in the deep ocean environment. However, cores are limited to 3 m length. Engineering proposals have existed for more advanced versions which can take longer cores by adding pipe and exchanging core barrels by remote control, but no reports of prototype development have been recorded.

Developments:
Objectives of ANTOSTRAT as well as Nansen Arctic Drilling in the Arctic Ocean have spurred development of an alternative approach using light weight mining technology for shallow drilling from Antarctic research vessels.

A concept using mining exploration equipment adapted for marine shallow drilling from a research vessel was first attempted during the Nordic Antarctic Expedition 1995/96 on the Queen Maud Land Shelf. Initial tests had been carried out in Norwegian fjords and offshore Helsinki by University of Bergen in cooperation with Geo Drilling A/S, of Namsos, Norway. The site was in 212 m water depth on the west side of Kvitkuven Ice Rise in a bay where the Finnish research vessel "Aranda" could be tied to fast ice. The rig was mounted on the stern of the vessel. The riser and drill string performed very well, but penetration of the glacial till was hampered by frequent loss of circulation. The drill bit reached 16 m below the seafloor before the site had to be abandoned because of a change in the ice situation. Total sediment recovery was 18% and included drilling through three basalt boulders.

A second trial was made from "Polar Queen" the following year with a different type of rig mounted over the side of the vessel. The riser and drill string was protected by a guard below the waterline. Drilling were attempted at three sites in water depths ranging from 200 m to 286 m with the ship docked in fast ice as well as under dynamic positioning in open water with drifting sea ice in up to 30 knots wind. Problems with repeated loss of circulation gave a penetration of 6-8 m with recovery varying from 0% to 70%.

These drill sites were located stratigraphically below and above a distinct seismic reflector which is apparent in reflection profiles across the shelf over a distance of several thousand kilometers along the Eastern Weddell Sea continental margin. This reflection event represent an unconformity and mark the onset of vigorous shelf progradation. Microfossils in the shallow drill cores have the potential of providing the first age reference points for Late Neogene and younger glacial advances of the East Antartic Ice Sheet in Queen Maud Land.

The most challenging attempt was carried out in August 1996 from the Swedish icebreaker "Oden" in the Arctic Ocean about 200 km from the North Pole. The vessel was able to keep position while breaking 2-4 m thick drifting sea ice of 8-9/10 cover. The riser was lowered through a moon pool and landed on the Lomonosov Ridge in 970 m water depth. As the drill string was run in the riser an obstruction was encountered at 250 m depth and eventually the attempt had to be aborted.

The experience from two Antarctic and one Arctic season have led to design of a new rig which will meet the specific needs for being mobile and adaptable to a wide range of polar research vessels. The rig comes as a regular 20 foot container sized unit which is positioned with one end extending 2 m over the side or stern of the vessel, or over the well if a moon pool is available. The derrick is mounted in port, and the drill unit and heave compensator guide folds out from the top of the container. Additional containers are used for storage, workshop, mud mixing and a 245 kW power plant. Sea trials are scheduled for the fall 1998.

Valuable experience has been gained in operating under a wide range of ice conditions, with and without a moon pool. Drilling from a ship is safe and can be done with a minimum impact on the environment. This approach has the potential of providing a cost effective tool for geological sampling on the Antarctic continental shelf and make shallow drilling an integral part of the marine research activity conducted by a number of nations around Antarctica in the quest for the climate history of the continent.

THE LATE MESOZOIC AND CENOZOIC PLATE TECTONIC AND CRUSTAL HISTORY OF ANTARCTICA: IMPLICATIONS FOR MARINE AND TERRESTRIAL SEQUENCES

D.H. Elliot
Byrd Polar Research Center and Department of Geological Sciences
Ohio State University

Much of the Late Mesozoic and Cenozoic geologic history of Antarctica is contained in the sedimentary sequences on the continental shelves. That history, however, in large measure reflects the evolution of the Antarctic Plate, both its plate tectonic and its crustal development.

The Antarctic Plate was created by the break-up of Gondwanaland and today, except for the Scotia Sea region, is bounded by spreading ridges. The Antarctic continental shelves rimming the East Antarctic craton are passive margins resulting from the separation of southeastern Africa, India and Australia. The remaining part of the continent has a complex history which includes fragmentation into microcontinents or blocks, rotations and displacements of those blocks, and subduction and passive margin evolution.

In general, the post-breakup history can be divided into: the mid Jurassic to mid Cretaceous, by which time the Antarctic continent had attained its present configuration and polar location (Grunow et al., 1991); and the mid Cretaceous (100 Ma) to Recent. During the latter time interval break-up between Antarctica and Australia/New Zealand occurred, the link between South America and the Antarctic Peninsula was broken, and events leading up to the present day rift system through West Antarctica took place.

The mid Cretaceous (100 Ma.) setting

During the 75 m.y. between Mid Jurassic break-up and the mid Cretaceous, Africa and India separated from Antarctica, and South America from Africa; in addition, rifting had begun between Australia and Antarctica but no oceanic crust had formed. The Antarctic rim of the Gondwana Plate was an active convergent margin throughout most of this interval, although in the backarc region there was extension associated first with break-up and emplacement of the Ferrar tholeiites and second following New Zealand/Pacific-Phoenix Ridge collision in mid Cretaceous time.

Regions rifted during Middle Jurassic break-up were of longstanding by 100 Ma, and included the Weddell Embayment, Pensacola Basin, Lambert Graben, and probably the Jutulstraumen embayment and Lützow-Holm Bay region; other rifts may well be present. These rifts were likely the sites of epicontinental seaways into the interior of Antarctica. Marine incursions may well have occurred in other locations as well.

Initial disruption of the Gondwana Plate margin was probably accompanied by local crustal thinning, and hence seaways may have been established through the Ross-Weddell embayment region and connected to the Panthallasan Ocean. Fission track data, however, suggest significant Early Cretaceous (ca. 141-117 Ma) uplift of the Ellsworth Mountains (Fitzgerald and Stump, 1991), possibly as a result of "docking" against southern Palmer Land, thus blocking any major shallow passages in this region. Uplift of the southern Transantarctic Mountains started at about 125 Ma (Fitzgerald and Stump, 1997), but must have had a different cause. Initial extension in the Ross Embayment-Campbell Plateau region, with accompanying development of the Ross Sea sedimentary basins, and uplift were doubtless linked (Lawver et al., 1994). The underlying driving force for all the Ross Embayment events was probably related to extension in the backarc region of the active plate margin.

Plate tectonic events of the last 100 m.y.

Plate tectonic events of the last 100 m.y. brought about the physical isolation of the Antarctic continent. Arguably this is one of earth's most important events in that it precipitated conditions leading to the inception and evolution of Cenozoic glaciation.

The fragmentation of East Gondwanáland was initiated with the development of the Pacific-Antarctic Ridge between Campbell Plateau and West Antarctica, at about 85-90 Ma. (Cristoffel and Falconer, 1972; Cande et al., 1982) and the SE Indian Ocean-Antarctic Ridge between Australia and East Antarctica, at about 90 Ma (Cande and Mutter, 1982). The boundary connecting those two is complex and also involves the opening of the Tasman Sea at the same time (Weissel and Hayes, 1977). Pacific-Antarctic spreading involved a dextral component of motion whereas the initial opening between Australia and Antarctica was more orthogonal but very slow until the mid Eocene (C20 time) when there was a significant increase in rate (Cande and Mutter, 1982). Transform fractures linked the two principal ridges but complete crustal separation did not occur until the Late Oligocene when the South Tasman Rise finally cleared north Victoria Land.

The other Gondwanaland link, that with South America, was finally broken at about 29 Ma with the formation of ocean floor in Drake Passage (anomaly C10). Shallow water connections may have existed earlier although deepwater circulation was not possible till about 23 Ma when the South American continental crust cleared Peninsula crust at the Shackleton FZ (Barker and Burrell, 1977).

Continental crustal events of the last 100 m.y.

Except for the Antarctic Peninsula, the continent has been rimmed by passive margins for the last 100 m.y. Those from the head of the Weddell Sea round to about 90EE are progressively younger, from Middle Jurassic to Early Cretaceous; the Australia-Antarctica sector dates from mid Cretaceous time, and the rest from the Late Cretaceous. All presumably have been subsiding at normal rates. The Antarctic Peninsula remained a convergent margin, where the Phoenix Plate was subducted, until Miocene time (Larter and Barker, 1991); since then the principal crustal motions there have been vertical.

In the rest of the continent, uplift and subsidence, together with extension and associated volcanism, have dominated crustal events. Uplift in the Lambert Graben region is thought to have occurred in Miocene to Recent time (Wellman and Tingey, 1982; McKelvey et al., 1995). The present elevation of the East Antarctic craton in the Queen Maud Land-Enderby Land sector may reflect the same episode of uplift. The Lambert Graben contains a number of small highly alkaline intrusive and extrusive bodies (Sheraton, 1983), suggesting the extensional regime is of longstanding and is probably still active. The subglacial Gamburtsev Mountains are possibly a major alkaline volcanic field related to the Lambert Graben (Elliot, 1994).

Uplift in the Ellsworth Mountains in the late Cretaceous and Cenozoic was limited (Fitzgerald and Stump, 1991). Nevertheless, the magnitude of the rifts between those mountains and the base of the Antarctic Peninsula suggests more recent continental block readjustments.

Episodic uplift is inferred from fission track data for the Transantarctic Mountains (Fitzgerald, 1992, 1994; Fitzgerald and Gleadow, 1988; Fitzgerald and Stump, 1997). The two principal episodes are Late Cretaceous and Eocene, the latter being the best documented and most widespread. Fission track data provide only a date on the inception of more rapid denudation and do not yield information on its termination. Thus the fission track data do not constrain the denudation/uplift history during the Late Cenozoic, except that in the lower Beardmore Glacier region there appears to have been as much as 4 km of denudation in the last 30 m.y. (Fitzgerald, 1994).

Episodic uplift is also inferred for Marie Byrd Land (Richard et al., 1994), with initial denudation at 100-94 Ma and a later event at about 80-70 Ma. Subsequent tectonic quiescence allowed the formation of a regional erosion surface in Marie Byrd Land, interpreted to be correlative with a similar surface in New Zealand and offshore on the Campbell Plateau and given a Late Cretaceous (75 Ma) age (LeMasurier and Landis, 1996). In Marie Byrd Land the surface is found at elevations up to 2,700 m. The cause of the uplift is thought to be a Late Cenozoic (<30 Ma) mantle plume which lead to eruption of the alkaline volcanic rocks of Marie Byrd Land.

The principal region of active extension in the last 100 m.y. is West Antarctica. The regionally thin crust (20-30 km) of the Ross Embayment was most likely formed following the mid Cretaceous Pacific-Phoenix ridge-crest collision with the trench off New Zealand and the Campbell Plateau (Bradshaw, 1989). Initial development of the elongate basins located on the shelf and extending beneath the Ross Ice Shelf occurred at this time. An extensional regime is also suggested by 100-105 Ma anorogenic granites in Marie Byrd Land (Weaver at al., 1994). This episode of extension, basin formation, and basin filling was terminated by rifting between Marie Byrd Land and Campbell Plateau. The Eocene changes in plate motions and the major episode of denudation in the Transantarctic Mountains may correlate with formation of the Ross Sea regional unconformity U6 (Davey and Brancolini, 1995). Late Cenozoic extension appears to be confined to the Terror Rift in south Victoria Land but contemporaneous alkaline volcanism is widespread in the Transantarctic Mountains and West Antarctica.

The age of the inferred rift basins in central West Antarctica - Byrd Subglacial Basin and the Bentley Subglacial Trench - is unclear but their development may also have a significant Late Cenozoic component. Magnetic data for the whole region have been interpreted to suggest the presence of a major subglacial flood basalt province of Late Cenozoic age (Behrendt et al., 1994).

The remaining region of possible crustal extension lies in Wilkes Land (about 90E-160EE) and includes the Wilkes Sub-glacial Basin, with its continuation into the Pensacola Basin, the Aurora Basin, and the graben-like setting of Lake Vostok and other narrow troughs. The Wilkes and Aurora Sub-glacial Basins may be the counterpart of the Cretaceous depression in Australia (Veevers, 1982). The Wilkes Basin may have been reactivated during the Cenozoic on uplift of the Transantarctic Mountains. The Wilkes-Pensacola Basin contains at least scattered evidence for marine incursions, as indicated by the reworked floras and faunas in the Sirius Group deposits.

Implications Of The Plate Tectonic And Crustal History

Antarctica's role in biotic evolution and dispersal.

Paleobiogeography: Antarctica is central to the issue of migration of vertebrates to Australia. Should reptiles, including dinosaurs, of Triassic through Early Cretaceous age be found in Australia, land bridges must have been maintained across Antarctica. With the inferred rifting and marine incursions in the Ross Embayment, the Ellsworth Mountains would have been a critical stepping stone between the Antarctic Peninsula and the Transantarctic Mountains. Marsupial migration (Woodburne and Case, 1996) occurred after the start of Tasman Sea opening and prior to about 64 Ma by which time the South Tasman Rise was submerged, although the submerged Rise did not clear Antarctica till about 30 Ma; similarly, the land connections must have included the Ellsworth Mountains.

The physical isolation and polar position of Antarctica are crucial factors in evolution of the present marine biota. The presence or absence of shallow-water paths across the Antarctic continent would have played an important role in dispersal and endemism.

Significant questions include: What were the the timing, duration, and elevations of the stepping stones that constituted the land bridges? Where will records of vertebrate dispersal be found and in what sort of sequences? Are there remnants of pre-glacial sedimentary sequences along the flanks or on the shoulders of outlet valleys of the Transantarctic Mountains? How did the evolving shallow and deep seaways influence the evolution of marine biota?

Climate history

Oceanic circulation: The reorganization of oceanic circulation to a thermo-haline driven system occurred during the Cenozoic. Today it is governed by processes occurring around Antarctica. The evolution to a thermo-haline driven system is not well documented but presumably is related to the development of the circumantarctic currents and the upwelling that is a consequence of the ice sheets.

Significant questions include: when was present day thermo-haline circulation initiated? What is the relationship between the evolving shallow and deep-water passages and the development of that circulation?

Glacial history: Glacial onset occurred in the Paleogene. Eocene (>49.5 Ma) glaciation has been reported from King George Island in the South Shetland Islands (Birkenmajer, 1991), but such early glaciation is in conflict with most paleoclimatic data (see Elliot, 1997); based on Sr isotope data, that glaciation is possibly Late Oligocene (Dingle and Lavalle, 1998). Kerguelen Plateau and Maud Rise data have been interpreted to suggest glacial conditions at about 46 Ma (Ehrmann and Mackensen, 1992), however the reported Eocene IRD is now thought to be downhole contamination (S. Wise, this workshop report). In the Ross Embayment, striated clasts in drill core (Hambrey and Barrett, 1993) suggest nearby glaciation in early late Eocene time (Wilson et al., 1998), but there remains the question of whether it reflects mountain glaciation rather than continent-wide ice sheets. Evidence for initiation of substantial ice sheets comes from Prydz Bay and suggests ice down to sea level by Eocene-Oligocene time (Barron et al., 1991; Hambrey et al., 1991). By Late Oligocene time ice-sheet glaciation was widespread and in the Miocene the marine ice-sheets of West Antarctica were first formed. The marine record suggests there have been major fluctuations since then.

The older terrestrial record of glaciation comes from King George Island off the Antarctic Peninsula where the only well documented sequences indicate glaciation (Polonez and Melville glaciations) in Early Miocene time (Smellie et al, 1998). The record from West Antarctica is no older than about 10 Ma. In East Antarctica the antiquity and subsequent fluctuations of glaciation is a matter of on-going debate (see GSA Today, 1998).

Significant questions include: when did ice sheets evolve from wet-based to the present day cold-based condition? To what extent have there been fluctuations in that aspect of the ice-sheets? What role has Cenozoic uplift played in the initiation of ice sheets and in the change to cold-based conditions? Can the timing of uplift, and its duration and amount, be better constrained for the various now-uplifted crustal blocks in and around the margin of the continent?

Key Issues

The timing and kinematics of tectonic events is critical for understanding cause and effect relationships. Paleo-oceanographic history is dependent on knowing the onset and duration of shallow and deepwater circulation patterns, which themselves are dependent on the tectonic history. The uplift and subsidence of crustal blocks, together with crustal extension, control the nature, extent and infilling of sedimentary basins. These vertical movements likewise exerted a major control on the location of centers for glaciation which affected at least regional climate. The patterns of biotic evolution in the South Polar region are similarly dependent on tectonic, glacial and paleo-oceanographic events.

Summary

In broad outline, the significant mid Cretaceous to Recent tectonic events were:

- vertical movements of crustal blocks, starting in the Early Cretaceous that created stepping stones for faunal and floral dispersal but barriers to surface water flow, and which also influenced sedimentary basin development and infilling,
- Late Cretaceous fragmentation of East Gondwanaland, marked by major sedimentary basin development in the Ross Sea-Campbell Plateau region, and in Wilkes Land,
- development of deepwater circumpolar circulation as first the South Tasman Rise cleared north Victoria Land and then the Drake Passage opened,
- physical isolation and vertical tectonism with associated glaciation.

References

Barker, P.F., and J. Burrell. 1977. The opening of Drake Passage: *Mar. Geol.*, 25, 15-34.

Barron, J., B. Larsen, and J.G. Baldauf. 1991. Evidence for Late Eocene to Early Oligocene Antarctic glaciation and observations on Late Neogene glacial history of Antarctica: Results from LEG 119, in *Proc. Ocean Drill. Program, Sci. Results*, edited by J. Barron, B. Larsen, et al., 119, College Station, TX (Ocean Drilling Program), 869-891.

Behrendt, J.C., Blankenship, D.D., Finn, C.A., Bell, R.E., Sweeney, R.E., Hodge, S.M., and J.M. Brozena. 1994. CASERTZ aeromagnetic data reveal late Cenozoic flood basalts(?) in the West Antarcic rift system. *Geology*, 22, 527-530.

Birkenmajer, K. 1991. Tertiary glaciation in the South Shetland Islands, West Antarctica: evaluation of data, in M.R.A. Thomson, J.A. Crame and J.W. Thomson, eds., *Geological Evolution of Antarctica*: Cambridge University Press, Cambridge, p. 629-632.

Bradshaw, J.D. 1989. Cretaceous geotectonic patterns in the New Zealand region. *Tectonics*, 8, 803-820.

Cande, S.C., and J.C. Mutter. 1982. A revised identification of the oldest sea-floor spreading anomalies between Australia and Antarctica. *Earth Planet. Sci. Lett.*, 58, 151-160.

Cande, S.C., E.M. Herron, and B.R. Hall. 1982. The early Cenozoic tectonic history of the southeast Pacific. *Earth Planet. Sci. Lett.*, 57, 63-74.

Christoffel, D.A., and R.K.H. Falconer. 1972. Marine magnetic measurements in the southwest Pacific Ocean and the identification of new tectonic features. In Hayes, D.E., ed., Antarctic Oceanology II: The *Australian-New Zealand Sector*. AGU Ant. Res. Ser., 19, 197-210.

Davey, F.J., and G. Brancolini. 1995. The Late Mesozoic and Cenozoic structural setting of the Ross Sea Region,. In A.K. Cooper, P.F. Barker, and G. Brancolini, eds., *Geology and Seismic Stratigraphy of the Antarctic Margin*. AGU Ant. Res. Ser., 68, 167-182.

Dingle, R.V., and M. Lavelle. 1998. Antarctic Peninsula cryosphere: Early Oligocene (c. 30 Ma) initiation and revised chronology. *J. Geol. Soc. London*, 155, 433-437.

Ehrmann, W.U., and A. Mackensen, Sedimentological evidence for the formation of an East Antarctic ice sheet in Eocene/Oligocene time. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 9, 95-112, 1992.

Elliot, D.H. 1994. The Late Mesozoic and Cenozoic tectonic history of Antarctica: some implications for sediment basin history, sediment provenance, and paleoclimate. *Terra Antarctica*, 1, 445-448.

Elliot, D.H. 1997. The planar crest of Graham Land, northern Antarctic Peninsula: possible origins and timing of uplift. In P.F. Barker and A.K. Cooper, eds., *Geology and Seismic Stratigraphy of the Antarctic Margin, Part 2*. AGU Ant.Res. Ser., 71, 51-73.

Fitzgerald, P.G., 1992, The Transantarctic Mountains of southern Victoria Land: The application of apatite fission track analysis to a rift shoulder uplift. *Tectonics*, 11, p. 634-662.

Fitzgerald, P.G. 1994. Thermochronologic constraints on post-Paleozoic tectonic evolution of the central Transantarctic Mountains, Antarctica. *Tectonics*, 13, 818-836.

Fitzgerald, P.G., and A.J.W. Gleadow. 1988. Fission track geochronology, tectonics and structure of the Transantarctic Mountains in northern Victoria Land, Antarctica. *Iso. Geosci.*, 73, 169-198.

Fitzgerald, P.G., and E. Stump. 1991. Early Cretaceous uplift in the Ellsworth Mountains of West Antarctica. *Science*, 254, 92-94.

Fitzgerald, P.G., and E. Stump. 1997. Cretaceous and Cenozoic episodic denudation of the Transantarctic Mountains: new constraints from apatite fission track thermochronology in the Scott Glacier region. *J. Geophys. Res.*, 102, 7747-7765.

Grunow, A.M., D.V. Kent, and I.W.D. Dalziel, 1991, New paleomagnetic data from Thurston Island and their implications for the tectonics of West Antarctica: *J. Geophys. Res.*, 96, 17935-17954.

GSA Today, 1998. 8(4), 1-8.

Hambrey, M.J., and P.J. Barrett. 1993. Cenozoic sedimentary and climatic record, Ross Sea region, Antarctica, in *The Antarctic Paleoenvironment: A Perspective on Global Change Part Two, Antarct. Res. Ser.*, 60, edited by J.P. Kennett, and D.A. Warnke, AGU, Washington, D.C., 91-124,

Hambrey, M.J., W.U. Ehrmann, and B. Larsen. 1991. Cenozoic glacial record of the Prydz Bay continental shelf, East Antarctica, in *Proc. Ocean Drill. Program, Sci. Results*, edited by J. Barron, B. Larsen, et al., 119, College Station, TX (Ocean Drilling Program), 77-132.

Larter, R.D., and P.F. Barker. 1991b. Effects of ridge crest-trench interaction on Antarctic-Phoenix spreading: Forces on a young subducting plate, *J. Geophys. Res.*, 96, 583-607.

Lawver, L.A., L.M. Gahagan, and A.K. Cooper. 1994. Comparison of eastern Ross Sea with Campbell Basin. *Terra Antarctica*, 375-377.

LeMasurier, W.E., and C.A. Landis. 1996. Mantle-plume activity recorded by low-relief erosion surfaces in West Antarctica and New Zealand. *Bull. Geol. Soc. Amer.*, 108, 1450-1466.

McKelvey, B.C., M.J. Hambry, M.C.G. Mabin, D.M. Harwood, and P.N. Webb. 1995. The Neogene Pagodroma Group in the northern Prince Charles Mountains, East Antarctica. Abstracts, VII International Symposium on Antarctic Earth Sciences, Siena, Italy, 10-15 September, 262.

Richard, S.M., C.H. Smith, D.L. Kimborough, P.G. Fitzgerald, B.P. Luyendyk, and M.O. McWilliams. 1994. Cooling history of the northern Ford Ranges, Marie Byrd Land, West Antarctica. *Tectonics*, 13, 837-857.

Sheraton, J.W. 1983. Geochemistry of mafic rocks of the northern Prince Charles Mountains, Antarctica. *J. Geol. Soc. Aust.*, 30, 295-304.

Smellie, J.M., I.L. Millar, D.C. Rex, and P.J. Butterworth. 1998. Subaqueous, basaltic lava dome and carapace breccia on King George Island, South Shetland Islands, Antarctica. *Bull. Volcanol.*, 59, 245-261.

Veevers, J.J., 1982, Australian-Antarctic depression from the mid-ocean ridge to the adjacent continents. *Nature*, 295, 315-317.

Weaver, S.D., B.C. Storey, R.J. Pankhurst, S.B. Mukasa, V.J. DiVenera, and J.D. Bradshaw. 1994. Antarctic_New Zealand rifting and Marie Byrd Land lithopsheric magmatism linked to ridge subduction and mantle plume activity. *Geology*, 22, 811-814.

Weissel, J.K., and D.E. Hayes. 1977. Evolution of the Tasman Sea reappraised. *Earth Planet. Sci. Lett.*, 36, 77-84.

Wellman, P., and R.J. Tingey. 1981. Glaciation, erosion and uplift over part of East Antarctica. *Nature*, 291, 142-144.

Wilson, G.S., A.P. Roberts, K.L. Verosub, F. Florindo, and L. Sagnotti. 1998. Magnetobiostratigraphic chronology of the Eocene-Oligocene transition in CIROS-1 core, Victoria Land margin, Antarctica: Implications for Antarctic glacial history. *Bull. Geol. Soc. Amer.*, 110, 35-47.

Woodburne, M.O., and J.A. Case. 1996. Dispersal, Vicariance, and the Late Cretaceous to Early Tertiary land mammal biogeography from South America to Australia. *J. Mammal. Evol.*, 3, 121-161.

CONTINENTAL SHELF SEDIMENTARY BASINS

P J Barrett,
School of Earth Sciences, Victoria University of Wellington,
P O Box 600 Wellington, New Zealand.

The most direct stratigraphic record of Antarctic climatic history over the last 100 million years is to be found in the blanket of sediment that covers the Antarctic continental shelf (Fig. 6). This record has been the subject of spasmodic study from the turn of the century to the end of the 1960s, followed by substantial activity in the 1970s and 80s with extensive seismic surveys and around a dozen drill holes, followed in the 90s by a period of review and assessment (Webb, 1990, Cooper et al., 1993, this meeting). With continuing concern over future climate and sea level change, a better knowledge and understanding of the past history of the Antarctic continent is needed to raise awareness of the sensitivities and thresholds in the earth-ocean-atmosphere-ice system, and data from shelf sediments should contribute to this.

Sediment on the continental shelf varies in thickness from nothing to around 14 km. The areas of greater thickness, the sedimentary basins, are typically tens to hundred of km across and vary in shape from subcircular depressions to half grabens to linear troughs. The troughs tend to be either parallel or perpendicular to the shelf margin. From the limited knowledge obtained thus far on the age of sediments in the basins, there appear to have been two main period of basin development, one a consequence of the stretching as Gondwanaland fragmented and firstly India and southern Africa and then Australia moved northwards in early and late Cretaceous times respectively. This rifting and fracturing set the pattern of basin geometry around the Antarctic margin and resulted in the first (syn-rift) episode of basin filling. A period of quiescence was followed by renewed differential subsidence through the Cenozoic with some basins accumulating sediment largely in the Paleogene (eg Victoria Land Basin, Ross Sea) and others in the Neogene (eg. Eastern Basin, Ross Sea).

Younger (post-rift) sediments in both basins and troughs commonly show an internal geometry of seaward dipping reflectors that has led to their description first as deltas (Hinz & Block, 1984) and then more neutrally as prograding sequences (Cooper et al., 1993) (Fig 1b). These features have also been interpreted as till-deltas (Alley et al. 1989), in which the join between topset and foreset bed records the contemporaneous grounding line of a marine ice sheet. It is plainly important to test such a model on both modern sediments and older sedimentary sequences when the feature is well-developed; however the practical difficulties of coring through a marine ice sheet and tens of m into the sediment beneath suggest that any testing may have to be carried out on older sequences, at least initially.

The differential subsidence history of shelf basins is important to recognise and exploit for two reasons. One is that the different basins active at different times in the same region will record events from different time period and when brought together allow a more complete history to be assembled for the region. The other is that in periods of rapid subsidence a basin has the potential for providing the high resolution record needed for icesheet-driven depositional systems, where cycles are only a few tens of thousands of years. However success in piecing together records from different basins requires unambiguous correlation and an accurate chronology, for which data from both seismic surveys and drill holes must be combined.

ANTOSTRAT (1988) identified 5 main regions on which to focus, with each considered to record the history of different parts of the Antarctic ice sheet, e.g. Antarctic Peninsula ice, West Antarctic Ice Sheet, East Antarctic Ice Sheet. Each of these parts of the ice sheet has a different sensitivity and response to climatic forcing (both direct and indirect - eg sea level change) because of their different size and geographic/geologic setting. These histories need to be documented and understood separately in order to understand the global influence of the Antarctic ice sheet as a whole on past climate and sea level change. The regions are (Fig. 1a).

Antarctic Peninsula -Pacific side - Neogene AP ice sheet
Weddell Sea- East Antarctic Paleogene ice sheet history with record of earliest ice
Prydz Bay - East Antarctic Paleogene ice sheet history with record of earliest ice
Wilkes Land - East Antarctic Paleogene/Neogene ice sheet history with record of
later ice growth
Ross Sea - West Antarctic Paleogene/Neogene ice sheet history with latest ice growth

Other useful regions need to be identified for study. For example, the sequence off James Ross Island on the Atlantic side of the Antarctic Peninsula overlies the Paleocene strata of Seymour Island and is likely to contain a detailed record of sedimentation and climate in this region through the Eocene and Oligocene when the first ice sheets were forming, according to current knowledge. The 5 ANTOSTRAT regions were selected for seeking the best glacial record and thus are places where ice has been focussed. Almost as important should be the basins around the east Antarctic margin away from the main outlet glaciers and recording contemporaneous complementary data on the local marine environment - temperature, currents , etc.

Although it is dangerous to be too much influenced by models, it is useful in planning to take into account ice sheet behaviour patterns as described by current ice sheet models. For example, Huybrechts (1993) suggests that the earliest large ice sheet developed over the Gamburtsev Mountains (with temperature 20 deg above present) and engulfed Queen Maud Land before extending Australia-wards to cover all of East Antarctica (15 deg above present, and then enlarge further over West Antarctica (9 deg above present) and the Antarctic Peninsula before reaching its present state and extent. The sedimentary record in basins around the periphery should reflect the differences in extent and timing of the limits of the icesheet at the different stages of its history. Furthermore with the acknowledged cyclic character of glaciations in the Quaternary and very likely throughout the Neogene, we should expect such cycles in the Paleogene and seek to document their extent (linked to temperature range) and frequency. Paleogene glaciations may not have involved the full development of this cycle.

References

Alley R.B., Blankenship D.D., Rooney M.T. & Bentley C.R. 1989 Sedimentation beneath ice shelves - the view from Icestream B. *Marine Geology* 85, 101-120.

Cooper A.K., Eittriem S., ten Brink U., Zayatz I. 1993. Marine glacial sequences of the Antarctic continental margin as recorders of Antarctic ice sheet fluctuations.

Hinz K., & Block M. 1984. Results of geophysical investigations in the Weddell Sea and in the Ross Sea, Antarctica, Proceedings 11th World Petroleum Congress, London, 1983.

Huybrechts, P., 1992. The Antarctic ice sheet and environmental change: a three-dimensional modelling study. *Rep. Polar Research*, 99, 241 p.

Webb P.N. The Cenozoic history of Antarctica and its global impact. *Antarctic Science* 2: 3-21.

MESOZOIC-PALEOGENE PALEOCEANOGRAPHY AND MARINE BIOSPHERE: KEY EVENTS

Sherwood W. Wise, Jr.,
Dept. of Geology, Florida State University and The Antarctic Marine Geology Research Facility
Tallahassee, Fl 32306-3026

A synopsis of key Mesozoic-Paleogene global and regional paleoenvironmental events that help delineate the evolution of the Southern Ocean was given recently by Harwood and Wise (1995), therefore this report will update or expand upon portions of their compilation with suggestions on how future drilling and exploration can address the many associated unsolved problems. For a recent comprehensive review of Antarctic paleoenvironments through the Cenozoic, the reader is referred to Barrett (1996).

The Development of incipient Mesozoic basins during the breakup and dispersal of southern Gondwana continents:

At present the no detailed paleoenvironmental history can be written of the early breakup history and the development of the Late Jurassic-Early Cretaceous anoxic "black shale" basins, although the rough outline of the tectonic history can be reconstructed via plate tectonics (see Eliot, this symposium). We do know from drilling along the Dronning Maud Land margin at ODP Sites 692 and 693 that total organic contents reached 18.4% by the Valangenian then decreased to about 2.5% by the early Albian, but much of that Lower Cretaceous section in that region remains to be drilled. Final ventilation of the basin occurred during the Albian and culminated with upwelling and enhanced productivity that produced a siliceous ooze of exquisitely well preserved diatoms, silicoflagellates, and radiolarians, many of which are new to science.

***Problem*:**

Not known is how and in what stages this incipient Weddell Sea basin came to be ventilated. Mutterlose and Wise (1990) could only speculate on how the opening of critical gateways may have led to the ventilation of this and adjacent basins. More importantly, no model for the development of basin anoxia can be agreed on for lack of deep water as well as shallow water drill sites (existing sites record paleo water depths of only 200 to 500 m). Thus it is impossible to invoke with confidence either a restricted basin (Zimmerman et al., 1987) or an high productivity, upwelling model (Farquharson, 1983).

***Approach*:**

Clearly, the remaining section through the entire Lower Cretaceous "black shale" sequence needs to be drilled out on the Dronning Maud Land margin (i.e., the interval between those recovered at ODP Sites 693 and 693). The section should be continued into and ideally through the

Jurassic section to the Explora Wedge dipping reflectors beneath. This will provide for this region a ventilation history of the basin and correlations to possible gateway events can be established. Secondly, equivalent strata need to be drilled on the floor of the adjacent Weddell Sea to provide deep water sites required to constrain the models of basin stagnation mentioned above.

Feasibility:

As with many of the problems discussed at this workshop, regional seismic studies are now far ahead of the drill bit when it comes to exploring the Jurassic-Lower Cretaceous of the Weddell Sea margins. As Jokat (this workshop) has outlined so thoroughly in his contribution, near surface outcrops of older strata are so accessible along this margin that both shallow and deep penetration drilling can be employed effectively in retrieving a detailed record of the early basin history. Of particular interest are the near surface occurrences of older strata over Polar Stern Bank on the floor of the basin off Dronning Maud Land. These could provide the needed deep basin comparisons with the shelf/slope sites.

ODP proposal #503 has been submitted to address the deep sea drilling aspect of this problem. The shallow-water drilling technology needed for broader coverage should ideally include a dynamically positioned vessel and a drilling rig with heave compensation to deal with the deep Antarctic shelves and any ocean swells that develop.

Late Cretaceous History:

At present there are virtually no Upper Cretaceous marine drill cores from the Antarctic continent. The most complete section in the region is provided by the well-studied DSDP Sites 327 and 511 on the Falkland Plateau, which provide a near continuous record from the upper Albian to Maastrichtian, and for which a stable isotope record has recently been developed (Huber et al, 1995; Huber and Hodell, 1996). The lack of such a record in the southern Weddell Sea area is attributed to a pervasive regional disconformity, above which lies lower Oligocene sediment at ODP Site 693. Not enough information is known from most other regions around the continent to even speculate on the existence of Upper Cretaceous sediments outside the Weddell Sea and Seymour Island. O'brien and Leitchenkov (this workshop) note seismic evidence for a significant thickness of undrilled sediments between the Paleogene and Lower Cretaceous in Prydz Bay; whether these are marine or non-marine is not known.

In addition the Falkland Plateau sequence, excellent carbonate Campanian-Maastrichtian sections have been drilled on Maud Rise and the Kerguelen Plateau. Middle Campanian sediments are missing, however, at all Southern Ocean DSDP/ODP sites drilled to date, apparently as a result of deep sea dissolution or strong current erosion associated with circulation changes at this time, which also witnessed the development of a Late Cretaceous coolwater, provincial austral planktonic calcareous fauna and flora. Huber and Watkins (1993) attribute this to the development of the first semblance of a "proto circum-Antarctic current", perhaps in response to the opening of a gateway between Australia and Antarctica and/or a rise of sea level. Why this circulation system apparently closed down near the end of the Cretaceous is not understood.

Problem #1. There is virtually no Upper Cretaceous record from the Antarctic margin proper (as indicated above), hence no geologic history for this interval of time.

Problem #2. There is no way to study the evolutionary pathways between the primitive diatom and silicoflagellate assemblages discovered at Site 693 and the more highly evolved high southern latitude Campanian-Maastrichtian assemblages from other sites in the region (e.g., DSDP Site 275, Campbell Plateau).

Problem #3. Because no deep sea sections record the establishment of the Late Cretaceous "proto circum-Antarctic current", expanded shallow water sections along the margins of Antarctica must be sought where dissolution and strong ocean currents may not have destroyed the record.

Approach:

A reconnaissance mode of deep sea drilling will be necessary to find Upper Cretaceous sections along the margins of the Antarctic continent. Most sites proposed today through the ODP panel complex are based on highly refined seismic and ground truth information, and a high degree of certainty usually exists as to what will be drilled. A high degree of uncertainty and risk-taking must be accepted for sites proposed along the margins of Antarctica. Similarly, our state of ignorance is such that the role of serendipity must not only be expected but exploited as a means of making major break throughs in knowledge. Drilling plans and objectives should not be so highly structured that they can't be easily modified to take advantage of unexpected discoveries, even if major changes in mission and objectives might have to be made at mid cruise. History has shown repeatedly that crustal/sedimentary models and seismic predictions can only be taken as a rough guides as to what will be encountered during reconnaissance drilling (e.g., ODP Sites 692 and 693; Barker, Kennett, et al., 1988). Unexpected surprises that provide highly valuable new information occur even in much better studied areas (e.g., ODP Site 1069, Iberia Abyssal Plain; Whitmarsh, Beslier, Wallace, et al., 1998, in press). Frontier areas must be approached with great flexibility and an open mind.

K\T Boundary Crisis:

Although many accept the hypothesis that the discovery of the Chicxulub structure in Mexico has provided the "smoking gun" behind the K\T biotic crisis, there is still speculation and contention as to the effect of that crisis on distant Antarctica, which is far removed from the meridional wind belts that would have circulated debris from the event around the globe. Although an iridium anomaly was detected at Site 690 on Maud Rise and on Seymour Island, no associated tektites or shocked quartz have been found at these localities or elsewhere around the Antarctic continent.

Problem #1: Based on a study of nannofossils across the K/T sections throughout the Southern Ocean and beyond, Pospichal (1994) concluded that there was no diminished response among calcareous nannoplankton to the K/T event at high latitudes. This stands in conflict with the conclusions of colleagues who have looked at other fossil groups in sequences on the Antarctic Peninsula (e.g., Zinsmeister et al., 1989; Keller, et al., 1993).

Problem #2: There is also disagreement over the mode and tempo of the extinctions. Do some Cretaceous forms traditionally thought to have gone extinct abruptly at the boundary actually survive the event and persist into the Tertiary to undergo a series of step-wise extinctions as suggested by Canudo et al. (1991)? A somewhat similar case has been made for ammonites of the Antarctic Peninsula by Zinsmeister, et al. (1989). Indeed, Elliot et al. (1994, p. 678) state that "The Seymour Island provides no compelling evidence for mass extinction at the K-T boundary", which seems to be true for the fossil groups they studied (dinoflagellate cysts and invertebrate macrofossils; calcareous microfossils, which many think were more sensitive to the event that siliceous or cellulose-walled groups, are not preserved in the boundary beds). Perhaps if there was a refugia from the K/T devastation seen elsewhere around the globe, Antarctica might be the place to look for it. Outside of Seymour Island, Site 690 on Maud Rise, Site 738 on the Kerguelen Plateau and Site 752 on Broken Ridge, however, no other stratigraphically complete K/T boundary sections are known from the Southern Ocean region, and none beyond Seymour Island have been reported from the continent itself.

***Approach*:**

As with the Albian diatomite discussed in the previous section, seismic stratigraphy cannot resolve intervals as thin as the K/T boundary, much less detect a complete boundary as opposed to an incomplete one. Thus a reconnaissance mode of exploration as discussed above will be necessary to add to our knowledge of this event in Antarctica. Expanded nearshore clastic sections have the advantage of allowing the event to be studied at a higher stratigraphic resolution, but such sections also dilute the content of open marine microfossils and can make age control more difficult.

The Paleocene-Eocene boundary thermal maximum and benthic foram extinction event; the reversal of latitudinal global circulation patterns:

This event, as well as hypotheses as to its significance and impact on global climate, was defined from the study of ODP Leg 113 cores from Maud Rise. In addition to recording the most massive extinction of benthic foraminifers in the last 80 m.y., it is marked by a carbon isotope excursion and an sharp increase in the percentage of warm-water loving discoasters. It has since been recognized in shelf sediments of the New Jersey coastal plain and in terrestrial sediments of the Paris Basin (Stott et a., 1993). A popular hypothesis attributes it to a short-term increase in atmospheric C02 as a result of excessive volcanism, presumably during the rifting of the Norwegian Sea or elsewhere, wuch as in the Carribean Sea.

Problem #1: It has been suggested that the event was accompanied by a reversal in the latitudinal circulation pattern of the oceans (Kennett and Stott, 1990, a suggestion that has engendered controversy and the need for further research.

Problem #2: The Paleocene record leading up to the event is cyclic, showing alternations in clay and carbonate content, with much of the clay being kaolinite derived from the Antarctic continent. Additional sequences of this nature are needed to provided a detailed climate history of Paleogene Antarctica prior to glaciation.

***Approach*:**

Kennett and Stott (1990) and subsequent workers based their findings on two drill holes, one near the crest and one near the base of Maud Rise. More rigorous constraints could be placed on their various models by completing a depth transect of sites down the flank of the Maud Rise so that a greater range of the paleo water mass(s) could be sampled, correlated and compared. In addition, the discovery of this short term (20 k.y.) event on the margins of Antarctica would provide not only the highest latitude record known, but also would show its effects on high latitude, shallow water fauna and flora.

***Feasibility*:**

APC coring on Maud Rise would be a relatively simple procedure because of the availability of good seismic data at the necessary water depths. This is an objective of ODP Proposal #530. Discovering evidence for the event on Antarctica would require a most aggressive program of drilling for seeking out and drilling Paleogene sediments.

Evolution of Southern Ocean and Antarctic Biota:

Much has been learned from DSDP/ODP about biostratigraphic correlations throughout the Southern Ocean region, where relatively cosmopolitan calcareous faunas and floras from the world ocean interface with the more endemic, siliceous high-latitude faunas and floras that vary more widely with latitude and water conditions. The siliceous groups displaced the calcareous forms northwards as climate cooled during the Oligocene to Recent, emerging as the mainstays of biostratigraphic correlations for the Neogene. Efforts are being made to integrate diatom and nannofossils stratigraphies throughout the region in order to enhance their utility (Baldauf and Ramsey, in preparation). Exploration of new areas around the continent, however, will inevitably lead to further modification and refinement of zonal schemes.

***Problems*:**

Virtually nothing is known about the effects of continental connections, barriers or seaways that may have influenced the dispersal capacity and adaptive stress of species as might be indicated by their endemism, provincialism, diversity and evolutionary rates. As noted by Harwood and Wise (1995), "...The degree that mechanisms such as basin rifting, surface water cooling, oceanic turnover, etc. influenced the paleobiogeography, evolution and morphological variation of Southern Ocean and Antarctic faunas is unknown.

***Approach*:**

Extensive and aggressive drilling, including drilling into the sub-ice sedimentary basins of Antarctica as called for by Webb (this Workshop), will be necessary before such complex issues as those stated above can possibility be addressed.

The inception of glacio-marine sedimentation during the Cenozoic (Eocene?) and transition from greenhouse to icehouse climates:

Of all the problems that have driven scientific exploration of Antarctica over the past 30 years, obtaining a record of the pre-glacial/glacial transition has been the goal sought most ardently but with the least amount of success. This has become the "Holy Grail" of many Antarctic crusades. Harwood and Wise (1995) outline previous attempts by deep sea drilling to obtain this record, all of which failed. The Cape Roberts Project will be the next major attempt in this endeavor.

Wise et al. (1991, 1992) summarized occurrences of known or suspected Paleogene Ice Rafted Debris, noting several reported examples from the early to middle Eocene, none of which were well accepted due to dating problems or suspected contamination. Nonetheless, these have remained as enigmas that could not be summarily dismissed despite the lack of supporting climatic evidence or other indicators of glacial activity during this relatively warm period in Earth history. Among these are the set of four Eltanin cores from the Southeast Pacific in which Margolis and Kennett (1971) found unmistakable ice-rafted sand grains together with lower to middle Eocene nannofossils and planktonic foraminifers of warm-water affinities. This paradox has apparently been resolved by Gersonde et al.'s (1996) discovery that the cores lie in the vicinity of a Pliocene extraterrestrial impact site, and that Neogene IRD has been mixed with the older materials.

Another middle Eocene date for glacial activity from the base of the CIROS-I core (Hambrey and Barrett, 1993; Hannah, 1994) has been reinterpreted as latest Eocene on the basis of a recent paleomagnetic study (Wilson, et al, 1998); reworked microfossils are suspected for the older date. Reported upper Eocene IRD from the Kerguelen Plateau (Ehrmann, 1991) has been shown to be down-core contamination (Breza and Wise, unpublished data). Thus, most reported direct evidence of Eocene Antarctic glaciation have come under challenge except for the late Eocene date for the CIROS I core as well as for ODP Sites 739 and 742 in Prydz Bay, which are based primarily on paleomagnetic reversal patterns. Neither of these cores are thought to have penetrated completely through glacial into preglacial marine sediments, therefore the pre-glacial\glacial sediments transition has yet to be documented.

The elimination of early to middle Eocene candidates for Antarctic glaciation is more in tune with independent paleoclimate evidence, including important new findings from the Antarctic continent, which is being compiled from erratics collected near McMurdo station. These include "an excellent paleo fauna and flora, including crocodiles, sharks teeth, and pelicanformes bird bones" best dated from microfossils as late mid Eocene to lower upper Eocene (D. Harwood, 1997, pers. comm.; these new studies are to be published in the Antarctic Research Series).

A consensus has developed within the community, however, that major glaciation began in the earliest Oligocene, and that "there has been at least some ice on that continent since that time" (Kennett and Barron, 1992, p. 9). The details of the subsequent history have yet to be revealed, however, and remains the subject of future research. This has been the subject of several reports in this workshop, and won't be further discussed here except to note that the same impact event associated with the Eocene Eltanin cores mentioned above might also be responsible for the emplacement Pliocene and older microfossils into the Sirius Formation, the origins of which have long been a subject of strong debate. An assessment of the impact of this new evidence on the Sirius problem will be given by D. Harwood at the symposium on Antarctic climate change that follows this workshop.

References

Barker, P. F., Kennett, J. P., et. al., 1988. Proc. ODP, Init. Repts., 113: College Station,TX (Ocean Drilling Program).

Barrett, P. J., 1996. Antarctic paleoenvironment through Cenozoic times—A review. *Terra Antartica*, 3(2):103-119.

Canudo, J. L., Keller, G., Molina, E., 1991. Cretaceous/ Tertiary boundary extinction pattern and faunal turnover at Agost and Caravaca, S. E. Spain. *Mar. Micropaleo.*, 17:319-314.

Ehrmann, W. U., 1991. Implications of sediment composition on the Southern KerguelenPlateau for paleoclimate and depositional environment. *In:* Baron, J., Larsen, B., et al., Proc. *ODP Sci. Results, 119:* College Station, TX (Ocean Drilling Program). pp. 185-210.

Elliot, D. H., Askin, R. A., Kyte, F. T., and Zinsmeister, W. J., 1994. Iridium an dinocysts at the Cretaceous/ Tertiary boundary on Seymour Island, Antarctica: Implications for the K/T event. *Geology*, 22:675-678.

Farquharson, G. W., 1983. The Nordenskjold Formation of the northern Antarctic Peninsula: An Upper Jurassic radiolarian mudstone and tuff sequence. *Bull. Br. Antarct. Surv.*, 60:1-22.

Gersonde, R., Abelmann, A., Diekmann, B., Gohl, K., Kuhn, G., Kyte, F. T., Bleil, U., Grahl, G., Voelker, D., and Flores, J. A., 1996. A late Pliocene asteroid impact into the deep ocean (Bellingshausen Sea) — Documentation and paleoenvironmetal implications: Am. Geophy. Union Meetings, San Francisco (poster OC32A-26).

Harwood, D. H. and Wise, S. W., 1995. Investigations in areas of marine and terrestrial paleontology and biostratigraphy; basin history, paleoclimate and paleoceanography; and stable isotopes. *In* Webb, P.-N. and Wilson, G. (Eds.), *Cape Roberts Project: Antarctic Stratigraphic Drilling*. Byrd Polar Res. Center, Rept. No. 10:49-53.

Huber, B. T., Hodell, D. A., Hamilton, C. A., 1995. Mid to Late Cretaceous climate of the southern high latitudes: Stable isotopic evidence for minimal equator-to-pole thermal gradients. Bull. Geol. Soc. Amer., 107:1164-1191.

Huber, B. T. and Hoddell, D. A., 1996. Middle-Late Cretaceous climate of the southern high latitudes: Stable isotopic evidence for minimal equator-to-pole thermal gradients (Reply). *Bull. Geol. Soc. Amer.*, 108:1191-1196.

Huber, B. T. and Watkins, D. K., 1992. Biogeography of the Campanian-Maastrichtian calcareous plankton in the region of the Southern Ocean. **In** Paleogeographic and paleoclimatic implications, in The Antarctic Paleoenvironment: A perspective on Global Change. Antarctic Research Series, Amer. Geophys. Union (Washington, D. C), 56:31-60.

Kennett, J. P. and Barron, J. (1992). The role of Antarctica in global climatic change. ODP White Paper from The Role of Southern Ocean and Antarctic in Global Change: An Ocean Drilling Perspective.

Margolis, S. V. and Kennett, J. P., 1971. Cenozoic paleoglacial history of Antarctica recorded in subantarctic deep-sea cores. *Am. Jour. Sci.*, 271:1-36.

Mutterlose, J. and Wise, S. W., 1990. Lower Cretaceous nannofossil biostratigraphy of ODP Leg 113 Holes 692B and 693A, continental slope off East Antarctica, Weddell, Sea. In Barker, P. F., Kennett, J. P., *et al.*, Proc. of ODP, Scientific Results, 113:325-351.

Pospichal, J. J., 1994. Calcareous nannofossils at the K/T boundary, El Kef: No evidence for stepwise, gradual or sequential extinctions: *Geology*, 22:99-102.

Wilson, G. S., Roberts, A. P., Versosub, K. L., Florindo, F., and Sagnotti, L., 1998. Magnetobiostratigraphic chronology of the Eocene-Oligocene transition in the CIROS-1 core, Victoria Land margin, Antarctica: Implications for Antarctic glacial history. *GSA Bulletin*, 110:35-47.

Wise, S. W., Breza, J. R., Harwood, D. M., and Wei, W., 1991. Paleogene glacial history of Antarctica, In McKenzie, J. A., Muller, D. W., Weissert, H. (Eds.), Controversies in Modern Geology: Cambridge, Cambridge Univ. Press, p. 133-171.

Wise, S. W., Breza, J. R., Harwood, D. M., Wei, W., and Zachos, J. C., 1992. Paleogene glacial history of Antarctica in light of Leg 120 drilling results. *In* Wise, S. W., Schlich, R., *et al.*, Proc. ODP, Sci. Results, 120: College Station, TX (Ocean Drilling Program), 1001-1130.

Zimmerman, H. B., Boersma, A., and McCoy, F. W., 1987. Carbonaceous sediments and paleoenvironment of the Cretaceous South Atlantic Ocean. *In* Brooks, J., and Fleet, A. J. (Eds.), M*arine Petroleum Source Rocks*: Oxford (Blackwell Scientific Publications., Ltd.), Geol. Soc. London., Spec., Publ., 26:271-286.

Zinsmeister, W. J., Feldmann, R. M., Woodburne, M. O., and Elliot, D. H., 1989. Latest Cretaceous/earliest Tertiary transition on Seymour Island, Antarctica. *J. Paleontol.*, 63:731-738.

GLACIER-SEA INTERACTIONS AND THE UTILITY OF PROCESS STUDIES FOR INTERPRETING THE ANTARCTIC GLACIAL AND CLIMATIC RECORD ON DIFFERENT TIME SCALES

Ross D. Powell,
Dept. of Geology, Northern Illinois University,
DeKalb, IL 60115, U.S.A.

Glacial and climatic records are best inferred by using quantitative, predictive models based on well documented processes. That is true for paleo-environmental studies on any time scale and therefore the well-documented processes need to be considered in both ANTOSTRAT and ANTIME initiatives. Few Antarctic environments have been documented by comprehensive process studies for geological purposes. Thus both initiatives should involve process studies and use the data produced by them. This discussion will concentrate on processes of the marine system with minor mention of coastal and terrestrial systems.

As way of background, a review of relevant recent developments in the glacimarine system is presented. One of the prime factors to recognize for interpreting a high latitude marine record is the potential for major *variability* in environmental conditions and processes through time and spatially. This consideration is important for both ANTIME and ANTOSTRAT science initiatives. Studies in both initiatives need to be established with sound knowledge of possible paleo-environmental conditions and an understanding of the potential record that could be produced. Spatial variability of processes around the Antarctic ice margin appears to be significant, which is especially important for both ANTOSTRAT and ANTIME. Recognizing that 57% of the margin is floating glacier-terminus, 38% is tidewater terminus, and the remaining 5% is exposed shoreline of mostly bedrock with rare beaches. Extending this concept through time is relevant for ANTOSTRAT studies because conditions favoring ice shelf formation and maintenance (embayments, pinning points, glacial flux, equilibrium line altitudes, sea ice conditions, oceanic parameters) change with glacial advance and retreat. Under current Antarctic polar conditions, ice shelves and floating glacier tongues are most commonly fed by ice streams or fast flowing outlet glaciers. During different advances and retreats will the glaciers be continually able to feed floating termini? Considering that rates of grounding line advance and retreat are likely to differ significantly for ice stream and interstream areas and that ice streams can migrate laterally through time, lead to speculation that the glacimarine sediment record could change significantly through time at a particular study site and vary around the Antarctic margin. For example, initial glaciation on Antarctica is inferred to have been mountain (perhaps temperate?) glaciation which then developed through time to polar ice sheets. Minor glacial fluctuations since ice sheet formation are generally accepted but major changes of glacial phases are strongly debated. How and where can these issues be resolved? Do we know what to look for in the glacial record? Furthermore, climatic changes on different time-scales (e.g., millennia versus say, 100s ka) have different forcing - what is the glacier response? What is the glacial record? Does the record differ for different forcing? Ice stream and interstream areas are likely to have different terminus conditions. Do they produce different sedimentary records? How important are subglacial conditions in producing different records, both in terms of sedimentary architecture and lithofacies and biofacies?

Recent studies have made important advances in addressing some of these questions, but they have also presented their own unknowns. For example, processes forming grounding-line wedges ("till deltas") of the Ross Ice Shelf inferred from geophysical remote sensing are yet to be verified. The inferred process of feeding sediment to the systems by subglacial till deformation is currently under debate. Furthermore, seismic reflection records on high latitude continental shelves in both hemispheres have been interpreted as displaying these grounding-line wedges (e.g., "till tongues"). Therefore, confirmation of processes of their formation is critical for establishing a reliable paleoglacial/paleoclimatic history on any time scale. In a related issue, marine geologists recently have been recognizing, especially on northern hemisphere, high latitude continental shelves, significant lateral variability in sedimentary facies along paleo-ice margins. They can be inferred to be caused by different subglacial and/or terminus conditions, but our present knowledge of such features and processes is very limited.

Verification of marine varves produced in both temperate and polar glacimarine settings is very encouraging for high resolution paleoclimatic studies if climatic controls can be linked to their forcing, as has been done in the Antarctic Peninsula. Are similar facies produced under other environmental settings? These climatic proxies have great potential for short term changes, which in ANTIME studies, can be linked to ice core records. But linkages to glacial dynamics and the consequent glacial sedimentary record still need verification. Other glacimarine records inferred to be glacially driven and being used as climatic proxies, the Heinrich layers of the North Atlantic, have recently been inferred to occur in the Southern Ocean. If correct, these findings raise numerous questions regarding processes and linkages feedbacks and lead/lag time effects, about which we now very little. How can icebergs produce extensive iceberg-rafted debris layers? What can be the teleconnections between the hemispheres? What are the glacial-climate linkages that require fast response times?

Recognition of glacimarine facies that characterize grounding line and calving line fluctuations is important especially for high resolution changes. These have been shown to vary among different glacial regimes and among terminus types due to different sedimentological processes acting.. Remotely operated vehicle (ROV) studies of grounding line areas have helped in this characterization and detailed high resolution stratigraphy combined with detailed core interpretations have advanced our understanding of some aspects to look for, but many remain unknown. Integrating sedimentological and biological/ paleontological data is an important step in the future.

Even some more basic aspects require attention. Absolute definition of glacial facies is still debated among geologists as is relating the facies to glaciological processes. Distinguishing among subglacial facies and between those and glacimarine facies remains also problematic although refinements continue. The meaning of variations in IRD signatures remains unresolved and such questions as "does an apparent increase in ice rafting indicate a glacial advance or retreat, or both, or changes in sea ice cover?" remain difficult to answer. The presence and extent of sea ice beyond calving termini are also important to consider in stratigraphic interpretations. Marine geological consequences of sea ice extent and thickness still requires more evaluation.

A list of some possible future objectives for process and related studies follows.

- Process studies at different types of glacial margins and documentation of their records (both ANTIME and ANTOSTRAT)
  - Both siliciclastic and biogenic/bioclastic
  - ROV studies
  - Sediment flux studies
  - Sea ice sedimentary facies
    -Modern transects of surface samples (new and archived)
  - STRATAFORM-type models
    -Quantitative sediment flux and dispersal models
    -Test with high resolution seismic reflection records
    -Establish interpretive and predictive models

Linked studies (both ANTIME and ANTOSTRAT)

  - Marine geology and geophysics
    - drilling (see below)
    - increased seismic coverage
    - swath mapping
    - 3D seismic (incl. high resolution)
  - Glaciology
    - ice dynamics
    - ice coring, subglacial processes
    - sea ice
  - Oceanography
    - physical, chemical, biological
  - Areal coverage of shelf for spatial variability
  - Correlations with paleoclimatic records from ice cores, deep marine cores, and coastal and terrestrial records
- Improved drilling capabilities
  - Marine:
    - site-intensive, ODP-style (ANTOSTRAT)
    - areal coverage, short drill cores ($\pm$50 m) (both)
  - Terrestrial:
    - land drilling with morphostratigraphic studies
    - lake gravity/piston, drilling and shoreline study (ANTIME)
  - Coastal:
    - beaches (dating, uplift rates, ecological studies) (ANTIME)
- Improved chronology
  - ^{14}C dating (reservoir effects) (ANTIME)
  - Terrestrial exposure dating (ANTIME)
  - Biostratigraphy improvement (both)
  - High precision, high resolution paleomagnetic re versal stratigraphy (ANTOSTRAT)

Addressing the questions and following the suggestions outlined above for process studies in Antarctica are important steps to follow to enable significant advances in understanding both the Cretaceous-Cenozoic and late Quaternary earth history. The studies need to be concomitant with and integrated into studies of the stratigraphic record to provide reliable models and interpretations of records of past glacial and climatic changes. They are also important for providing constraining data used to build predictive models for high resolution ice and climatic changes during the late Quaternary. The data produced will also be useful for interpreting high latitude continental shelf sequences world wide. Currently, our state of knowledge of Antarctic marine glacial history falls behind many other areas in the world even with the important new results over recent years. Since initiation of IGBP's PAGES programme, the northern hemisphere data base well exceeds that of the Antarctic for the late Quaternary. Beyond Antarctica process studies are much farther advanced. They are probably best documented for temperate settings, then subpolar settings, with many fewer studies of polar processes. If these studies are not conducted progress in integrating the Antarctic glacial record with those of other areas around the world and with global climate models (GCMs and OAGCMs) will be impacted. Reliable interpretations of stratigraphic successions will be impaired because quantitative interpretive and predictive models require modern data sets for baseline testing. The late Quaternary record for the ANTIME initiative requires process studies because they are so closely linked to the ice sheet record and its use as a climate proxy to compare with ice core records.

To achieve the goals of processes studies integrating data from different fields of science that are also closely integrated with stratigraphic studies, high levels of technology are required with instrumentally intensive, logistically complex (and/or expensive) field operations. As mentioned above, process studies of Antarctic environments relevant to interpreting the paleo-environmental record, are few. Consequently, much of the future work will be at a reconnaissance level. Field studies for data collection will require ice and sub-ice drilling, ROV work, marine and terrestrial sediment drilling, and selected long-term monitoring sites with instrumentation having smart technology to operate remotely. Circum-Antarctic studies are needed to provide a broad data base to include the natural variability in processes and to document the Cretaceous-Cenozoic and late Quaternary records.

THE LATE PHANEROZOIC TERRESTRIAL REALM

Peter-N. Webb
Department of Geological Sciences & Byrd Polar Research Center
The Ohio State University, Columbus, Ohio, 43210

Introductory Remarks

The terrestrial record of late Phanerozoic (the last 100 m.y., or Late Cretaceous-Cenozoic) Antarctica is the most poorly understood of all major continental landmasses, even after forty years of intensive investigation since the International Geophysical Year (1957-58). It is sobering that we have probably documented no more than about 15 percent of late Phanerozoic time in the the Antarctic terrestrial realm. Conclusions and hypotheses based on proxy data rom Deep Sea Drilling Project and Ocean Drilling Program investigations provide generalized views of events on Antarctica at different points in the Cretaceous and Cenozoic but these are unable to contribute high resolution detail or portray events in specific regions of the continent.

It is often observed that Gondwana fragmented and dispersed during the late Phanerozoic, leaving Antarctica isolated in a high latitude location and surrounded by a major ocean system; that a hothouse (greenhouse) world evolved into an icehouse world during the same interval of time; and that geosphere-hydrosphere-atmosphere events in the southern high latitudes were major factors in global evolution from a non-glacial to a bi-polar (cryospheric) Earth. This scenario seems reasonable, but Antarctic data *sensu stricto* has played little direct role in arriving at currently accepted doctrine.

The presence of two large ice sheets are the principal reasons why we are at an impasse as far as the terrestrial record is concerned. We must now ask ourselves two major questions. First, should we accept the fact that long-time-scale global change can and should be resolved, at all temporal levels, via a bigger and better *proxy* (usually paleoceanographic) records. Second, if the answer to this question is NO, then what actions do we propose to to take to improve the *proximal* (continental) record.

If the decision is made to redouble our efforts in building a more complete late Phanerozoic terrestrial data base, then we must urgently reassess our science strategies and also count the cost of the major technological and logisitic efforts that will be required.

Available Terrestrial Data

Most existing terrestrial data are documented at points along the margins of the continent. Late Cretaceous and Paleogene data are best developed along the Pacific and Atlantic margins of the Antarctic Peninsula; and most Neogene data derive from the Amery Graben-Prince Charles Mountains and Transantarctic Mountains regions of East Antarctica, and Marie Byrd Land. Little or no information is available from outcrops in the interior of West or East Antarctica, although some indirect information comes from material transported to the contininent margins. A rough estimate suggests the total terrestrial data base is representative of no more than 15 percent of the area of West and East Antarctica. No one will seriously suggest that late Phanerozoic terrestrial history and its impact at the global level can be argued from such a restricted geographic sample. It is fortuitous, however, that in this relatively small area there is a close association of sedimentary and datable volcanic rocks and so what we have had to work with is quite well time-constrained.

Priorities

I now suggest and comment on priorities one might include in a future long-time-scale terrestrial science plan. This discussion assumes that new programs of scientific drilling are necessary and will lead to the successful recovery of geological materials which provide significantly improved temporal and geographic data point coverage for the last 100 m.y. It is suggested that each topic discussed below be categorized in terms of macro-temporal (5 to10 m.y.), meso-temporal (0 .1 m.y. to 1 m.y.), and micro-temporal (1 yr to 10,000 yr) scales.

Standard chronostratigraphy, biochronostratigraphy, & magneto-chronostratigraphy - The best known terrestrial localities occur at the continental margins, usually in passive and compressional tectonic environments, and with sedimentary successions having a close association with volcanic and marine sediments. These areas will continue to be essential in refining terrestrial histories in marginal environments, and in providing linkages to high resolution deep sea data bases. Standard isotope dating procedures and marine biostratigraphy will continue to provide temporal resolutions at the million year scale. However, it is unlikely that the amount of time accounted for in these areas will be increased substantially.

Terrestrial successions from the tectonically stable continental interior will be more difficult to date by conventional methods. Opportunities for refined time control will arise if interdigitating terrestrial and marine successions and infra-cratonic volcanic provinces are encountered. Ash shower penetration across the interior montane and basinal regions might provide additional time control for pre-glacial or deglacial episodes on the continent. Wherever possible these and other methods should be used to provide time-constraints of major erosional, weathering and depositional phases; and in assessing the duration of high latitude geosphere processes.

Paleotopography and geomorphology - Present knowledge of sub-ice sheet topography relies on a combination of geophysical techniques, glacio-isostatic adjustment estimations, and hypsometric contouring. Time-slice physiographic contouring procedures should be devised at macro-temporal scales (i.e. 10 m.y. intervals of time). More refined paleotopographic controls might be possible for some intervals of time by the use of accurately dated elevational datums provided by paleontological, eustatic and other data. Improved paleotopographic analysis will allow a pinpointing of both upland topography and the lowland drainage patterns which acted as major sediment transport conduits to infra and peri-cratonic freshwater and marine deltas. Factors to be considered here include: evolving deep crustal tectonic history, glacial and non-glacial erosion phases and associated crustal adjustments, ice volume changes and associated glacio-isostacy, characterization of the terrestrial hydrosphere and cryosphere through time, environmental diversity (i.e. fluvial, lacustrine, cold and warm deserts, etc), weathering and pedogenic development, and landscape evolution.

Terrestrial stratigraphic record - Formal lithostratigraphy (i.e. groups, formations, and members) should be proposed, disconformities highlighted, with both constrained by age control wherever possible. Sub-ice sheet drillhole data should be coupled with acoustic and other geophysical surveys in attempts to understand the thickness and extent of the probable very extensive sub-ice sheet sedimentary basins. Physical property measurements would be undertaken on all core material and drillholes subjected to geophysical logging.

Terrestrial-marine stratigraphic interfaces and relationships - Because of the very extensive coastal zone around Antarctica and the probability of marine advances and retreats across the continental margin and into the continental interior (produced by glacial-deglacial cycles, eustatic oscillations, and tectonic emergence and subsidence), there exists the probability of very complex but meaningful terrestrial-marine succession relationships. This provides a unique opportunity to examine a number of significant regional and global problems. These include ice history-sea level history, mass transport of sediment to the continental shelf basins, maritime paleoclimate, and evolving littoral distribution patterns.

Biosphere - Plate tectonic events, involving the fragmentation of the Gondwana supercontinent, the northward flight of the component fragments, and the geographic isolation of Antarctica in a polar setting, make for a unique late Phanerozoic terrestrial biospheric history. The fate of the greenhouse biological isolates and their icehouse (cryosphere) successors is of central importance in assessing global change in the southern high latitudes. Current terrestrial data bases provide a wealth of information on the paleobotanical record for West and East Antarctica, but the invertebate and vertebrate paleozoological record is surprisingly meager. A concerted effort should be maintained to build on current paleontological data bases through systematic and assemblage studies. Equally important are contributions these floras and faunas make to understanding biogeographic range (provinces) across the continent, and the significance this holds in the tracing paleoenvironment and paleoclimate shifts. Attempts should be made to portray provincial range oscillation at the macro-temporal (5-10 m.y.) and meso-temporal (1 m.y.) scales. Such studies will provide indicators, by geographic and topographic region, of the magnitude and rapidity of climate change, events surrounding the greenhouse to icehouse transition, patterns of evolution, migration, biotic thresholds, refugia, extinctions, and the emergence of the modern Antarctic biota after the demise of the Paleoaustral elements. Studies of taxa at the micro-temporal scale (1 y. to 10,000 yrs), particularly floral elements from the Neogene, provide essential data on survivorship, adaptation, propagation, seasonality, and decadal macro- and microclimate.

Paleoclimate - The documentation of paleoclimate over the past 100 m.yrs., at several levels of temporal resolution, demands synthesis of all available data sets. Firstly, specific data sets are not universally applicable through the entire late Phanerozoic. Secondly, specific data sets are not equally well preserved through all 100 m.y. We must then, use any and all available information that can be gleaned from geosphere, hydrosphere, cryosphere, atmosphere and biosphere sources. The following factors consitute high priority objectives: variability, periodicity, frequency and amplitude in climate; seasonal and multi-season records including temperature extremes and averages, duration of major climate phases, thermal thresholds, lower atmosphere temperature gradients between terrestrial and marine environments, recognition of the active phases of water (ice, water, rain, snow, cloud, vapor, etc), the recognition of catastrophic change (floods), and comparisons between different terrestrial Paleoaustral regions and between the Paleoaustral region and lower latitudes.

Recommendations

- Prepare a prioritized list of terrestrial thematic and topic objectives, accompanied by justifications, and technical requirements for task execution.

- Match terrestrial science objectives against relevant data sets, and categorize elements of each data set in terms of its/their ability to solve problems at various temporal scales.

- Consider whether science priority listings test prevailing assumptions and hypotheses.

- Discuss where and how future conventional outcrop field geology might contribute further to science objectives enumerated above.

- Review/preview future priorities in geophysical surveying of regions presently veiled by the West and East Antarctic ice sheets; with emphasis on detailed sub-ice sheet contouring, mapping of sub-ice sheet crustal geology and structure, and the delineation of extent and thickness of late Phanerozoic sedimentary basins. These programs should be coupled with site surveys as preparation for deep stratigraphic drilling beneath ice sheets, ice streams and glaciers.

- Plan future sub-ice deep stratigraphic drilling "legs." Future drilling should have a wide geographic distribution. The basic geology for vast areas of the Antarctic interior is unknown and so all regional geological activities should maintain a prominent reconnaissance survey element in their planning. Regional geophysical surveys are an essential component in this reconnaissance program. This level of investigation will serve as preparation for future more specialized drillhole based studies.

- Because studies of late Phanerozoic history over such a large area are likely to have a strong regional flavor, it is suggested that site selection be planned to test the existence of discrete major pre-glacial, glacial, and deglacial drainage systems which probably entered the Southern Ocean at many points around the continent. Close ties should be maintained with those planning future Ocean Drilling Program activity in the peri-Antarctic region. It is recommended that onshore-offshore drilling arrays be expressed as multi-sector longitudinal transects. Obvious candidates for this type of exploration include the Wilkes and Pensacola subglacial basins, Aurora subglacial basin, and Amery Graben.

- There already exists sufficient background information in some areas to allow selection of sub-ice drilling sites. Major "trunk" drainage systems occur at many locations around the periphery of Antarctica and in some instances these extend for hundreds of kilometers into the continent. Results from outcrop geology and earlier stratigraphic drilling projects confirm that these drainage systems have existed through much of the Cenozoic, and that they preserve both terrestrial and marine strata associations. Data from this category of physiographic environment would address many of the priority issues enumerated above, particularly those concerning glacial histories, sea level oscillations, tectonism, and terrestrial-marine linkages. It is recommended that ~300 km long deep drilling transects be planned along one or more of the major "trunk drainage systems," for example, the Reedy, Shackleton, Beardmore, Byrd, Skelton, and David and Amery glaciers. Drilling transects through the Transantarctic Mountains should include "pinning" sites in the interior subglacial basins and in the marine rift basins seaward of the TAM Front.

ANTARCTIC SEISMIC STRATIGRAPHY: STATUS, QUESTIONS, AND FUTURE PRIORITIES

Alan K. Cooper
U.S. Geological Survey, Menlo Park, CA, USA

Background

Seismic stratigraphy is a general technique for stratigraphic correlation. The reflection characteristics (e.g., as amplitude, continuity, geometry, etc.) of regional unconformities and stratal surfaces are used to empirically estimate rock properties, facies and chronostratigraphy, to infer structural evolution and paleo-environmental histories. Seismic sequence stratigraphy, as defined by Vail et al., 1977 is a relatively recent refinement of the general technique, to also derive sea-level history from seismic sequence geometries. Both techniques have been used on the Antarctic continental margin (i.e., shelf, slope and rise) with success in regional mapping studies of acoustic-unconformities, acoustic-units, and seismic-sequences. Yet, because few continuous drill cores and down-hole log data exist, it has not been possible to correlate seismic reflections to sub-surface geology regionally, and thereby unequivocally decipher paleoenvironments and ice/sea-level histories of the continental margin.

Seismic stratigraphic surveys have been done across nearly all accessible regions of the Antarctic margin, collecting more than 300,000 km of small-airgun single-channel data (SCS) and nearly 200,000 km of large-airgun multichannel seismic reflection data (MCS) (see Cooper et al., 1990, 1991, 1994 for many references). Various seismic sources with different frequency bands and inherent resolutions have been used (Table 1), and have imaged geologic features ranging from less than a meter to kilometers in size, and buried at depths of a meter to up to 10-15 km. In general, MCS (low to intermediate resolution) data image the deeply buried and large features, and SCS (intermediate to very-high resolution) data resolve the shallow and small features.

Table 1: Ability of seismic-reflection systems to resolve geologic features.

Seismic System (as commonly used)	Center Frequency/ fire rate	Approx. Resolution* Vertical/Horizontal	Depth Penetration
Very-high resolution	3500 Hz / 0.5 sec	0.2 m / 3 m	up to 50-100 m
High resolution	800 Hz / 1 sec	0.8 m / 6 m	up to 250 m
Intermediate resolution	150 Hz / 5 sec	10 m / 100 m	up to 1-2 km
Low resolution	60 Hz / 50 m		up to 10-14 km

Assumptions: vertical = quarter wavelength with sediment velocity of 2.5 km/s and horizontal=2 times shot interval at ship speed of 6 kt

The regional stratigraphic framework of the continental margin has been reasonably well defined, with thick sedimentary sections of Paleozoic and younger age covering many margin segments. Stratigraphic features common to many segments of the Antarctic margin include the thick Paleozoic and Mesozoic strata of pre- to post-rift times that fill basement rift-structures, a thick 'wedge' of prograding Cenozoic glacial sedimentary sequences that extend from the mid-shelf to continental rise areas, thick oceanic sediments covered by large-scale sediment mounds (i.e., drifts) on the continental rise, and numerous regional unconformities throughout the sections across the margin. These features are believed to reflect the general Paleozoic-Mesozoic continental breakup sequences (or Paleogene collision sequences in the Antarctic Peninsula region) overlain by the Cenozoic glacial sedimentary units.

Seismic sections from all parts of Antarctica exhibit a large variety of acoustic geometries and acoustic characteristics that are typical of today's non-glaciated and glaciated margins. These geometries are seen in outer shelf sequences that range widely from hundreds of meters (as local bank deposits) to hundreds of kilometers (as regional submarine deltas/fans). The thickness can be meters (topset strata) to kilometers (continental slope sequences). The thickest prograding sequences are commonly, but not always, located adjacent to the seaward end of broad (up to 100 km wide) erosional, sea-floor or buried cross-shelf troughs. And, along several margin segments, high-standing (up to hundreds of meters) drift deposits on the continental rise lie opposite the prograding shelf sequences.

From these observations, investigators have speculated that Antarctic margin sequences were influenced principally by sea-level changes (e.g., the Vail et al., 1977 model) in pre-glacial times (e.g., Hinz and Block, 1984; Bartek et al., 1991) and principally by severe fluctuations of the Antarctic Ice Sheet during at least late Cenozoic times (e.g., Larter and Barker, 1989; Cooper et al., 1991; Bart and Anderson, 1995). Before the Antarctic continental shelf areas were overdeepened by erosion to their current depths of 200-1400 m in early to late Miocene times (Cooper et al., 1991), sea-level changes would have resulted in high-stand and low-stand acoustic geometries (e.g., Vail et al., 1977); however, after shelf overdeepening other factors such as grounded ice sheets and bottom currents have strongly influenced stratal geometries (e.g., ten Brink et al., 1995). The outer-shelf wedges, delineated largely by ANTOSTRAT studies, are thought to be sub-glacial and glacio-marine deposits derived from polar and temperate sediment-ladened glaciers with broad internal ice streams that move at up to meters per day (e.g., Alley et al., 1989). These glaciers have fluctuated widely in size since late Eocene time, and have intermittently extended onto and across the continental shelf and uppermost slope to their stable grounding position (e.g., Larter and Barker, 1989; Eittreim et al., 1995).

The general concepts and models, noted above, about possible origins, processes, and paleoenvironments for acoustic units, unconformities and seismic sequences of the Antarctic margin are, however, largely untested by geologic sampling. The comprehensive compilations of Antarctic seismic data have greatly extending our knowledge of the geometric characteristics of the sedimentary sequences at local to regional scales. However, the underlying factors and processes (e.g., subsidence/uplift rates, sedimentation/erosion rates, eustacy, currents, sediment delivery mechanisms, etc.) that have resulted in these characteristics are still poorly understood, and will remain so until adequate ground truth drilling and coring information are collected.

The remainder of this report describes some limitations of our current models, significant questions that remain unanswered, and topics of study that could be addressed in the coming decade to build on our past ANTOSTRAT studies and enhance our understanding of Antarctic paleoenvironments and processes, from seismic stratigraphy. Three broad topics are addressed: Technology and Data, Geology and Glacial History, "Global" Connections.

Technology and Data

Our ability to correctly infer regional geologic processes from seismic data (with or without drilling control) is strongly dependent upon the consistency, resolution, and quality of the seismic data.

Consistency: Our perceptions and interpretations are based on what seismic data we are given to analyze. Hence, it is critical that similar types of data with equivalent resolutions and similar trackline grids be compared from different regions to accurately assess if the same acoustic features and processes indeed occur. Today, the density of seismic tracklines is highly variable around Antarctica, and detailed comparisons of 2-dimensional (2-D) geometries and seismic character of acoustic units for all but the largest (i.e., more than tens of kilometers) scales cannot be made, for deriving processes and paleoenvironments. Now, comparisons are principally made on combinations of 2-D profiles, and yield only approximate 3-D real-world geometries. 3-D industry-type surveys would be most useful, but are fiscally impractical.

Seismic resolution: Resolution is another fundamental attribute of seismic studies that has not been uniformly applied in comparisons of geometric features, and hence the causative processes of acoustically-resolved features remains equivocal. The direct comparisons of low-resolution and high-resolution data across the prograding glacial sequences of the outer shelf (e.g., Antarctic Peninsula, Ross Sea) has led to long-raging debates about the underlying processes and depositional environments of these sequences – an excellent example of how unjustified comparisons lead to equivocal interpretations. With the advent of precision navigation and multichannel low- to very-high-resolution systems, it is important to establish guidelines for vertical and horizontal sampling rates to more uniformly resolve, than previously, the sub-surface stratigraphic features of the margin.

Quality of seismic data: As herein used, quality is the variable appearance of seismic data from similar systems due to natural-geologic, instrumental-noise, and variable-data-processing factors. Because seismic data are strongly susceptible to the above factors, quality is variable and in turn has led to widely different interpretations of processes from the same environment. The interpretation of sub-glacial and marine-glacial deposits, a fundamental difference, is commonly based on the lack or presence of internal reflections along seismic profiles — in digital processing, this may, for example be the difference solely between applying or not applying an AGC filter, or may be a function of different system gain settings. For accurate comparisons and interpretations of seismic and geologic data, criteria are needed to assure that uniform data collection and processing techniques are used or otherwise attainable.

Technology and data factors (noted above, and others) are significant fundamental parameters that must be "normalized" when developing a seismic stratigraphic model for the Antarctic margin, to accurately discern local features, processes and environments from circum-Antarctic ones. The first decade of ANTOSTRAT studies focused on existing data compilations. In the next decade, uniform standards of resolution, trackline density, processing parameters, etc. should be established and applied to seismic surveys for at least several select margin transects around Antarctica. Along these transects, all current acoustic systems should be used to image the full suite (small to large) of acoustic features. These transects would define "type sections" to be drilled/cored and compared in detail to derive a high-resolution seismic stratigraphic process-model for the Antarctic margin, like that of the Vail et al. (1977) sea-level model for low-latitude margins. *Very high priority should be given to conducting the acoustic surveys needed to define the "type sections" around Antarctica.*

Geology and Glacial History

Ground-truth information: The fundamental objective of Antarctic seismic stratigraphic analyses – to decipher regional processes, paleoenvironments and chronostratigraphy – can only be attained by directly relating seismic reflectors to geology. Without geologic samples and in-situ information, the inferences and uncertainties inherent in nearly all existing studies cannot be documented and clarified. The near absence of cores that penetrate below the ubiquitous glacial diamicton of the last glacial advance on the shelf, and below a few meters of Pleistocene and younger strata on the continental slope and rise has not allowed seismic reflections to be tied directly to subsurface geology. Instead, the geology below most parts of the Antarctic continental margin has necessarily been inferred from comparison of Antarctic seismic records with those from (a) Antarctic regions hundreds to thousands of kilometers away where deep drill cores exist (e.g., Prydz Bay, Ross Sea, Weddell Sea) and (b) northern high-latitude regions where seismically-defined units have been drilled and cored. *Highest priority should be directed to acquiring continuous geologic cores and down-hole logs from all possible seismic units and sequences around Antarctica.*

Greater resolution of geologic features: As noted above, our ability to resolve the 3-dimensional shape and internal geometry of seismic sequences, which by convention contain the key geologic features that characterize an inter-related suite of depositional environments, will determine the degree to which we can understand the structural- and facies-relationships of each particular environment. Even though greater resolution will be possible principally for glacial sedimentary sequences (i.e., pre-glacial sequences are commonly too deeply buried, except on the inner shelves, to be reached by high-frequency seismic energy), the improved definition will help answer critical questions such as: what is the seismic signature of a single glacial advance across the shelf, if such is preserved? What are the internal geometries of thin-bed topset strata, and can these geometries reliably be related to subglacial and open-water environments? What are the seismic facies relationships within individual foreset strata, and can they be traced reliably onto the continental rise, to directly link the shelf and abyssal paleoenvironments? What are the characteristic seismic attributes, that can be reliably used to discriminate between sub-glacial and glacial-marine strata, and between sub-glacial deposits derived from temperate glaciers and polar glaciers? Seismic variability in Antarctic glacial sequences is well known to be large, laterally and vertically, but at what seismic resolution (cm to m?) can characteristic universal seismic facies be defined, if at all, to provide greater help in interpreting local and regional glacier systems? In any case, the greater the seismic resolution, the greater the potential for accurate geologic assessments. *High priority should be placed on conducting high- and very-high-resolution seismic surveys to attain precise lateral- and vertical-resolution of geologic features, for better ascertaining the processes by which they formed and their relationship to features elsewhere on the shelf, continental slope and rise.*

Origin of unconformities and sequences: The regional unconformity is the fundamental building block of seismic stratigraphic studies, and prior investigators (e.g., Anderson, 1984; Hinz and Kristoffersen, 1987; Cooper et al., 1991) have attributed many processes (e.g., shelf currents, grounded ice, slope boundary-currents, etc.) to their origins in Antarctica. Yet, few (if any) detailed studies have been done to decipher and document formative processes of unconformities, and hence, the evolution of, and linkages between, depositional paleoenvironments for the interleaved sedimentary sequences of the continental margin. Prior to glaciation, it is commonly assumed that Antarctic unconformities formed by processes similar to those of today's non-glaciated margins. But, did the processes change with the initiation of glaciation or with overdeepening of the shelf? Which processes are similar? And, what are the new processes, if any, resulting from extensive glaciation of the continental shelves? Can the effects of glaciation be separated from the effects of shelf overdeepening? How have sea-level fluctuations affected the development of Antarctic unconformities during the initiation of Cenozoic Antarctic glaciation, and since then with the overdeepening of the Antarctic continental shelves? *High priority should go to detailed seismic and geologic-core studies of seismically-defined regional unconformities, to ascertain the relationships between the formation of these unconformities with their interleaved sedimentary sequences, and changes in global sea levels and other paleoceanographic factors.*

Global" Connections

The term "global" herein is used to mean the continental shelf to abyssal basin environment of the entire circum-Antarctic region. Seismic stratigraphy has previously been used to attempt "global" connections via mapping of unconformities and acoustic units across the continental margin (e.g., Wannesson et al., 1985; Kuuvas and Leitchenkov, 1992; Larter and Cunningham, 1993) and via comparison of unconformity progressions on different parts of Antarctica (e.g., Hinz and Kristoffersen, 1987). Such correlations, if they can be confirmed by drilling, would provide important clues about the "global" processes that resulted in those features with common acoustic properties over thousands of kilometers. Sea-level change has been the only process yet identified (e.g., Vail et al., 1977) at this scale, although bottom-water currents have been widely implicated. Expansions of the Antarctic Ice sheet, with coeval carving of continental shelf unconformities has been widely suggested as a mechanism for "global" connections, but is not documented. What are the geologic processes that could result in similar acoustic properties in rock units to allow seismic unconformities to form and be traceable over hundreds to thousands of kilometers? Is this realistic? Or, are we seeing an aggradation of many separate processes over these same distances that provide the appearance of acoustic continuity? At what seismic resolutions do we see, and do we lose, the acoustic continuity needed for "global connections"? *Priority should be given to investigating in detail the acoustic and geologic attributes of regional seismic features to ascertain how seismic stratigraphy in Antarctica can best be used, if at all, to make "global" connections.*

Summary

ANTOSTRAT studies have significantly advanced our knowledge of the stratigraphic framework of the Antarctic margin. In the next decade, stratigraphic studies should focus primarily on acquiring drill/core data to "groundtruth" the known acoustic stratigraphy. Secondarily, the emphasis should be on collecting more-detailed acoustic images of "type sections" (within the Cenozoic sequences that underlie all segments of the Antarctic margin), to derive a unified model that accurately inter-relates Antarctic glaciation, sea levels, and other "global" processes that control sediment deposition across the entire margin.

References

Alley, R. B., Blankenship, D. D., Rooney, S. T., and Bentley, C. R., 1989, Sedimentationbeneath ice shelves—The view from ice stream B: *Marine Geology*, v. 85, p. 101-120.

Anderson, J. B., Brake, C. F., and Myers, N. C., 1984, Sedimentation on the Ross Sea continental shelf, Antarctica: *Marine Geology*, v. 57, p. 295-333.

Bart, P. J., and Anderson, J. B., 1995, Seismic record of glacial events affecting the Pacific margin of the northwestern Antarctic Peninsula, *In* Cooper, A. K., Barker, P. F., and Brancolini, G., editors, *Geology and Seismic Stratigraphy of the Antarctic Margin* (Antarctic Research Series 68): American Geophysical Union, p. 75-96.

Bartek, L. R., Vail, P. R., Ross, M. R., Emmet, P. A., Liu, C., and Wu, S., 1991, effect of Cenozoic ice sheet fluctuations in Antarctica on the stratigraphic signature of the Neogene: *Journal of Geophysical Research*, v. 96, n. B4, p. 6753-6778.

Cooper, A. K., Barker, P. F., Webb, P. N., and Brancolini, G., editors, 1994, The Antarctic Continental Margin: Geophysical and Geological Stratigraphic Records of Cenozoic Glaciation, Paleoenvironments, and Sea-Level Change: *Terra Antarctica*, p. 237-480.

Cooper, A. K., Barrett, P. J., Hinz, K., Traube, V., Leitchenkov, G., and Stagg, H. M. J., 1991, Cenozoic prograding sequences of the Antarctic continental margin: a record of glacio-eustatic and tectonic events, *Marine Geology*, v. 102, p. 175-213.

Cooper, A. K., Eittreim, S., ten Brink, U., and Zayatz, I., 1993, Cenozoic glacial sequences of the Antarctic continental margin as recorders of Antarctic ice sheet fluctuations, In Kennett, J. P., and Warnke, D. A., editors, *The Antarctic Paleoenvironment: A Perspective on Global Change* (Part Two): Washington D. C., American Geophysical Union, v. 60, p. 75-89.

Cooper, A. K., and Webb, P. N., Editors, 1990, *International Workshop on Antarctic Offshore Acoustic Stratigraphy (ANTOSTRAT): Overview and Extended Abs.* (Open-File Report 90-309): Menlo Park, U.S. Geological Survey, 250 p.

Eittreim, S. L., Cooper, A. K., and Wannesson, J., 1995, Seismic stratigraphic evidence of ice sheet advances on the Wilkes Land margin of Antarctica, *Sedimentary Geology*, v. 96, p. 131-156.

Hinz, K., and Block, M., 1984, Results of geophysical investigations in the Weddell Sea and in the Ross Sea, Antarctica Proceedings of the Eleventh World Petroleum Congress: New York, Wiley, p. 279-291.

Hinz, K., and Kristoffersen, Y., 1987, Antarctica - Recent advances in the understanding of the continental shelf: Geologisches Jahrbuch, Reihe E, v. 37, p. 1-54.

Kuvaas, B., and Leitchenkov, G. L., 1992, Glacigenic turbidite and current controlled deposits in Prydz Bay, *Antarctica, Marine Geology*, v. 108, p. 367-383.

Larter, R. D., and Barker, P. F., 1989, Seismic stratigraphy of the Antarctic Peninsula Pacific margin: a record of Pliocene- Pleistocene ice volume and paleoclimate: *Geology*, v. 17, p. 731-734.

Larter, R. D., and Cunningham, A. P., 1993, The depositional pattern and distribution of glacial-interglacial sequences on the Antarctic Peninsula Pacific margin, *Marine Geology*, v. 109, p. 203-219.

Larter, R. D., and Cunningham, A. P., 1993, The depositional pattern and distribution of glacial-interglacial sequences on the Antarctic Peninsula Pacific margin, *Marine Geology*, v. 109, p. 203-219.

ten Brink, U. S., Schneider, C., and Johnson, A. H., 1995, Morphology and stratal geometry of the Antarctic continental shelf: Insights from models *In*: Cooper, A. K., Barker, P. F., and Brancolini, G., editors, *Geology and Seismic Stratigraphy of the Antarctic Margin* (Antarctic Research Series 68): American Geophysical Union, p. 1-25.

Vail, P. R., Mitchum, Jr R. M., Todd R.G., Widmier, J. M., Thompson, 111 S., Sangree, J. B., Bubb, J. N., and Hatlelid, W. G., 1977, Seismic stratigraphy and global changes of sea level, *In*: Payton, C. E., editor, Seismic Stratigraphy-*Applications to Hydrocarbon Exploration* (Memoir 26): Tulsa, American Association of Petroleum Geologists, p. 49-205.

Wannesson, J., Pelras, M., Petitperrin, B., Perret, M., and Segoufin, J., 1985, A geophysical survey of the Adelie margin, East Antarctica, *Marine and Petroleum Geology*, v. 2, p. 192-201.

SEISMIC STRATIGRAPHY AND SEDIMENT PROPERTIES: A NEED FOR GROUND TRUTH

Anders Solheim

Background

In a regional sense, the Antarctic continental margin (at least the accessible parts of it) has an extensive coverage of seismic data, acquired by a number of countries over the last 20 years or so (Cooper et al., 1995). This includes both multi-channel seismic data (MCS, more than 200,000 km) and single channel data (SCS, at least an equal amount, probably more), using a variety of tools and seismic configurations. The interpretation of these data, however, suffers greatly from the sparcity of "ground truth". Sediment sampling campaigns around Antarctica have mainly involved conventional piston- and gravity coring, usually limited to the upper 10 m sediment depth. Most commonly core recovery on the continental shelf is much less than 10 m, recovering the Holocene, while overcompacted tills from the last glacial maximum prevent further penetration. Given a seismic resolution of 5-10 m at best, it is clear that piston coring and related techniques have a limited potential for ground-truthing seismic data.

In addition to the CIROS-1 and MSSTS-1 drilling projects in the Ross Sea (Barrett, 1986, 1989), drilling operations offshore Antarctica are limited to a few DSDP / ODP legs, of which only four (Legs 28, 35, 113 and 119) drilled on the Antarctic margin (Hayes, Frakes et al., 1975; Hollister, Craddock, et al., 1976; Barker, Kennett, et al., 1988; Barron, Larsen, et al, 1989). Of these again, only Legs 28 and 119 drilled on the continental shelf, in the Ross Sea and Prydz Bay, respectively. Including the CIROS-1 and MSSTs-1 sites, a total of 10 wells are drilled on the Antarctic shelf, confined to two areas. Considering the size of Antarctica, and the fact that is is surrounded by continental shelves, the difficulties and discrepancies in seismic interpretation are not surprising.

Another problem is the relatively poor core recovery of the few boreholes that do exist. An exception is the CIROS-1 borehole, drilled from fast sea ice, in which a core recovery of 98% was obtained (Barrett, 1989). The DSDP / ODP sites have recoveries varying roughly between 20 and 60%. The recovery problems mostly relate to the diamictic character of the glacial sediment encountered around Antarctica (as well as in other glacial continental margins). On the shelf, the diamictons are often heavily overcompacted, enforcing the need for rotary coring, which often severely disturbes the recovered sediments. Such disturbance makes them useless for physical property measurements and, consequently, for calculations of acoustic impedance logs to create synthetic seismograms.

Therefore, in future work there is a great need for:

- Increased number of drillholes.
- Smaller, more flexible and less costly operations than ODP type drilling.
- Improved coring techniques which give udisturbed samples, adequate for geotechnical testing.
- Downhole logging of all drilled wells.

Drilling plans are treated under other parts of the workshop agenda, but it should be mentioned that ODP drilling is proposed by a Detailed Planning Group (DPG) for a four year campaign, starting in 1998. The DPG proposed drilling legs in all of the five main "ANTOSTRAT areas"; the Antarctic Peninsula, Ross Sea, Wilkes Land, Prydz Bay and the Weddell Sea. Until now, however, only the Antarctic Peninsula proposal is approved by ODP, and is scheduled for February - April 1998, as

Leg 178. Shallow, light-weight drilling, using a mobile rig to mount over the side of an oceanographic vessel, has been tested over the last two years by a Norwegian group. This equipment is currently designed to diamond drill to depths of around 50 mbsf and obtain 4.5 cm diameter cores. Further development will take place over the next couple of years. The most recently scheduled drilling operation in the Antarctic is the Cape Roberts Project (Barrett et al., 1995), planned to start drilling from fast sea ice in the Ross Sea during the austral summer of 1998.

Physical Property Measurements; Parameters And Techniques

Age, biostratigraphy and lithology represent of course crucial pieces of information for an interpretation of paleo-environments and paleoclimate. These are to a large extent dependent on the study of core samples. There are many examples that interpretations of lithology and paleoenvironment based on seismic data are far from straightforeward, even using very high resolution tools. Often acoustic variations are not associated with any significant lithologic change, when drilled (e.g. Stoker, 1997). In the Barents Sea, structures which could be interpreted as a buried moraine topography from the seismic records turned out to be slabs of glacitectonized Mesozoic bedrock when subsequently drilled (Gataullin & Polyak, 1997). The boundary between pre-glacial and glacial deposits in dipping continental margin sequences is another important environmental boundary which is difficult or impossible to determine by seismic data alone.

However, to tie various borehole information, for instance ages, to seismic records and thereby extend the borehole information regionally, require sediment physical properties data. Seismic velocity information is necessary to enable conversion from two-way travel time to sediment depth (and vice versa). Wet bulk density is needed in addition to the velocities, to compute acoustic impedance logs and construct sythetic seismograms, a tool of great importance for the correlation between sediment cores and seismic sections.

Downhole Logging

Physical property measurements are particularly well suited for down-hole logging. Not only can this give continuous records, but the results will also be much closer to real, *in-situ* conditions. Logging tools used in ODP operations have been adapted from industry-standard tools to fit the 3.8 inch drillstring bore used aboard the "Joides Resolution". However, a wide range of logging tools are available for "slim-hole" operations and can be used in holes with diameters down to two inches (BPB Slimline Services, 1996). There are no minimum limitations to hole depth. Any hole longer than the tool length (usually 1-4 m) can be logged if the hole conditions are adequate. Although open holes give the most reliable results, many tools can also be used with relatively good results in cased holes. The slim-hole logging possibilities are particularly interesting for alternative (to ODP) drilling operations on the Antarctic continental margin.

A number of different sensors, combined in a variety of ways, are available. For studies of Cenozoic, glacial sequences the most essential parameters to measure are P-wave velocity, bulk density, lithology and magnetic properties (susceptibility and polarity). These are all standard parameters measured in ODP Logging operations. With the possible exception of magnetic polarity, slim-hole tools are available for all these parameters. Acoustic velocity can be measured with a vertical resolution of 20 cm, magnetic susceptibility with a resolution of 25 mm, to mention a couple of examples. Lithology and porosity information can be obtained from natural gamma tools combined with neutron tools. These are only examples, but the essential point is that most physical sediment properties (as well as lithological information) can be measured or extracted from downhole logging.

In shallow holes, primarily in unlithified sediments, unstable hole conditions may be a severe limiting factor for downhole logging. Another important point is cost. The company BPB Slimline Services, which is a world leader in slim-hole logging operations, estimates operating charges of USD 1600 - 2200 per day for equipment and crew (2 persons). Freight, travel, mobilisation, demobilisation, etc., would accrue. For a 50 days cruise a total cost of USD 100.000 - 150.000 is likely. However, as logging provides continuous data from near in-situ conditions, this investment may prove to be "good value for money". Furthermore, careful correlation between downhole logs and ship / shore based measurements may help finding the correct stratigraphic position for cores in poor-recovery holes.

Shipboard and Shore Based Measurements

For correlation with seismic data, a MST (Multi-Sensor Track; velocity, density, magnetic susceptibility and natural gamma ray activity) provides the most useful set of measurements. Dependent on core recovery, the MST provides near-continuous measurements of acoustic impedance information for construction of synthetic seismograms. Parameters like susceptibility, natural gamma intensity and bulk density often vary in response to climatic variations, and because of its high stratigraphic resolution (1-3 cm) the MST has therefore proved to be an important tool for quick studies of climate variability which can be carried out immediately after core retrieval. An important aspect of MST measurements is that they are non-destructive to the core. Since poor contact between sediment and core liner introduces a serious source of error, an MST system which also can measure split cores is to be preferred. Given a good MST set-up, other index property measurements on discrete samples can be kept to a minimum, for calibration/checking purposes vs. the MST.

Geotechnical tests of whole-round core sections from the Antarctic margin have only been carried out on material from Prydz Bay, cored during ODP Leg 119 (Solheim et al, 1991). Such testing is important for an evaluation of the loading history of a sediment. This is particularly important in relation to discussions of glacial impact on the continental shelf. Consolidation tests can verify whether seismic sequence boundaries result from erosion and can also provide stimates of minimum past overburden, whether caused by sediment or ice. The usefulness of geotechnical testing is, however, totally dependent on a non-disturbed character of the core. This is often a major problem in rotary coring, like the XCB or RCB techniques used by ODP in hard, glacial diamicts.

Suggestions and Topicsto Discuss

- ANTOSTRAT related efforts over the next five years should focus on ground truthing existing seismic stratigraphy data rather than acquiring more seismic data. Seismic acquisition should primarily be carried out as site surveys prior to drilling, and/or to tie drill-sites to regional seismic lines. An exception could be to acquire high resolution data in areas which are mainly covered by older, low-resolution data.

- As ODP activity will be limited, in particular on the continental shelf, alternative drilling platforms and/or techniques must be sought. Options are drilling from fast ice (like the Cape Roberts Project), smaller drilling vessels, and mobile rigs to deploy from other vessels. (Other?)

- The most flexible and time-economic option, given the present-day technology, is to use a smaller, ice strengthened drill ship. On the other hand, this is an expensive option.

- At present, to use mobile rigs deployed from oceanographic vessels in Antarctica, requires willingness to take the risk of investing time in testing and development of technology. This is important, however, and somebody has to take this risk(?).

- Coring techniques must be designed to maximize core recovery and minimize core disturbance. Such techniques may be time consuming, but must be preferred over techniques resulting in many, but poor quality sites.

- Downhole logging should always be an integrated part of a drilling campaign.

- After MST investigations, carefully selected whole-round core samples should be cut off, sealed and stored for later geotechnical testing at all sites where past loading history is of interest.

- To follow the above suggestions may requires multinational efforts. Is this realistic to any volume, or should the focus rather be on smaller operations, feasible under each individual country's' reources?

References

Barker, P.F., Kennett, J.P., et al., 1988: Proc. ODP, Init. Repts., 113: College Station, TX (Ocean Drilling Program).

Barrett, P.J. (Ed.),1986: Antarctic Cenozoic history from the MSSTS-1 drillhole, McMurdo Sound. DSIR Bull. N.Z., 237, 174pp.

Barrett, P.J. (Ed.),1989: Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound. DSIR Bull. N.Z., 245, 251pp

Barrett, P.J., Henrys, S.A., Bartek, L.R., Brancolini, G., Busetti, M., Davey, F.J., Hannah, M.J. & Pyne, A.R., 1995: Geology of the margin of the Victoria Land Basin off Cape Roberts, southwest Ross Sea, *In*: Cooper, A K, Barker, P F & Brancolini, G (Eds.) *Geology and seismic stratigraphy of the Antarctic margin*. Antarctic Research Series, Vol. 68, p.183-207, AGU, Washington, D.C.

Barron, J., Larsen, B., et al, 1989: Proc. ODP, Init. Repts., 119: College Station, TX (Ocean Drilling Program).

BPB Slimline Services, 1996: Unpublished catalogue of available tools.

Cooper, A.K., Barker, P.F. & Brancolini, G. (Eds.), 1995:*Geology and seismic stratigraphy of the Antarctic margin*. Antarctic Research Series, Vol. 68, 301pp., atlas, CD-ROMs, AGU, Washington, D.C.

Gataullin, V. & Polyak, L.,1997: Glaciotectonic features, southeastern Barents Sea. *In*: Davies, T.A., Josenhans, H., Polyak, L., Solheim, A., Cooper, A., Bell, T., Stoker, M. & Stravers, J. (Eds.) *Seismic Atlas of Glacimarine Features*. Chapman & Hall, England, in press.

Hayes, D.E., Frakes, L.A., et al., 1975: Init. Repts. DSDP, 28: Washington (U.S.Govt. Printing Office).

Hollister, C.D., Craddock, C., et al., 1976: Init. Repts. DSDP, 35: Washington (U.S.Govt. Printing Office).

Stoker, M.S., 1997: Seismic-stratigraphic record of glaciation on the Hebridean margin, north-west Britain. In: Davies, T.A., Josenhans, H., Polyak, L., Solheim, A., Cooper, A., Bell, T., Stoker, M. & Stravers, J. (Eds.) "*Seismic Atlas of Glacimarine Features*". Chapman & Hall, England, in press.

PALEOCLIMATE MODELING OF ANTARCTICA: WHAT IT HAS DONE? WHAT IT CAN DO?

Robert Oglesby
Department of Earth and Atmospheric Sciences
Purdue University, West Lafayette, Indiana, USA

Summary

Previous GCM modeling of past Antarctic climates helped consolidate our understanding of key processes (especially those responsible for the presence or absence of Antarctic glaciation), but was severely restricted due to model (and data) l!imitations. Over the past few years tremendous advances have taken place in our ability to simulate earth climate in general, and of more importance for this community, the climate at high southern latitudes. For the first time, polar meteorologists are saying that current GCMs can adequately (though not perfectly) simulate high latitude climates. The new generation GCMs can also be run at higher resolution, which both improves the overall simulated climate and also allows a better discrimination at the regional and local level. For paleoclimate studies this higher resolution is much more demanding of geology because locally-detailed reconstructions over a wide geographic area must be made both to provide model boundary conditions such as topography, surface/vegetation type, etc. and to validate the model results. This also means that strict geologic time controls are needed so that boundary conditions and forcings match up properly.

What Can Paleoclimate Modeling of Antarctica Accomplish?

The major goal of any (physically-based) modeling effort is to serve as a test of our understanding of how some observed or reconstructed phenomena came to be. A secondary, but crucial, goal is to use the model to make a prediction (either a forecast or a hindcast). These goals inevitably lead to a complex iterative procedure between climate modelers and geologists who work on geologic reconstructions using data collection and interpretation. The climate modelers want the geologic data in order to provide boundary conditions for, and validate their models, while the geologists want the model results to guide and then validate their reconstructions. More specifically, paleoclimate modeling can be used to help examine and 'test' ideas and assumptions about geologically-relevant forcings, feedbacks, and reconstructions.

Previous paleoclimate !modeling has focused on mechanisms responsible for the presence (or absence) of Antarctic glaciation. Key results obtained were that to first order the topography and polar position of the continent are most important in explaining the presence or absence of large ice sheets over Antarctica, while SST play a more secondary role, acting to modify the extent of glaciation but not its occurrence. Continentality (that is, the size of the continent without regard to geographic, or polar, position) played a tertiary role at best, meaning for example that the attachment of Australia to Antarctica prior to about 40-50 Ma has little effect. Atmospheric CO^2 concentration has little impact on the presence or size of the Antarctic ice sheet. Most studies have had difficulty obtaining or inferring ice-free conditions, such as might have occurred at times in the Cenozoic and much of the Cretaceous. These studies, while pioneering, need to be remade with the better models now available. It should also be possible to better refine the questions that are addressed.

Major Issues

- Previous modeling efforts have effectively been reconnaissance-level because of model limitations and also because of uncertain or ambiguous geologic evidence and reconstructions. The situation has matured considerably over the past five years, because our models now run at higher spatial resolution, represent important physical processes more accurately, and in particular perform much better at high southern latitudes, and because we understand the geologic issues better. Thus we are poised, I think, to make tremendous advances over the next 10 years in our ability to model (and hence to understand) the past climatic and glacial history of Antarctica.
- Working with models and geology (data) is an iterative process. Geologists need understanding and guidance from mo!dels; modelers need data to evaluate their results (and pose the problems in the first place). There is a significant distinction between the way I as a modeler (and atmospheric scientist) might view things compared to a geologist or paleoceanographer. My primary interest is in explaining how the climate system can accommodate large fluctuations of Antarctic glaciation, that is, what combination of boundary conditions (e.g., paleotopography), forcings (e.g., solar or CO^2) or climatic variability (e.g., ocean-atmosphere feedbacks) are necessary to account for a particular glacial state and how these interactions change through time.
- A full understanding of late Mesozoic and Cenozoic earth history demands a full understanding of Antarctic glaciation, which in turn requires a combined modeling and data approach. Understanding Antarctic glaciation is therefore also a key factor in understanding all of global climate, including how it has changed in the past and how it might change in the future.

Problems, Goals, and Priorities

From my perspective the key outstanding problem (and goal) is to model successfully the climate history of Antarctica for the past 100 million years. Obviously one cannot just let a sophisticated climate model go at 100 mybp and let it fly to the present. Instead key intervals must be chosen, presumably representing periods of maximum and minimum ice sheet extent, or times when rapid changes were taking place. A key objective of the ANTOSTRAT Workshop should be to help define the specific modeling priorities. Some possible (and general) examples of these priorities might include 'hothouse' and 'icebox' climates in high southern latitudes (and the related 'snowgun' hypothesis), times of extreme change versus more normal patterns of climate seasonality and variability,! linkages between the cryosphere and ocean and atmosphere circulation, and the relationships between topography, crustal deformations, and ice sheet volume.

Impact Within and Beyond Antarctica

Paleoclimate modeling is necessary to help explain and understand the history of Antarctic climate (especially concerning glaciation) over the past 100 Myr. Geologic proxy data, reconstructions, and modeling form a tightly coupled system. Only when we have sufficient data interpreted properly and explained from modeling results will we fully understand the past history of Antarctica.

These results also have major implications for climate on all scales, including global, because the climate of Antarctica plays a major role in modulating climates over the entire earth, primarily because of its ability to act as a refrigerator. The effects of this refrigeration may propagate directly through the atmosphere (as a consequence of interactions with the polar vortex) but are probably more important by affecting ocean circulation and sea ice.

Thus understanding the past climatic history of Antarctica is essential to a) an understanding of past climates for the entire earth and b) how changes to Antarctic climate might affect future global climatic change (e.g., will the West Antarctic ice sheet collapse).

Major Knowledge and Data Deficiencies

The major deficiencies that remain outstanding in paleoclimate modeling of Antarctica fall into two major areas: 1. model inadequacies which still exist even though the models themselves have gotten much better. 2. insufficient geologic data (or data too poorly-understood) for model boundary conditions and evaluation. Models are constantly being improved and indeed results from paleocli!mate modeling frequently serve as a guide to how the models need to be and can be improved (cf. the Paleoclimate Modeling Intercomparison Project PMIP). Improving the geologic data is a major topic of this workshop and a coordinated plan must be developed so that model and geologic data improvements are synthesized in the best manner.

Impact on Progress if Suggestions Not Heeded

If the suggestions presented here are not heeded we will lack crucial understanding of the past history of Antarctica. We may waste considerable time and resources collecting a variety of data from a variety of locations and yet have no way of synthesizing the individual results into a coherent, meaningful whole that describes and interprets the past history of Antarctica.

ANTARCTIC PENINSULA REGION

Peter Barker
British Antarctic Survey, High Cross, Madingley Road, Cambridge, United Kingdom

The last time the ANTOSTRAT Antarctic Peninsula Regional Working Group met was in 1993, in Cambridge. There, the first thing it did, in order to work effectively, was to split into 3 subgroups (one of which then split again). The RWG has been effective in promoting data syntheses and joint interpretations, but the scope of scientific problem that could be addressed by use of marine seismic reflection data was much broader than elsewhere around Antarctica, and the splits reflected that diversity of opportunity and interest.

The ANTOSTRAT-promoted ODP drilling proposal had a comparatively narrow focus on the regional contribution to glacial history and related processes, but the original breadth of opportunity is still there. In essence there are several potential fields of study, in addition to what will be extensively examined by ODP drilling, for example:

- pre-glacial palaeoclimate of the Antarctic Peninsula region
- the glacial/interglacial cycle in the particular enclosed environment of Bransfield Strait
- the dynamics of ridge subduction along the Pacific margin
- active back-arc extension in Bransfield Strait
- subduction dynamics at the South Shetland Trench
- active strike-slip plate motion, along the South Scotia Ridge and Shackleton Fracture Zone

- the distribution and origins of bottom-simulating reflectors on seismic reflection profiles

We should consider the possibility also that the ODP drilling, and an ANTIME interest in modern depositional processes, will direct attention to other aspects of glacial margin evolution. For example, some processes important to glacial sediment transport may be only poorly understood. In general, we should be agreed that, whatever the situation in other regions, seismic reflection investigation of the Antarctic Peninsula margin is now well beyond the reconnaissance stage, and insights are more likely to come from different and more detailed studies.

There has been some geophysical interest recently in the Bellingshausen Sea, which has glacial and tectonic histories similar to those of the Antarctic Peninsula and is most sensibly considered alongside it. This apart, however, the region is different from other regions of the Antarctic margin which are the concerns of other existing WG. It will be interesting to observe, during the progress of the W/S, the extent to which its interests and future plans will be confined to those topics which can be addressed at several places around Antarctica. Assuming that there should be some kind of focus to future activities, what will that focus be?

WEDDELL SEA, LAZAREV SEA, AND RIISER-LARSEN SEA

Wilfried Jokat
Alfred Wegener Institute, Bremerhaven, Germany

From the present knowledge of geodynamic movements, the Weddell Sea faced the earliest rifting events, which ended in the break-up of the Gondwana super continent. After South America and Africa had separated from Antarctica, the rift process continued into the recent Lazarev and Riiser Larsen seas to split off India. The break-up of these continental masses resulted into the creation of new restricted basins. At approximately 130 Myr a major reorganisation of the sea floor spreading occurred. Altimeter data indicate an almost continuos herring bone pattern of gravity anomalies, which are interpreted to result from a drastic decrease of spreading velocities. Around the same time the formation of a large volcanic feature, the Maud Rise, was in progress. From ODP holes 693 and 692 it is known that a large hiatus started at 110-120 Myr and ended at approximately 40 Myr. During the same time span oceanic crust formed along the South Atlantic/Indian ocean sector of East Antarctica. Madagascar and India split off latest 110 Ma ago. The rifting continued with the separation of Australia and New Zealand. Till 30 Myr Antarctica still was connected with the South American continent preventing the establishment of a Circum-Antarctic current system as it is present today. The separation of both continents afterwards led to an oceanographic isolation of the Antarctic continent, which might have accelerated and/or initiated the large scale glaciation of the whole continent. Till today several glacial/interglacial periods with different strengths occurred. No age control exists to describe this glacial events in greater detail, e.g. when did the Filchner-Ronne Ice Shelf advance to the shelf break.

This brief description of the geodynamic history of the South Atlantic/Indian ocean sector is of course not complete but summarises also the main scientific objectives of geophysical programmes in this area. In general it is the understanding of the tectonic and glacial history of this region. In the following some specific areas will be described in greater detail, some to a lesser degree as only few geophysical data are available.

North-Western Weddell Sea (64°S 60°W/70°S 50°W)

This area is extremely poor investigated as here the most difficult ice conditions are found. The Larsen Shelf between 64°S and 66°S has been surveyed during two American expeditions in 1991 and 1993. Based on these results the shelf can be divided into three major units:

- In the west chaotic reflection pattern are interpreted to represent Jurassic basalts.
- East to this unit faulted and slightly eastward tilted (3-5°) sediments are found. In a zone which is up to 60 km wide the Cretaceous to Oligocene (?) sediments are outcropping at the sea floor and/or are only covered by a thin veneer of sediments.
- The easternmost unit is interpreted to represent Miocene to Pleistocene(?) mainly glacial deposits.

Filchner-Ronne Shelf

Like the previous region this area is poorly and unsystematically sampled due to the varying ice conditions. Only three MCS lines crossing the whole Ronne Shelf in N-S direction exist. The seismic data show mostly flat-lying sediments across the whole 500 km wide Ronne Shelf at least down to 5 km depth. At the margins towards the Antarctic Peninsula in the west and East Antarctica old sediments of most likely Jurassic/Cretaceous age are outcropping and/or are covered by a thin veneer of sediments.

The glacial deposits across the Ronne Shelf along 35°W show no large variation in structure for more than 400 km. Even MCS lines perpendicular (E-W direction) to them show no structural changes. This might be interpreted as evidence for a grounded but static ice shield or for the presence of a non-grounded ice shelf on most of the Ronne Shelf. There might be areas where a complete glacial sedimentary record can be recovered by shallow drilling.

Clear evidence for grounded ice is found in the Ronne and Filchner Troughs bordering the huge shelf area. The troughs are strongly eroded by glaciers.

South-Western Weddell Sea Off Filchner Trough Mouth Fan

Seismic surveys of several institutions have mapped at least four large scale channel/leve complexes having their origin along the Crary Trough mouth fan. The full extent of these structures is now known due to the new Weddell Sea bathymetric map (in press). However, the age, development and dynamic relations of the channel/ levee complexes are unknown at all. It is evident that most of the glacial material of this part of the Weddell Sea have been drained through the Crary Trough mouth fan.

Continental Margins between 20°W and 30°E

From bathymetric mapping it is known that the non-ice covered shelf is quite narrow. At some locations the present ice shelf edge is almost above the bathymetric shelf break. Between 19°W and 0° a prominent escarpment, the Explora Escarpment, is present at water depths of less than 2000 m. Here, two ODP holes were drilled on the shoulders of the Wegener Canyon. The oldest drilled rocks were of Cretaceous age. A 70 Myr hiatus between 110 Myr and 40 Myr prevented the recovery of a more complete geological record. However, these holes delivered the only age information for the Weddell Sea, which have been used for seismic stratigraphy interpretations. Borehole information had to be extrapolated over more than 1000 km and consequently the interpretation is quite vague.

Further to the east two large submarine ridges, Astrid (14°E) and Gunnerus (28°E) ridges have been mapped with seismics, gravity and magnetics. They are regarded as remnants of early break-up processes during the separation of Antarctica from Africa and India. The sedimentary column is in parts quite thin but most likely continuos since its formation.

Central Weddell Sea

Altimeter data show a herring bone gravity anomaly pattern at 68°S running in E-W direction across the whole Weddell Sea basin. These anomalies have been interpreted to result from a drastic drop in spreading velocity at approximately 130 Myr. They were considered to be caused by rough oceanic basement, which is typically for slow mid-ocean spreading ridges. This structural interpretation has been confirmed by a recent geophysical survey (seismic, gravity). Approximately 100 to 200 km to the north the oceanic basement ridges are outcropping and can be sampled directly.

Summary

The whole problem in understanding any geodynamic and glacial processes in the areas described is the missing age and structural control on prominent seismic units. The existing ODP holes on Maud Rise and on the Explora Escarpment are either too shallow to detect basement for dating the break-up and/or are difficult to correlate with the deep sea deposits. An ODP hole in the center of the Weddell Sea is of lesser value for any seismic interpretation as dating is quite problematic. Even dating by magnetic spreading anomalies is not possible as only few data exist. Most of the geodynamic history is extrapolated from the conjugate margins off South Africa and the onshore volcanic record. In brief, in large areas no direct age control exists. Therefore, any published ages concerning the geodynamic and glacial history of this area are not validated by samples and are tentatively. This is in strong contrast to the huge amount of geophysical data which were collected in the last decades.

Current Mapping Projects

- Within a British-Russian project all aeromagnetic data of both countries have been gathered, mapped and are published. Areas covered: Antarctic Peninsula, Filchner Ronne Shelf, Coats Land, Dronning Maud Land.
- Within a Russian-German project all potential field and radar data (gravity, magnetic, ice thickness) from earlier expeditions have been gathered and maps will be produced. There is only some overlap with the British-Russian maps for the aeromagnetic.
- Gravity data from all marine expeditions (Germany, Norway) have been gathered, processed, adjusted.
- Most of the multichannel seismic data in the Weddell Sea, Lazarev and Riiser-Larsen seas have been gathered at AWI and have been interpreted in terms of tectonic and glacial history.
- Recently altimeter data from ERS1 and ERS2 satellites are available, showing the gravity field over all areas under discussion.
- The marine magnetic data in the Weddell Sea have been gathered at BAS to understand the origin of the herring bone gravity anomalies.
- American-Argentine-Chile aeromagnetic data are partly published now.
- A new bathymetric chart of the southern Weddell Sea is in press
- Sub ice topography map of the Filchner-Ronne Shelf is published. Data from Russian, British and German expeditions were used.

Scientific Problems/Questions which Might Be Answered in the Next Decade

I. Glacial History

Time span: 0-60 Myr

Eastern Weddell Sea, Lazarev Sea and Riiser-Larsen Sea

What are the differences between the sediment input during glacial/interglacial periods comparing margins covered by large ice shelves (Filchner, Ronne, Larsen shelves) with margins covered by minor ice shelves (East Antarctic coast between 20°W and 30°E)? This would allow to judge in which periods the shelves were covered by floated, grounded ice or uncovered by ice shelves.

- *Action*: Systematic bathymetric, Side scan sonar and seismic mapping of the margins, Shallow coring,
- *Data*: Not available

South Western Weddell Sea

- When did the glaciation of East Antarctica start?
- How sensitive did the East Antarctic Ice shield behaved in the past due to climate changes? How stable and/or unstable were the East and West Antarctic ice shields in the past?
- Are there any time delays in the reaction of the different areas in Antarctica in terms of ice shield growth or retreat due to climate changes?
- How did the opening of the Drake Passage influence the glacial record of the Weddell Sea? Did it initiate the glaciation of the continent or did it only accelerate it?

  Action: ODP drilling into the channel/levee complexes and on Polarstern seamounts

  Presite Data: All necessary data are available
- Was the Ronne Ice shelf grounded in the past (at least during the last glacial)? Verifying of numerical modelling.
- Further understanding of links between shelf and deep sea glacial deposition.

  Action: Shallow drilling on the Ronne Shelf; ODP will due to ice coverage not be able to drill in this area.

  Presite Data: Most of the data are available; some more seismic data are needed to give better constraints on the drill location.
- How does the continental climate record from ice cores correlate with the marine data from gravity or piston cores? Which kind of information can be derived concerning growth and disintegration of the East Antarctic ice shield during the last 300ky?
- Action: Drilling on the East Antarctic ice shield. Gravity cores from the Weddell Sea.
- Data: European Drilling programme EPICA is intended to start in 1999. Gravity cores are already available.

II. Tectonic/Paleoceanographic History

Time span: 0-180 Myr

Eastern Weddell Sea, Lazarev Sea, and Riiser-Larsen Sea

- When did the break-up of Gondwana start in the Weddell Sea and how did it continue eastward?
- How did the restricted anoxic Mesozoic basins evolve with time? How was the productivity and paleobiogeographic development of Mesozoic Antarctic faunas and floras? How was the development of high latitude and global Mesozoic climates?
- When did gateways open after break-up of Africa and/or India to connect the Weddell, Lazarew and Riiser Larsen seas to the world oceans? Which role did the Maud Rise, the Astrid and Gunnerus ridges play? For this a detailed knowledge of the magnetic spreading anomalies in this area is essential.

  Action: ODP drilling along the margins and the adjacent deep seas to date volcanic wedges and the adjacent deep sea magnetic anomalies.

  Data: MCS seismic is available to choose drilling locations along the margins. The magnetic anomaly pattern is extremely poorly charted. EMAGE project intends to collect aerogravity and aeromagnetic data within the next 6 years along the margin to map the potential field anomalies across the adjacent deep seas (20°W to 30°E).

Western and South Western Weddell Sea

Shallow drilling into the outcropping old sequences along the Larsen Shelf, Ronne and Filchner troughs would provide first information on the Mesozoic environment of the Weddell Sea. It would also put strong constraints on any geodynamic models for this area. Furthermore, it would provide first information on the presence of paleogateways in the Filchner-Ronne Shelf area.

Is the southern Weddell Sea (Filchner Ronne shelves) an extensional basin or is it a part of a highly mobile terrane (Ellsworth Withmore mountains) having moved into its position in Jurassic/Cretaceous times?

Action: Shallow drilling into outcropping sequences

Presite Data: All necessary data are available; enough alternate sites can be specified

Central Weddell Sea

- Determination of the age and composition of the outcropping basement ridges in the northern deep Weddell Sea. Dating of the youngest magnetic anomalies present in the Weddell Sea.
- What is the age of the E-W gravity anomaly at 68°S in the Weddell Sea? If the age of this event is known it might play an important role for geodynamic models.Action: ODP drilling; dredging of outcropping basement ridges in the deep sea part of the Weddell Sea

  Data: Some presite data are available; no dredging of the ridges have been performed so far.

The short summary clearly demonstrates that the most valuable information in understanding the glacial and geodynamic history of the areas described can be expected from deep and shallow drilling. Without that information most of the above mentioned interpretations will continue to be pure speculation.

Not mentioned at all are activities over ice performing e.g. seismic experiments on the Filchner-Ronne Ice shelf and on the East Antarctic craton. Various experiments (seismics, hot water drill etc.) can be carried out here to increase our understanding for the geodynamic history and recent glacial processes (e.g. dynamics of the grounding line, sediment thickness etc.).

PRYDZ BAY AND MAC.ROBERTSON SHELF

P.E. O'Brien

Antarctic CRC and Australian Geological Survey Organisation, GPOBox 378, Canberra, ACT, 2601

and

G. Leitchenkov

VNIIOkeangeologia, Antarctic Branch, 1 Angliysky Av. 190 121, St Petersburg, Russia

Although Prydz Bay is one of the more intensely studied parts of the Antarctic margin there are still many important questions that can be addressed by studying it further. The Mac.Robertson Shelf is relatively poorly known but recent work along its eastern end suggests that it also provides opportunities to address major scientific problems.

Theme 1. Structure, Tectonics and Continental Margin Development

Prydz Bay is a key region in understanding the early history of break-up between Antarctica and Greater India and the development of the Indian Ocean.The major crustal and tectonic feature of this region is the prominent north-east south-west trending rift system, the Lambert Graben, which crosses the continental margin obliquely and extends into the continent toward the south.(Fig.1). Two parallel riftgrabens, divided by a crystalline basement high occur within the shelf, continental slope and rise of Prydz Bay, representing a typical 'Double Rift' system, with intracontinental and pericontinental branches. The pericontinental rift branch shows transfer faults with offsets of up to 100 km (Fig.1).

The inner basement high features half-grabens oriented parallel to the mainrift with rotated crustal blocks that switch polarity across transfer faults. Similar features are recognised in the basement of the pericontinental rift branch (Fig.1) and all reflect the first (early) phase of large-scale extension, which has resulted indevelopment of the broad double rift structure and dog-leg pattern of the intracontinental branch (Fig.1). Another group of tilt blocks occurs beneath the outer shelf and continental rise and shows the latitudinal strikes. This variation in strike of extensional structures was possibly caused by a change of stretching direction from NW-SE to N-S. Continental extension has produced more than 350 km of continental margin underlain by stretched continental crust, implying extension of as much as 300 %. This extension was followed by the opening of the Indian Ocean. The change of stretching regime in the Prydz Bay region probably corresponds to the onset of sea-floor spreading on the Western Australia margin at M11 time (about 132 Ma). Sea-floor spreading in Cooperation Sea started at M10 Time (about 118 Ma).

The Mac.Robertson Shelf west of Prydz Bay also contains a record of the rifting history of this margin. It is a scalped shelf with Precambrian basement,Mesozoic and pre-glacial Cenozoic sediments cropping out on the sea floor. Recent seismic and sampling have identified an inner shelf half graben filled with Cretaceous sediments. Gently dipping Jurassic, Palaeocene and Eocene sediments underlie the outer shelf. The Palaeocene and Eocene units are clearly post-rifting shelf sediments but it is not clear how the Jurassic sediments fit into the to the tectonic history of the margin. The Cretaceous age of the synrift sediments is at odds with interpretations of the rifting of India from Gondwana based on evidence from the Jurassic age of oceanic crust off Western Australia.

Research Possibilities

The geometry of rifting and hence the mechanism of extension during rifting are still poorly constrained in Prydz Bay and the adjoining continental margin. Investigations of these aspects of structure and tectonics would be greatly enhances by additional deep-penetrating seismic surveys with recording parameters designed to see below the strong multiple. Seismic refraction using Ocean Bottom Seismometers would also be useful. Parts of the Mac.Robertson Shelf has never been visited by shipsequipped with seismic reflection systems. Dating of the half grabens associated with extension in Prydz Bay would require ODP-style drilling. The Mac.Robertson Shelf, however, has abundant sea floor outcrop of Mesozoic synrift and Palaeogene post rift sediments which could be accesses using small drilling rigs which need only penetrate about 10 meters to obtain good samples for dating and interpreting thesediments.

The position of the continent-ocean boundary is poorly known and would require additional seismic reflection, refraction, magnetics and gravity studies to constrain. Also, the timing of sea floor spreading in the Cooperation Sea and its relationship to the formation of the Kerguelen Plateau is poorly understood and requires additional magneticdata and more studies of satellite gravity data.

Theme 2. Mesozoic and Palaeogene Environments

Mesozoic non-marine sediments were recovered in ODP sites 740 and 741 and examination of seismic sections from the inshore part of the Bay suggests that they may crop out in places. Two units are present. The younger unit yielded early Cretaceous (middle Albian) palynomorphs and consists of sandstone, siltstone, mudstone and coal beds with abundant plant matter in fining-up cycles indicative of fluvial deposition (Turner and Padley, 1991). The underlying, undated unit also featuresfining-up sandstone-mudstone cycles but is reddish to greenish-grey and lacks coal beds (Turner, 1991). This unit could be Jurassic or be part of the Amery Group which crops out in the Prince Charles Mountains and is of Permian to Triassic age.

The oldest Palaeogene sediments recovered in Leg 119 holes were of late Eocene to Oligocene age in site 742A (Barron, Larsen and Baldauf, 1991). It is possible that the hole reached pre-glacial sediments but the sandstone bed at the base of the hole could also be interbedded with glacial facies. Seismic data indicates a significant thickness of sediment between the horizon reached by site 742A and the top of the early Cretaceous sequence. This sequence was deposited during the preglacial and early glacial part of the Palaeogene and thus may be a unique record of the initial transition into the Cenozoic glaciation.

Although there has been no drilling on the Mac.Robertson Shelf, gravity cores have yielded Jurassic, Cretaceous, Palaeocene and Eocene palynomorphs and foraminifera (O'Brien et al., 1995). These fossils occur in discrete, unmixed assemblages and are well preserved, indicating minimal reworking and transport. Therefore, they probably represent the fossil content of the sediments cropping out on the shelf. Plant matter, glauconite and fish teeth indicate non-marine to shallow marine conditions of deposition.

Research Possibilities

Jurassic to Eocene sediments are poorly known for the Antarctic, largely because of the scarcity of outcrop and drill material. The Palaeocene and Eocene in particular span the period of transition from cool temperate to glacial environments with the accompanying change in flora and fauna. The Eocene to Palaeocene section in Prydz Bay can be most effectively reached using ODP drilling on the western side of the bay in Prydz Channel where erosion by a fast-flowing ice stream has removed much of the thick glacial sediments which hindered drilling on ODP Leg 119. Proposal 790 (O'Brien et al., 1996) includes a proposed site to intersect the preglacial Palaeogene section. The Mac.Robertson Shelf provides and excellent opportunity for coring of these sediments using small sea floor or ship board rigs because of the extensive sea floor outcrop. Additional seismic and sidescan data from the area would facilitate selection of drill sites.

Theme 3. Cenozoic Glacial History

Prydz Bay is a key location for the study of Antarctic Cenozoic glaciation. About 20% of the East Antarctic Ice Sheet drains through the Lambert Glacier into Prydz Bay. Included in this drainage basin are the Gamburtsev Subglacial Highlands which could have been the initial site of ice sheet development on the continent. Sediments delivered by the Lambert Glacier are preserved in the bay, on the continental slope and on the rise and a fortunate juxtaposition of rock types means that ice fed by local, coastal precipitation on the western side of the bay carry distinctly different sediments from ice originating in the interior.

The oldest glacial sediments known in ODP holes in Prydz Bay are late Eocene to early Oligocene (Barron et al., 1991). These sediments accumulated as vertically accreting sheets until a distinct shelf break developed at the limit of glacial deposition. From the mid Oligocene, significant amounts of debris reached the shelf break and prograded seawards. Thin topsets of glacial till accumulated on the shelf during glacial maxima or the shelf was eroded. Glacial maxima probably occurredin the late Oligocene and late Miocene.

Glacial debris was distributed evenly across the bay until the early Pliocene when a change in ice behaviour saw the development of a fast flowing ice stream on the western side. This ice stream cut a channel 100 km across to the shelf edge. Debris entrained in the base of the ice and in its deforming bed was then transported to the shelf edge and deposited in a large trough mouth fan. Seismic and core data from the fan indicate that thin turbidites were deposited during glacial maxima with proximal glacial meltwater plume deposits near the shelf edge. Preliminary thermo- luminescence dating suggests that the last advance to the shelf edge took place during isotope stage 6 (c.a. 140 ka.). Hemipelagic muds and ooze were deposited during episodes of reduced ice extent or an erosion surface developed on the fan. Some 16 sequences representing major glacial-interglacial cycles can be mapped in the post early Pliocene deposits of the continental slope of Prydz Bay. Large slump deposits are not apparent on existing seismic and echo sounder profiles, unlike adjacent parts of the slope, indicating a relatively undisturbed record of glacier advances to the shelf edge may exist in the trough mouth fan. Fine sediments which have bypassed the fan now reside in contourite and distal turbidite drifts on the continental rise.

Research Possibilities

Prydz Bay has great potential for ODP drilling to identify the oldest Cenozoic glacial sediments on the Antarctic margin in the bay itself and to provide relatively complete records of major ice advances in the trough mouth fan. Continental rise drifts have potential to preserve sediments from both glacial and interglacial episodes, particularly for the Plio-Pleistocene. An ODP proposal(Proposal 790) is active at present but still requires some site survey data to be completed. Both the trough mouth fan and continental rise drift deposits would be attractive targets for long piston coring cruises.

REFERENCES

Barron, J., Larsen, B. and Baldauf, J.G., 1991 - Evidence for late Eocene to early Oligocene Antarctic glaciation and observations on the late Neogene history of Antarctica: results from leg 119. *In* Barron, J., Larsen, B. *et al.*, 1991 - Proceedings of the Ocean Drilling Program Scientific Results, 119, 869-894.

Cooper, A., Stagg, H., & Geist, E., 1991 - Seismicstratigraphy and structure of Prydz Bay, Antarctica: implications from Leg 119 drilling. *In* Barron, J., Larsen, B. et al., 1991 - Proceedings of the Ocean Drilling Program Scientific Results, 119, 5-26.

O'Brien, P.E., Harris, P.T., Quilty, P.G., Taylor, F. and Wells, P., 1995 - Post-cruise report, Antarctic CRC marine geoscience, Prydz Bay, Mac.Robertson Shelf and Kerguelen Plateau. Australian Geological Survey Record, 1995/29.

O'Brien, P.E., Leitchenkov, G., Kuvaas, B., Ishihara, T., Harris, P.T., and Cooper, A. K., 1996 - Glacial history and palaeoceanography: Prydz Bay-Cooperation sea, Antarctica. Ocean Drilling Program Proposal 790.

Turner, B. R., 1991 - Depositional environment andpetrography of preglacial sediments from Hole 740A, Prydz Bay, Antarctica. *In*: Barron, J., Larsen, B. et al., 1991 - Proceedings of the Ocean Drilling Program Scientific Results, 119, 45-56.

Turner, B. R. and Padley, D., 1991 - Lower Cretaceous coal-bearing sediments from Prydz Bay, Antarctica. *In*: Barron, J., Larsen, B. et al., 1991 - Proceedings of the Ocean Drilling Program Scientific Results, 119, 57-60.

LATE PHANEROZOIC (100-0 MA) STUDIES ON THE WILKES LAND MARGIN OF EAST ANTARCTICA

Carlota Escutia
U.S. Geological Survey , Menlo Park, CA 94025

The Wilkes Land is a key area to reconstruct the evolution of the Wilkes Land continental margin and Indian Ocean region during the past 100 Ma. The existing data base (i.e. mainly the ANTOSTRAT MCS data base and numerous sediment cores) give a regional knowledge of the area, which will be very useful for planning future surveys into selected areas. At present, interpretation on the nature and age of the seismic sequences and events in the Wilkes Land margin are mainly based on the seismic character and indirect correlations with DSDP 268 and 269. Thus, many of the questions outlined below are focussed on obtaining the ground truth (coring/drilling) information of the sedimentary sequences to establish stratal ages and environments of deposition. Three main future thematic areas of study are envisioned, in order of priority: 1) glacial history and paleoenvironments, 2) sedimentary basin evolution, and 3) patterns and events in the tectonic and structural history. Studies in the patterns and events in the tectonic and structural history of the Wilkes Land may not be attainable whithin the next 10 years, but they represent the present and future research interests of international working teams in this margin, and they provide the scientific community with a full view of the achievements that can be expected from this margin.

I. Glacial History and Paleoenvironments

Problem

The Wilkes Land region is a key area to:

- reconstruct the Cenozoic and late Quaternary depositional and glacial history of the East Antarctic Ice Sheet. The growth history of the Antarctic Ice Sheet is of great importance because its link with global climate changes and sea level fluctuations. At present, the growth history of the Antarctic Ice Sheet is not well known, being inferred principally from deep-ocean oxygen isotopic measurements, and from the nonpolar continental-shelf seismic-stratigraphic records. The inferences are equivocal and in some cases disagree.

- study the depositional processes related to grounded ice sheets and glaciers in polar regions, for example, what are the linkages among the shelf, slope and rise settings in terms of glacial/interglacial processes?

The short-and-long term depositional and glacial history of the Wilkes Land Antarctic margin region, which is sensitive to East Antarctic ice sheet fluctuations, can be obtained from the study of the sedimentary sections in three depositional environments: a) nearshore shelf basins, b) shelf troughs, and c) rise drifts.

- Nearshore shelf basins (e.g. Mertz, Ninnis) sediment records, will provide a high-resolution Holocene record of coastal productivity, climate and/or glacial dynamics. These records will help answer questions such us: what is the climatic variability along the coastal setting of the Wilkes Land and what is the response of the marine ecosystem and sedimentation to these changes?
- Continental shelf troughs and banks. Study of sedimentary record on shelf troughs and banks will help resolve questions such as:

  - What is the role of shallow banks and deep troughs on sediment supply and sedimentary processes?
  - What is the history of glaciation in the shelf?
  - When was ice at its maximum extent?
  - Where was the ice edge?
  - What are the regional differences in ice maxima (timing and extent)?
  - How is the retreat of the last glacial maximum characterized in the sediment record?
  - What is the rate of retreat?
  - How does ice reatreat correlate with external factors such as sea level?
  - Are there rapid or episodic events (e.g. Dansgaar-Oeshger, Heinrich) in the late Quaternary record as we see in the Northern Hemisphere?
  - What are the differences if any between sedimentary processes in convergent and divergent ice drainage systems?
  - What are the differences if any between convergent and divergent ice drainage systems (i.e. Wilkes Land margin vs. Prydz Bay stratigraphic records)?
  - Are divergent ice margins such as the Wilkes Land and Queen Maud Land acting as line sources?
  - Do ice streams shift with time?
  - What is happening on the banks during the glaciations?, No ice? Slow ice?
  - How has climate impacted the sratigraphic record on the shelf, slope and rise?
  - How the sedimentary record vary across the shelf?
  - What processes are influencing sedimentation on the shelf and how are they linked?
  - Can the stratigraphy of the shelf be correlated with the slope and rise?

- Continental-rise drift deposits. Drift deposits, which appear to have high-sedimentation rates and depositional continuity on the rise, can provide us with a high-resolution continuous and datable record of Pliocene-Pleistocene glacial/interglacials, that are depositionally linked to the glacial sedimentation processes of the adjacent shelf.

Objectives

- To determine the timing of glacial onset (middle Eocene or older), in this part of the East Antarctic margin;
- To determine changes in the glacial regime and sea-level recorded in prominent change in sedimentary wedge geometry (middle Miocene?);
- To determine in detail Pliocene-Pleistocene glacial history, and a high-resolution record of paleoenvironmental and paleoceanographic changes during glacial/interglacial cycles; and
- To obtain high-resolution Holocene through sedimentologic and micropaleontologic analyses of long (9m piston cores) and high-resolution seis mic profiles (Huntec/'Chirp') collected from deep (>1000m) inner shelf basins.

Logistics

Late Quaternary (including Holocene) studies will require long/jumbo piston cores, multibeam bathymetry, and high-resolution Huntec/'Chirp' and 3.5 kHz seismic profiles. These technologies can easily be deployed from most research vessel. However, to recover the Holocene record from deep (>1000 m) inner-shelf basins such as the Mertz and the Ninnis located close to glacier outlets an ice breaker may be required to work in areas covered by sea ice.

On the Wilkes Land margin longer-term Cenozoic depositional and glacial objectives can be achieved by using shallow drilling techniques and by ODP drilling. Shallow drilling devices are currently being developed and tested (e.g. the shallow penetration Terrabore, has been tested by the Norwegians in Antarctica over the last field season). Because key stratigraphic horizons are exposed at shallow depths the shelf a transect of 50-100 m cores would sample a long and potentially continuous stratigraphic section.

Target areas

- Inner- basins: Mertz, Ninnis and Vincennes Bay
- Shelf troughs located west of the Adelie Bank on the Adelie Coast of the Wilkes Land, and west of the Dibble Ice Tongue.
- Drift deposits developed on the continental rise in front of the Mertz Trough, and the shelf trough west of the Dibble ice tongue.

II. Origin of Sedimentary Sequences

Problem

At present the nature and age of the seismic sequences and events recorded on the Wilkes Land margin are mainly based on the seismic character, relative stratigraphic position and indirect correlation of these sequences to DSDP 269 (Eittreim and Smith, 1987; Wannesson et al., 1985; Tanahashi et al., 1994). Unfortunately this site is separated from the margin by a topographic high, and all but the uppermost strata are truncated. Two key unconformities (unconformities WL4 and WL3 of Tanahashi et al., 1994) occur in the seismic records which relate the stratigraphic sequences to times before, during or after rifting. A third unconformity, WL2, occurs at shallower levels of the postrift section (Eittreim and Smith, 1987). WL2 marks the beginning of a new style of deposition characterized by progradation on the continental shelf (Eittreim et al., 1995), and increased turbidite deposition on the rise with development of large channel-levee complexes and drift deposits (Escutia et al., 1995; Escutia et al., in press). The WL2 unconformity has been interpreted to represent the onset of glacial conditions in this segment of the East Antarctic margin.

Objectives

To constrain the age, nature and paleoenvironment of the main sedimentary sequences. For example,

- What is the nature and age of the deepest stratified sequence (i.e. sequence D of Eittreim and Smith, 1987)? Eittreim and Smith (1987) interpret this sequence to represent prerift continental strata based on the erosionally-truncated edges of fault blocks of this sequence. Veevers (1987) however interpret sequence D as synrift, because the amount of extension experienced by this sequence is anomalously small to be explained by extensional faulting associated with significant crustal thinning. An interpretation of how far north the Antarctic continental crust extends depends on the interpretation of this sequence.
- What is the nature and age of sequences C, B and A of Eittreim and Smith (1987)?
- What is the paleoenvironment of the Wilkes Land margin building?

Logistics

Recovery of the sequences targeted in this theme can only be achieved by means of ODP drilling, in areas of the continental rise where buried oceanic basement highs reach to within 1000 m below seafloor.

Target areas

Hakurei seamount or any of the other seamounts in the same region.

III. Patterns and Events in the Tectonic and Structural History

Problem

Earliest oceanic crust separating Australia from Antarctica is estimated at about 96Ma, according to the oldest identified magnetic anomalies in this area (i.e. anomaly 34, 85 Ma), and an interpretation of the edge effect magnetic anomaly at the oceanic crust edge during the Cretaceous Magnetic Quiet Zone (MQZ) (Cande and Mutter, 1982; Veevers, 1987). The transition zone from continental to oceanic crust (COB) in the western Wilkes Land margin runs parallel to the continental margin (Eittreim, 1994). In the eastern Wilkes Land margin, there are two interpretations of where the COB is located: 1) based on magnetic and seismic profiles Veevers (1990) locates the COB south of the Hakurei (former Homachi seamount); 2) based on gravimetric Geosat vertical profiles, Royer and Sandwell (1989) locates the COB north of the Hakurei/Homachi seamount. NE of the Hakurei seamount recently recovered peridotite derived from sub-continental mantle, has been interpreted as being emplaced in connection with the early stages of ocean basin development (Yuasa et al., in press). The origin of the magnetic quiet zone may be explained by the presence of underlying remnant continental crust. The existence of thick manganese crusts is also consistent with the seamount having been exposed for a period of several tens of millions of years.

Objectives

- To determine the timing of the breakup between Australia and Antarctica which is believed to have occurred in early-Late Cretaceous times (96 Ma) (Cande and Mutter, 1982).
- To determine the thickness and nature of the continental-oceanic crust boundary (COB) and the transition between the two types of crust.
- To determine nature and age of subbottom highs (e.g. Hakurei Seamount) located in an area of crustal anomalies.

Logistics

MCS, gravity and magnetic profiles, ocean bottom seismometers, and large volume (70 liter) airgun arrays are needed.

Two approaches have been proposed to solve these problems:

- to sample the crustal and mantle rocks from seafloor around the seamount by ODP drilling,
- to get many kind of rocks consisting the seamount by short core drilling and dredging.

Target areas

Hakurei seamount and the seamount NE of Hakurei where the peridotite was recovered.

IV. Current and Planned Projects

Approved research

A 25-day cruise with the Research Vessel from the Osservatorio Geofisico Sperimentale, Trieste (Italy), is scheduled for 1999 under the WEGA (Wilkes Land Glacial History) Project. This cruise will acquire multichannel and high-resolution seismic profiles, gradiometric and gravity profiles, subbottom and side scan sonar profiles and gravity cores, across the Wilkes Land continental margin from about 200 to 4000 m. The aim of this project is to reconstruct the late Cenozoic history of the East Antarctic Ice Sheet and its link with global climate changes and sea level fluctuations, by providing statements of the continental shelf, slope and rise paleoenvironment particularly over the Holocene, the last Glacial cycle, and the Pliocene.

Pending research

- A drilling proposal (#482 and 482-rev), has been submitted to ODP as one of five ANTOSTRAT drilling proposals. The Wilkes Land drilling will sample glacial and interglacial Cenozoic sedimentary sections, to acquire ground-truth proximal data for the glacial and sea-level histories of this segment of the East Antarctic continental margin. It has been proposed to drill the prograding-shelf sequences and continental rise drift deposits. Wilkes Land drilling, when combined with other Antarctic margin drilling, should provide a proximal record for the Cenozoic history of continent-wide fluctuations of the Antarctic Ice Sheet. By drilling the Wilkes Land margin, we anticipate recovering cores that will

  - establish the times for initiation of glaciation and major inferred middle Miocene and Plio-Pleistocene fluctuations of the Antarctic Ice Sheet in this part of East Antarctica;
  - establish times of expanded ice sheets grounded to the continental shelf edge (i.e. glacial maxima) and open waters on the shelf (i.e, interglacial), to link oxygen isotope ratios and sea-levels directly to ice volumes for this part of the Antarctic margin.
  - provide paleoenvironmental data for sedimentary sequences, to help derive regional Neogene climate and depositional variabilities from high-resolution seismic data.

- A marine geological study has been proposed to the U.S. Antarctic to obtain very high-resolution (Huntec and CHIRP), high-resolution (3.5kHz) seismic data, and long piston cores (10m) from a transect across the Wilkes Land margin (i.e. inner-shelf basins, shelf troughs and rise drift deposits). It is proposed to conduct a detailed (laminae by laminae) study of the sediment cores to determine late Quaternary including Holocene, depositional and glacial histories. Additionally, it has been proposed to collect new MCS data, and to use the recovered sediment cores to augment existing data for site surveys for the ODP drilling proposal.

V. Future Projects and Cooperative Considerations

Other than the above mentioned projects that concentrate mainly in the eastern Wilkes Land margin, there is a need to for reconnaissance studies in the western Wilkes Land margin. At present, the western Wilkes Land margin is poorly surveyed, and most of the existing data has been collected by JNOC. Although JNOC's research in the following years will not focus on surveying the Wilkes Land, the existing data set could be an important resource and the base for planning future surveys and for future collaboration.

Potential cooperative studies can be established between the Australia, France (Ice breaker Astrolabe supplies yearly the Dumont D'Urville base which can do some geophysical work in the way back and the Marion D'Ufre, not an icebreaker has multibeam, side scan sonar and a long-45 m- piston coring system), Italy and the US.

REFERENCES

Cande, S.C., and Mutter, J.C., 1982. A revised identification of the oldest sea-floor spreading anomalies between Australia and Antarctica: Earth and Planetary Science Letters, 58, 151-160.Eittreim, S.L., 1994. Transition from continental to oceanic crust on the Wilkes-Adelie margin of Antarctica. *Journal of Geophysical Research*, 99, 24189-24205.

Eittreim, S.L., Cooper, A.K., and Wannesson, J., 1995. Seismic stratigraphic evidence of ice-sheet advances on the Wilkes Land margin of Antarctica. *Sedimentary Geology*, 96, 131-156.

Eittreim S.L. and Smith G.L., 1987. Seismic sequences and their distribution on the Wilkes Land margin. *In*: S.L. Eittreim and M.A. Hampton (eds.), *The Antarctic Continental Margin: Geology and Geophysics of Offshore Wilkes Land.* (Circum-Pacific Council for Energy and Mineral Resources Earth Sciences Ser., 5A) Houston, 15-43.

Escutia, C., Eittreim, S., and Cooper, A.K., 1995, Cenozoic glaciomarine sequences on Wilkes Land continental rise, Antarctica. VII International Symposium on Antarctic Earth Sciences, Siena, Italy, Abstracts Volume, p. 121.

Escutia, C., Eittreim, S.L., and Cooper, A.K., in press. Cenozoic glaciomarine sequences on the Wilkes Land continental rise, Antarctica: Proceedings Volume-VII International Sysposium on Antarctic Earth Sciences: p.791-795.

Rebesco, M., Larter, R., Barker, P.F., Camerlenghi, A., and Vanneste, L.E., in press, The history of sedimentation on the continental rise west of the Antarctic Peninsula, *In*: Barker, P.F. and A.K. Cooper eds., *Geology and Seismic Stratigraphy of the Antarctic Margin - Part* 2, AGU Antarctic Research Series.

Tanahashi, M., Eittreim, S., and Wannesson, J., 1994. Seismic stratigraphic sequences of the Wilkes Land margin. *Terra Antartica*, 1 (2), 391-393.

Veevers, J.J., 1987. The conjugate continental margin of Antarctica and Australia. *In*: S.L. Eittreim and M.A. Hampton (eds.), *The Antarctic Continental Margin: Geology and Geophysics of Offshore Wilkes Land.* (Circum-Pacific Council for Energy and Mineral Resources Earth Science Ser., 5A) Houston, 45-74.

Wannesson J., Pelras M., Pettitperrin B., Perret M., and Segoufin J., 1985. A geophysical survey of the Adelie margin, East Antarctica, *Mar. Petrol. Geol.*, *2*, 192-201

THE ROSS SEA REGION: GEOLOGY OF THE LAST 100 M.Y.

F. J. Davey
Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand

Introduction

The Ross Sea lies along the Pacific margin of the Jurassic rift [Schmidt and Rowley, 1986] that is delineated by the extensive dolerite sills of the Ferrar Group in the Transantarctic Mountains, and coincides in part with the active, Cenozoic, West Antarctic Rift System[LeMasurier, 1978; Behrendt et al., 1991], considered to be caused by a mantle plume [Hole and LeMasurier, 1994; Behrendt et al., 1992]. The Transantarctic Mountains, one of the world's great mountain chains, forms, for a large part of its length, the rift shoulder of the West Antarctic Rift System. It is over 4000 km long, reaches elevations of over 4000 m, and is block faulted and backtilted to the west (craton). The complementary rift shoulder in Edward VII Peninsula and western Marie Byrd Land is far more subdued and has more of a horst and graben (basin and range) style of morphology [LeMasurier and Rex, 1983] that is mostly ice covered and extends about 1000 m above and below sea level [Drewry, 1983]. The different flexural rigidity for the lithosphere of the two rift margins, an old craton and a younger orogenic belt [e.g., Stern and ten Brink, 1989], may give rise to this difference in character [e.g., Behrendt et al., 1991].

The Ross Sea and its southern continuation under the Ross Ice Shelf form the Ross Embayment, which is about 500 m deep and generally has a gentle ridge and valley morphology with a maximum depths (1200 m) are along the western margin, adjacent to the Transantarctic Mountains. The depth of the Ross Sea is significantly deeper than is normal for a continental shelf (50-200 m). This is considered to arise largely by crustal thinning [Fitzgerald et al., 1986; Stern et al., 1992] but glacial erosion, which over deepened the inner shelf, and sediment loading on the continental rise during the time of a more extensive ice sheet, may also contribute, as proposed by ten Brink and Cooper [1992] for the Antarctic continental shelf in general.

The sedimentary basins in the Ross Sea were probably formed largely by rifting processes during and since the break-up of this part of Gondwana in the Late Cretaceous [e.g., Davey, 1981]. Cooper and Davey [1985] and Cooper et al. [1987, 1991] noted two phases to the basin formation: i) an initial regional extension phase related to the Gondwana break-up episode and ii) a possibly mid-Cenozoic phase, which was localized in the western Ross Sea. Elliot [1992] suggested that the earliest extensional event in the formation of the basins and the morphologically depressed Ross Sea - Ross Ice Shelf region was the poorly defined rifting episode associated with the intrusion of the Ferrar dolerites at about 180 Ma. The subsequent tectonic development of the region resulted from the development of the West Antarctic Rift System in the late Mesozoic [Behrendt *et al.*, 1991], associated with the initial sea-floor spreading between New Zealand, Australia and Antarctica [e.g., Weissel *et al.*, 1977] and with the presumed concurrent development of a mantle plume [Weaver *et al.*, 1994]. Hole and LeMasurier [1994], however, associate the beginning of plume activity with the onset of active volcanism in the region and uplift in western Marie Byrd Land at about 30 Ma. Uplift of the adjacent Transantarctic Mountains appears to have occurred in several phases commencing about 115 Ma [Fitzgerald, 1994].

Tectonic Events in the Ross Sea Region

The eastern margin of Ross Sea (western Marie Byrd Land and Edward VII Peninsula) forms the present continental margin of western Antarctica. In general terms, the limited geological outcrop in Marie Byrd Land shows a Paleozoic crystalline basement overlain by young, Cenozoic basaltic volcanics with a major erosion surface of Late Cretaceous to early Cenozoic age (80 Ma to 28 Ma) separating the two [LeMasurier and Rex, 1994]. Mid-Cretaceous to Late

Cretaceous mafic dikes occur parallel to the coast in Marie Byrd Land, and granitoids of same age have been intruded [LeMasurier and Rex, 1994]. Extensive basaltic hyaloclastite deposits, less then 28 Ma, overlie the erosion surface and are overlain by felsic shield volcanoes of less than 16 Ma [LeMasurier, 1990]. The uniformity of alkaline basalt composition throughout the West Antarctic rift is interpreted to indicate a mantle plume and uniformly minimal crustal extension during the late Cenozoic by Hole and LeMasurier [1994].

In the Ford Ranges of western Marie Byrd Land, Ar-Ar, U-Pb and apatite fission track data show several episodes of heating and denudation [Luyendyk et al., 1992; Luyendyk, 1993; Richard et al., 1994]. The subduction of the Phoenix-Antarctic spreading center beneath Marie Byrd Land resulted in the elevation of the geothermal gradient by magmatic advection, and high-temperature low-pressure metamorphism of the middle crustal rocks by about 104 Ma. Between about 104 and 100 Ma, granites were intruded into the metamorphic rocks (the present Fosdick metamorphic complex), and was followed by rapid exhumation (about 1.5 mm/yr) and cooling over 6 m.y. (100-94 Ma). [Richard et al., 1994]. This uplift, possibly involving removal of up to 15 km of overburden, was accompanied by N to NNE extension, consistent with dextral transcurrent rifting at the coast [Luyendyk et al., 1992]. The geology of the Alexandra Mountains in the Edward VII Peninsula is similar. Weaver et al. [1992] give an age of 95-100Ma for extensional processes (anorogenic granites), with the commencement of regional uplift at about 100 Ma, immediately after granite emplacement. I type granites dated at 108-124 Ma and A-type granites dated at 95-120 Ma, indicate a rapid change from subduction related magmatism (I type) to rift related magmatism (A-type).

Between about 94 Ma and 80 Ma, the cooling and denudation rate in the Ford Ranges slowed significantly. A period of rapid cooling of crustal rocks from 80 to 70 Ma, nearly coeval with the initiation of sea-floor spreading between New Zealand and West Antarctica, can be related to further exhumation, possibly associated with faulting and N-S extension [Richard et al., 1994]. Since 70 Ma, slow cooling and exhumation (about 3 km), with possibly minor faulting, has occurred [Richard et al., 1994]. This prolonged stability led to the the development of a widespread Late Cretaceous to early Tertiary erosion surface of very low relief over most of West Antarctica [LeMasurier and Rex, 1994]. Post 50 Ma changes in the trend of the glacial striations have been interpreted by Luyendyk [1993] to indicate a late Cenozoic trend of extension of about N-S to NE-SW (Figure 4). At 28-30 Ma, volcanic activity started in the Marie Byrd Land volcanic province [LeMasurier, 1990], with peaks of activity at 8-12 Ma and 0-1 Ma, contemporaneous with block faulting and uplift. Significant post-Eocene vertical tectonics have occurred, similar to basin and range tectonics [Luyendyk et al., 1992] with up to 1.5 km vertical movement in western Marie Byrd Land. Uplift rates, derived from displacements of the erosion surface associated with volcanic activity, average about 100 m/m.y. for the past 25 Ma [LeMasurier and Rex, 1989].

The Transantarctic Mountains form the western margin of the Ross Sea. Indicators of horizontal deformation since Jurassic time are few. Wilson [1992], from a study of fracture and dike orientations, has derived a NE trend for Jurassic extension and a SE trend for Cenozoic extension in South Victoria Land. Fission track data for the Transantarctic Mountains show an onset of rapid denudation beginning at about 50-55 Ma with an indication of rapid denudation in the early Cretaceous (115 Ma) at Scott Glacier and in the Beardmore Glacier region [Fitzgerald, 1994]. Rapid denudation in the Late Cretaceous (about 85 Ma) is suggested at Scott Glacier and possibly at Admiralty Mountains in North Victoria Land and in South Victoria Land, and in the latest Cenozoic in lower Tucker Glacier region of North Victoria Land [Fitzgerald and Gleadow, 1988]. Uplift rates reach at least 200 m/m.y. for about 10 to 15 m.y. after uplift commenced at 55 Ma in South Victoria Land [Fitzgerald, 1992]. The present elevation of sub-aerial volcanics indicate a maximum uplift of 209 m since 2.57 Ma in the Dry Valleys of South Victoria Land [Wilch et al., 1993]. Uplift rates derived from drill hole information in the Dry Valleys and McMurdo Sound region, based on microfossils, give 150 m/m.y. [Wrenn and Webb, 1982], and Ishman and Webb [1988] derived a rate of 125 m/m.y. since 3 Ma. McKelvey et al. [1991] and Webb et al. [1994] have demonstrated that, at the Beardmore Glacier, the Sirius Group is essentially terrestrial strandline deposits which have been uplifted by about 1300 m to 1700 m since Pliocene time. A detailed study of the Cenozoic glacial geology of North Victoria Land [van der Wateren and Verbers, 1992] has suggested uplift of the Transantarctic Mountains with rates of about 100 m/m.y. in the early Pliocene rising to about 1000 m/m.y. in the Pleistocene to present. Behrendt and Cooper [1991] also suggest that high uplift at a rate of about 1000 m/m.y. since mid-Pliocene is possible.

The segmentation of the Transantarctic Mountains into several crustal blocks is indicated by the differing amounts of uplift between major crustal blocks [Fitzgerald, 1994] and within the same crustal block (e.g., within South Victoria Land and the Scott Glacier region) [Fitzgerald, 1992; Stump and Fitzgerald, 1992]. Uplifts of 6 km are inferred for South Victoria Land and 10 km for the lower Tucker Glacier of North Victoria Land during the mid-Cenozoic. Differential uplift of North Victoria Land is suggested by Cenozoic glacial geology [van der Wateren and Verbers, 1992], and inferred major cross range faults along the major outlet glaciers through the Transantarctic Mountains also supports segmentation of the Transantarctic Mountains [Tessensohn, 1994; Tessensohn and Woerner, 1991; Redfield and Behrendt, 1992; van der Wateren et al., 1994].

The tectonic history of the Transantarctic Mountains is also reflected in its Cenozoic igneous history [LeMasurier and Thomson, 1990]. Alkali basaltic volcanism of the McMurdo Volcanic Group commenced between 25 and 18 Ma in three elongate (N-S) provinces along the Ross Sea margin: Hallett (Cape Adare to Coulman Island, 0 to 13 Ma), Melbourne (0 to 26 Ma) and Erebus (0 to 19 Ma). Most of the volcanics are younger than 10 Ma. Volcanic sediments, interpreted to be derived from the McMurdo Volcanic Group, were sampled throughout the CIROS-1 drillhole in western McMurdo Sound [George, 1989]. The interpretation of the age of the oldest sediments in CIROS-1 as middle Eocene [Hannah, 1994] suggested that late Cenozoic volcanism commenced in this region about middle Eocene times (about 45 Ma).

The structural and depositional framework of the Ross Sea is formed by four main depocenters, trending approximately north-south across the continental shelf: the Victoria Land basin, the Northern basin, the Central trough and the Eastern basin, [Houtz and Davey, 1973; Davey, 1981, 1983; Hinz and Block, 1984; Cooper et al., 1987, 1994].

The crustal thinning processes in the Ross Sea that formed these major basins are probably related to the separation of Antarctica, Australia and New Zealand [Davey, 1981; Cooper et al., 1987, 1991; Behrendt et al., 1991]. Two main rifting episodes have been proposed: i) an early, essentially non-magmatic, rifting event throughout the Ross Sea which formed all the main depocenters, and ii) a late rifting event, with associated bimodal alkali basalt volcanics, which was localised in the western sectors and formed the Terror Rift in the Victoria Land basin in western Ross Sea. The ages of these two events are not well constrained. A late Mesozoic age has been suggested for the early rifting, associated with Gondwana break-up, and an Eocene and younger age for the later rifting event [Cooper et al., 1987, 1991].

Hinz and Kristofferson, 1987 delineated the major features of the main basins of the Ross Sea and identified a structural trend across the western Ross Sea aligned with the onshore Bowers structure of North Victoria Land Davey [1981] proposed that a major transform fault zone divided the Ross Sea into eastern and western parts, linking up with Late Cretaceous and post-Cretaceous spreading on the Pacific-Antarctic ridge. Cooper at al. [1987] noted major normal faulting in the western Ross Sea of two ages: faults forming basement half grabens, which frequently terminated within the sedimentary section, and more recent Cenozoic faulting which, in places, reached the sea floor. Some of the recent faulting is associated with Cenozoic volcanism. The trend of faulting is largely north-south. This style of faulting is documented in more detail for the whole of the Ross Sea and transverse trends (NW-SE and NE-SW) are defined by Cooper et al..

Aeromagnetic data over the western Ross Sea margin show a north-south fabric in the magnetic anomalies over the western Ross Sea and a major magnetic anomaly, the Polar 3 anomaly, between Coulman Island and Mount Melbourne [Bosum et al., 1989]. Bosum et al. [1989] interpreted the magnetic data in terms of basic igneous bodies and inferred an extensional direction for the formation of these features. Recent magnetic data [Damaske et al., 1994] delineate a highly magnetic province east of Ross Island. Damaske et al. [1994] inferred that this anomaly group and the Polar 3 anomaly correspond to transfer faults between the extensional systems giving rise to the volcanic provinces along the western Ross Sea margin and the Victoria Land basin.

Crustal structure studies of the Ross Sea [Smithson, 1972; Davey and Cooper, 1987; McGinnis et al., 1985; Behrendt et al., 1991; Trehu et al., 1993] indicate a crustal thinning from between 30 and 40 km to about 20 km, indicating 100% extension. Under the Central trough, the extension is far higher with the crystalline crust thinned to about 5 km in places[Trehu et al., 1993]. Here the stretching has been modelled for associated crustal/mantle decompression melting, and is consistent with thin (1 km) volcanics at the base of the basin and a high velocity wedge of mantle melt, now inferred to be incorporated into the lower crust under the basin [Trehu et al., 1993]. Crustal thicknesses modelled from gravity and seismic data vary from 4 km (under Victoria Land basin) to 20 km (under Central high), with the crust underlying the Eastern basin showing as a distinct unit at 12-16 km thick. Assuming a normal crustal thickness of 30-40 km, these crustal thicknesses indicate an average extension of about 100 to 140% (beta = 2-3) over the width (900 km) of the Ross Sea, or 350 to 450 km of extension. This compares with previous estimates of 350 km by Behrendt and Cooper [1991] and the post 100 Ma extension of 1130±690 km derived by DiVenere et al. [1994] from paleomagnetic data in Marie Byrd Land.

Seismic data linked to drillhole information has shown that some thousands of meters of sediments are present in the deepest part of the Ross Sea depocenters [ANTOSTRAT, 1996]. The sediments form two major sequences. In the upper sequence, 6 major unconformities, U1-U6, have been identified [Hinz and Block, 1984] and the intervening units mapped [Busetti and Zayatz, 1994; ANTOSTRAT, this volume]. Unconformity U6 separates these sediments from the underlying sediments, which are probably early Eocene and Paleocene to early Mesozoic in age, and perhaps older [Cooper et al., 1987]. However the history in the basins is not well defined because of the lack of age control.

The significance of unconformities recognized on the seismic data in terms of vertical deformation may vary considerably. Unconformities may arise from tectonic or sea-level changes. They may also be caused by the action of ice erosion associated with an expansion of the Antarctic Ice Sheet that can erode to depths several hundred meters below sea level [Barnes and Lien, 1988; Bartek et al., 1991]. Differential erosion may result from the differential flexural response of the continental shelf to ice loading or unloading [ten Brink and Schneider, 1994].

The identification of significant tectonic events or eustatic events, and estimates of the rates of subsidence for the Eocene and younger sediments, may be deduced at the drill sites in the region. The correlation of the drillcore ages with the identified unconformities is not well constrained, and extrapolation of these ages to other areas depends on the unconformities not being time transgressive with respect to the sediments above or below [ANTOSTRAT, 1996]. Subsidence rates for the older sedimentary section (Eocene and older) depend on the assumption of the age of these sediments. Drill hole data are available from the eastern and central Ross Sea: on the western margin of the Eastern basin (DSDP site 270, 271 and 272 [Hayes et al., 1975]), from the central Ross Sea - over the Central trough (DSDP site 273 [Hayes et al 1975]) and from the western Ross Sea (McMurdo Sound), where the section sampled may be affected by local tectonic and glacial events (MSSTS-1 and CIROS-1 & -2 [Barrett, 1986, 1989] and DVDP sites 8 to 15 [McGinnis, 1981]).

Major changes in sedimentation rate may result from tectonic events. Rates of several tens of meters per million years are indicated by the drillhole data. Savage and Ciesielski [1983] recognise an extremely high sedimentation rate (over 150 m/m.y.) at site 272 and 273 suggesting an increase in subsidence rate for the early and middle Miocene. Cores from CIROS-1, initially, were also interpreted to show sedimentation rates which differed greatly downhole: 40 m/m.y. for the upper sequence and 200 m/m.y. for the lower sequence [Barrett, 1989]. However, the recent reassessment of the age of the deepest sediments in CIROS-1 as middle Eocene [Hannah, 1994], suggests a rate of about 40 m/m.y. or less for the whole sequence, and reassessment, based on better age control on diatom biostratigraphic events from recent Southern Ocean drilling, indicates lower sedimentation (and subsidence) rates for the DSDP sites than previous published [D. Harwood, pers. comm.]. The very high sedimentation rate derived for site 273 is critically dependant on the short time range inferred for the lower sedimentary unit.

The outstanding problems of the Ross Sea region are related to timing - of events and processes. The timing (and amount) of the main extensional events in the Ross sea, and associated with the major depositional (subsidence) episodes in the Ross Sea sedimentary basins. is only inferred. The timing of the uplift episodes in the TAM is poorly constrained and it is not known whether uplift over periods of several tens of millions of years was episodic or continuous. The relationship of extension and subsidence in the Ross Sea to TAM uplift and to Marie Byrd Land is unknown.

Additional problems to be studied include

- the origin of the Polar 3 magnetic anomaly and its relationship to the tectonics of the region,
- the identification and quantification of transcurrent movement along (?) Transantarctic Mountains front - to accommodate plate motion misclosures.
- late Cretaceous - early Tertiary paleoenvironment
- the "Plume" theory

References

Provided in:

Davey, F.J. and G.Brancolini, 1995, The late Mesozoic and Cenozoic structural setting of the Ross Sea Region, *In*: Cooper, A. K., Barker, P. F., and Brancolini, G., editors, *Geology and Seismic Stratigraphy of the Antarctic Margin* (Antarctic Research Series 68): American Geophysical Union, p. 167-182.

List of Acronyms and Abbreviations

ADPG	Antarctic Detailed Planning Group
AIS	Antarctic Ice Sheet
ANTIME	Antarctic Ice Margin Environment Group
ANTOSTRAT	Antarctic Offshore Stratigraphy Programme
ATCM	Antarctic Treaty Consultative Meeting
CIROS	Cenozoic Investigations of the Western Ross Sea
COB	Continental to oceanic crust
DSDP	Deep Sea Drilling Program
DPG	Detailed Planning Group
DVDP	Dry Valley Drilling Project
EOS	Earth Observing System
EMAGE	Aero-geophysical program
GCM	General Climate Models
GLOCHANT	Global Change and the Antarctic
GOSC	Group of Specialists on Cenozoic Paleoenvironments of the Southern High Latitudes
IRD	Ice-rafted detritus
IGBP	International Geosphere–Biosphere Programme
ISAES	International Symposium on Antarctic Earth Sciences
JNOC	Japanese National Oil Company
MQZ	Magnetic Quiet Zone
MSSTS	McMurdo Sound Sediment and Tectonic Studies
MST	Multi Sensor Track
MCS	Multichannel seismic-reflection
OAGCM	Ocean Atmosphere General Climate Models
ODP	Ocean Drilling Program
OGS	Osservario Geofisico Sperimentale
PAGES	Past Global Environmental Changes
ROV	Remotely operated vehicle
SCAR	Scientific Committee on Antarctic Research
SDLS	Seismic Data Library System
SCS	Single-channel data
STRATAFORM	US Low-latitude offshore seismic stratigraphy programme
TAM	Trans Antarctic Mountains
WEGA	Wilkes Land Glacial History

SCAR Report

SCAR Report is an irregular series of publications, started in 1986 to complement *SCAR Bulletin*. Its purpose is to provide SCAR National Committees and other directly involved in the work of SCAR with the full texts of reports of SCAR Working Group and Group of Specialists meetings, that had become too extensive to be published in the *Bulletin*, and with more comprehensive material from Antarctic Treaty meetings.

SCAR Bulletin

SCAR Bulletin, a quarterly publication of the Scientific Committee on Antarctic Research, is published on behalf of SCAR by Polar Publications, at the Scott Polar Research Institute, Cambridge. It carries reports of SCAR meetings, short summaries of SCAR Working Group and Group of Specialists meetings, notes, reviews, and articles, and material from Antarctic Treaty Consultative Meetings, considered to be of interest to a wide readership. Selections are reprinted as part of *Polar Record*, the journal of SPRI, and a Spanish translation is published by Instituto Antártico Argentino, Buenos Aires, Argentina.

Polar Record

Polar Record appears in January, April, July, and October each year. The Editor welcomes articles, notes and reviews of contemporary or historic interest covering the natural sciences, social sciences and humanities in polar and sub-polar regions. Recent topics have included archaeology, biogeography, botany, ecology, geography, geology, glaciology, international law, medicine, human physiology, politics, pollution chemistry, psychology, and zoology.

Articles usually appear within a year of receipt, short notes within six months. For details contact the Editor of *Polar Record*, Scott Polar Research Institute, Lensfield Road, Cambridge CB2 1ER, United Kingdom.
Tel: 01223 336567 (International: +44 1223 336567)
Fax: 01223 336549 (International: +44 1223 336549)

The journal may also be used to advertise new books, forthcoming events of polar interest, etc.

Polar Record is obtainable through the publishers, Cambridge University Press, Edinburgh Building, Shaftesbury Avenue, Cambridge CB2 2RU, and from booksellers. Annual subscription rates for 1999 are: for individuals £52.00 ($88.00), for institutions £84.00 ($144.00); single copies cost £23.00 ($40.00).

Printed by The Chameleon Press Limited, 5–25 Burr Road, London SW18 4SG, United Kingdom