PROPOSAL FOR A SCAR
SCIENTIFIC RESEARCH PROGRAMME
ON
ANTARCTIC CLIMATE EVOLUTION (ACE)

An international research initiative to study the climate and glacial history of Antarctica through palaeoclimate and ice-sheet modelling integrated with the geological record.

ACE Scientific Programme Planning Group, July 29 2004.

http://www.ace.scar.org/

This proposal was prepared using guidelines provided the 'Implementation of the SCAR Review, June 2002'.
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List of acronyms used in this document

AABW  Antarctic Bottom Water
ACC  Antarctic Circumpolar Current
ACE  Antarctic Climate Evolution
AGCS  Antarctica and the Global Climate System
ANDRILL  Antarctic Drilling Consortium
ANTEC  SCAR Group of Specialists on Antarctic Neo-Tectonics
ANTIME  Antarctic Ice Margin Evolution
ANTOSTRAT  Antarctic Offshore Stratigraphy Project
AP  Antarctic Peninsula
ATCM  Antarctic Treaty Consultative Meeting
DSDP  Deep Sea Drilling Project
EAIS  East Antarctic Ice Sheet
EBM  Energy Balance Model
EMICS  Earth Models of Intermediate Complexity
EPICA  European Project for Ice Coring in Antarctica
GCM  Global Climate Model
GLOCHANT  Antarctic Global Change Program
IMAGES  International Marine Global Change Study
IODP  Integrated Ocean Drilling Program
IPCC  Intergovernmental Panel on Climate Change
LGM  Last Glacial Maximum
PANGEA  A project focusing on super-continent accretion and dispersal from the Carboniferous to the Jurassic, when much of Pangea's climate appeared to be disposed in an icehouse mode
PB  Prydz Bay
RCM  Regional Climate Model
RS  Ross Sea
SALE  SCAR Group of Specialists on Subglacial Antarctic Lake Exploration
SCAR  Scientific Committee on Antarctic Research
SDLs  Seismic Data Library System
SHALDRIL  Shallow Drilling along the Antarctic Continental Margin
SPPG  Scientific Programme Planning Group
SRP  Scientific Research Programme
TAM  Transantarctic Mountains
THC  Thermohaline Circulation
WAIS  West Antarctic Ice Sheet & programme called The West Antarctic Ice Sheet Initiative
WAISCores  Part of WAIS to study two ice cores in West Antarctica.
WDC  World Data Centre
WL  Wilkes Land
WS  Weddell Sea

The Cenozoic

<table>
<thead>
<tr>
<th>Quat.</th>
<th>Pleistocene</th>
<th>1.8 Ma</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pliocene</td>
<td>5 Ma</td>
</tr>
<tr>
<td>NEogene</td>
<td>Miocene</td>
<td>24 Ma</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Oligocene</td>
<td>34 Ma</td>
</tr>
<tr>
<td></td>
<td>Eocene</td>
<td>58 Ma</td>
</tr>
<tr>
<td></td>
<td>Palaeocene</td>
<td>65 Ma</td>
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</table>
PROPOSAL FOR A SCAR SCIENTIFIC RESEARCH PROGRAMME ON ANTARCTIC CLIMATE EVOLUTION (ACE)

Executive Summary
ACE is a new international initiative that promotes the exchange of data and ideas between research groups focussing on the evolution of Antarctica’s climate system and ice sheet. ACE will exist to facilitate scientific exchange between the modelling and data acquisition communities for the purposes of project development and hypothesis testing. The broad outcomes of the programme will be: (1) quantitative assessment of the climate and glacial history of Antarctica; (2) identification of the processes which govern Antarctic change, and those which feed back this change around the globe; (3) improvements in our technical ability to model past changes in Antarctica; and (4) precisely documented case studies of past changes, which models of future change in Antarctica can be tested against.

The Southern Ocean plays a lead role in the development and maintenance of the Earth’s climate system. Equator-to-pole heat transport through the ocean and atmosphere is largely controlled by the latitudinal thermal gradient, which in turn is mostly a function of polar temperatures. Past variability in Antarctic temperatures and the extent of glacial and sea ice thereby impacts climate systems throughout the globe. The Antarctic ice sheet is the largest reservoir of fresh water on Earth and exerts an influence on global sea levels and hydrology, as well as ocean chemistry. The seas surrounding Antarctica contain the world’s only zonal circum-global current system wherein mixing occurs between water masses from all the ocean basins. Circum-polar flow maintains the thermal isolation of Antarctica from warmer surface waters to the north and has been linked to the development of continental glaciers and a dynamic sea ice regime. The Southern Ocean impacts the global thermohaline circulation as a major site of bottom and intermediate water formation. The southern seas are also important for ventilation of CO₂ between the atmosphere and the ocean, by virtue of large-scale processes of upwelling, downwelling, and isopycnal mixing in a region of cold surface waters and strong winds. Antarctica, thus, has a key position in global climate processes now and in the past. To understand these processes it is necessary to examine their role in documented past climate change. The ACE programme aims to do this by formulating geological-based hypotheses on past changes in Antarctica and testing them using coupled climate/ice-sheet models.

1. Science aims/outcomes & rationale for their quality, importance & feasibility
ACE is a new, international research initiative to study the climate and glacial history of Antarctica through palaeoclimate and ice sheet modelling investigations, purposefully integrated with terrestrial and marine geological and geophysical evidence for past changes (Fig. 1).

Antarctica has been glaciated for approximately 34 million years, but its ice sheets have fluctuated considerably and have been one of the major driving forces for changes in global sea level and climate throughout the Cenozoic Era. The spatial scale and temporal pattern of these fluctuations has been the subject of considerable debate. Determination of the scale and rapidity of the response of large ice masses and associated sea ice to climatic forcing is of vital importance because ice-volume variations lead to (1) changing global sea levels on a scale of tens of...
metres or more and (2) alteration to the capacity of ice sheets and sea ice as major heat sinks/insulators. It is thus important to assess the stability of the cryosphere in the face of rising CO₂ levels (IPCC, 2001), particularly as modelling of the climate shifts from a warm, vegetated Antarctica to a cold, ice-covered state 34 Myrs ago has shown the powerful influence of trace gases on the Earth’s climate systems (DeConto and Pollard, 2003a). Concern is justified when CO₂ levels are compared with those of the past. As Antarctica is a major driver of Earth’s climate and sea level, much effort has been expended in deriving models of its behaviour. Some of these models have been successfully validated against modern conditions. Modelling the past record of ice-sheet behaviour in response to changes in climate (inferred from ice cores, sedimentary facies, and seismic data), palaeocceanographic conditions (inferred from palaeoecology and climate proxies in ocean sediments) and palaeogeography (as recorded in landscape evolution) is the next step.

The ACE programme aims to facilitate research in the broad area of Antarctic climate evolution over a variety of timescales. The programme will link geophysical surveys and geological studies on and around the Antarctic continent (Fig. 1) with ice-sheet and climate modelling experiments. ACE is designed to determine both climate conditions and climatic changes during the recent past (i.e., the Holocene prior to anthropogenic impacts, as well as at the last glacial maximum and other Quaternary glaciations, when temperatures were cooler than at present) and the more distant past (i.e. the pre-Quaternary, when global temperatures were several degrees warmer than today). This new cross-disciplinary approach, involving climate and ice sheet modellers, geologists and geophysicists, will lead to a substantial improvement in the knowledge-base on past Antarctic climate, and our understanding of the factors that have guided its evolution. This in turn will allow us to build hypotheses, examinable through numerical modelling, as to how Antarctic climate is likely to respond to future global change. Equally important, the development of data-driven models for Antarctic climate will allow us to extend our results to the analysis and prediction of global climate variability. Details of the specific outcomes and deliverables of ACE are provided in Section 4, p21.

A previous SCAR programme, ANTOSTRAT (ANtarctic Offshore STRATigraphy project), focused principally on developing a stratigraphic framework for the Cenozoic Antarctic margin through seismic stratigraphy and direct sampling through offshore drilling and coring. In addition, the goals of the short-lived SCAR initiative ANTIME (Antarctic Ice Margin Evolution) were transferred to ACE following the termination of GLOCHANT (Antarctic Global Change Program) in 2002. During the lifetime of ANTOSTRAT, significant advances were made to ice sheet and climate models in terms of their ability to replicate the modern environment and to reconstruct former conditions. As yet, there has been no concerted effort to employ such models to determine the Cenozoic climate evolution of Antarctica. The ACE programme will build on the achievements of ANTOSTRAT by focusing on linking palaeoenvironmental records, from current and future drilling and coring, with new ocean-ice sheet-climate modelling efforts in order to provide both constraints and tests for this new generation of models.

Figure 2. Variation in the Earth's temperature during the last 80 million years, based on reconstructions from deep-marine oxygen isotope records. Note the general cooling trend from 50 million years ago. Also note the abrupt "climatic threshold events". For example at 34 million years ago when abrupt global cooling led to the first ice sheets developing on Antarctica. Future atmospheric temperature scenarios, based on IPCC greenhouse gas projections, are shown at top of diagram. Given the worse case scenario, in 100-300 years planetary temperatures could increase to a level where, according to our knowledge of previous Antarctic glaciations, ice cover on Antarctica could not be sustained.

27 November, 2003
The science plan we propose will necessarily depend on outcomes from a range of regional programmes for gathering field data (Fig. 1). Some of these have been completed, while others are now in progress or are still in the planning stage (Table 1). The role of ACE will be to organise theme-based meetings and workshops to review past work and develop volumes for publication in international journals, and to promote planning and international collaboration for future field programmes. The themes that ACE will focus on are listed in Table 2.

Most Antarctic Earth science research is necessarily regional in character, with different countries normally operating in relatively limited sectors of the continent. Even multinational programmes typically focus on one particular area of the continent. Understanding climate evolution calls not only for a continent-wide view of past records of Antarctic climate change, but also for an understanding of the connections between continental margin and deep-sea processes and their separate but related histories. Progress in making these connections can only succeed through international collaboration that SCAR has mandated.

The rationale for the ACE programme, outlined herein, was developed and refined before, during, and after an Antarctic Earth science symposium in Erice, Italy in September 2001 (Cooper et al., 2002; Florindo and Cooper, 2001) and at the EUG/EGS/AGU meeting in Nice (April, 2003). Over 100 scientists gathered in Erice, almost all presenting posters or papers, and reflecting the interest and enthusiasm of the scientists who are active in this field. We believe that this enthusiasm can be maintained and fostered through well-planned programmes of international interest and relevance. Such programmes should be considered and set up in a timely fashion as a dedicated group (i.e. ACE) to continue the momentum gained from existing science initiatives.

<table>
<thead>
<tr>
<th>Programme (and year)</th>
<th>Location</th>
<th>Type of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean Drilling Program Leg 178 (1998)</td>
<td>Pacific margin of Antarctic Peninsula</td>
<td>Cores and down-hole logs for last 10 m.y. from outer shelf and rise</td>
</tr>
<tr>
<td>Cape Roberts Project (1997-1999)</td>
<td>Coastal south Victoria Land</td>
<td>Cores and down-hole logs for 34 to 17 Ma from inner shelf</td>
</tr>
<tr>
<td>Ocean Drilling Program Leg 188 (2000)</td>
<td>Prydz Bay</td>
<td>Cores and down-hole logs from outer shell (90 and 30-36 Ma), slope (0-2 Ma) and rise (0-22 Ma)</td>
</tr>
<tr>
<td>Ocean Drilling Program Leg 189 (2000)</td>
<td>Tasman Sea</td>
<td>Cores and down-hole logs for the Eocene and Oligocene</td>
</tr>
<tr>
<td>ANDRILL (2003-2011)</td>
<td>McMurdo Sound (initially)</td>
<td>Several cores up to 1000 mbsf from Palaeogene to Quaternary-age strata</td>
</tr>
<tr>
<td>SHALDRIL (2003- )</td>
<td>Weddell margin of Antarctic Pen (initially)</td>
<td>Many cores to 200 mbsf for sampling thick dipping sedimentary sections and expanded Holocene sections. May become an IODP alternative platform</td>
</tr>
<tr>
<td>SALE (2000- )</td>
<td>Central Antarctica</td>
<td>Sediment cores to depths of several hundred m in subglacial lakes beneath EAS. Bedrock samples to constrain age of subglacial terrain</td>
</tr>
<tr>
<td>IMAGES (2004-2007)</td>
<td>Continental rise around Antarctic margin Drake Passage</td>
<td>Many giant (up to 80 m) piston cores from late Quaternary drift deposits, basin fill, and older sediments in outcrop</td>
</tr>
<tr>
<td>IODP (2005 -)</td>
<td>Ross Sea and Wilkes Land</td>
<td>Proposals to drill in these areas are developed and, if funded, would contribute to the database useful for ACE research</td>
</tr>
<tr>
<td>ANTIME (1997–2001) – now part of ACE</td>
<td>Antarctica</td>
<td>Determine the Late Quaternary sedimentary record of the Antarctic margin</td>
</tr>
<tr>
<td>ANTEC (2000— )</td>
<td>Antarctica</td>
<td>Determine Antarctic neotectonics and understand the nature of coupling between tectonics, climate and erosion</td>
</tr>
<tr>
<td>WAIS (incl. WAIS-cores) (1990— )</td>
<td>West Antarctica</td>
<td>West Antarctic ice sheet initiative to study rapid climate change and future sea level</td>
</tr>
<tr>
<td>EPICA (1996— )</td>
<td>Dome C and Dronning Maud Land, East Antarctica</td>
<td>Establishing palaeoclimate records for the last few glacial-interglacial cycles in East Antarctica</td>
</tr>
<tr>
<td>AGCS (SCAR SPPG) (planned 2004— )</td>
<td>Antarctica, and global processes</td>
<td>Antarctic and the Global Climate System, concerned with the troposphere, stratosphere and higher levels, where they affect the conditions near the surface. The programme will focus primarily on the last 2000 years and out to 100 years in the future, but will extend back several glacial cycles where necessary.</td>
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</table>

Table 1. List of programmes and projects generating data useful for research within the science plan of ACE.

2. Approach to implementation
We propose that the Scientific Research Programme be led by a committee of 10-12 persons. We consider this to be large enough to cover the range of disciplines, scientific and technical expertise and experience that we consider necessary for the successful implementation of the programme, but small enough to ensure that each member has a significant and clearly identified role. We believe that the proposed programme has attracted sufficient interest among scientists to allow these requirements to be met, and indeed we have taken these points into account in the formation of the Scientific Programme Planning Group (SPPG). We propose that two people in the committee be identified as convener and deputy convener. The committee would meet formally once a year, and conduct the rest of its business remotely. Members would serve for a 3-year term, with the possibility of extension depending on contribution and performance.

The committee should have knowledge of thematic issues and have appropriate regional (field) and technical/logistical experience. Eight members would focus principally on thematic issues (to cover the areas of palaeoclimate modelling, ice-sheet and sea ice modelling, ice-sheet history, chronostratigraphy, biostratigraphy, Southern Ocean history, subglacial and marine sedimentary processes, and glacial processes). Two further members would focus principally on regional and technical issues to provide expertise on the Antarctic Seismic Data Library (SDLS), regional working group activities/co-ordination, rock and ice drilling systems/operations, seismic-reflection systems/operations, data access and archiving, workshops/symposia and publications coordination. Members selected for the thematic component would come from a geoscience discipline. They would assist members selected for the regional/technical component in workshop/symposia and publications, who may come from either a geoscience background (with regional/technical experience) or from a technical background (with regional geoscience experience). In addition, we propose to have an advisory group of up to six senior researchers from the geoscience community who would agree to assist the committee on request.

An appropriate model for the individual expertise of the committee is as follows:

**Thematic components**
1. Geophysics (sea-floor morphology, multi-resolution seismic stratigraphy, regional structure and basin analysis, etc.)
2. Sedimentology (glacial/interglacial sequences and processes onshore and offshore, high resolution stratigraphy, etc.)
3. Palaeoceanography (ocean-basin history, water mass processes, sediment-ocean-air interfaces, etc.)
4. Geochemistry (tracer geochemistry, biogeochemistry, carbon cycle, provenance, etc.)
5. Geochronology and palaeomagnetism (age-dating techniques, rock-magnetic properties, chronostratigraphy, etc.)
6. Palaeontology (biostratigraphy, palaeoecology, evolution of polar biota, palaeoenvironmental proxies)
7. Ice sheet modelling (used to ‘test’ hypotheses derived from interpretation of the geological record AND establish glacial-interglacial accumulation patterns by integrating results to internal ice-sheet layers identified by ice-penetrating radar)
8. Palaeoclimate modelling (ice-sheet models coupled with atmosphere-ocean General Circulation Models (GCM’s) to examine glacial feedback mechanisms will be used to examine physical processes responsible for ice sheet configurations outlined in component 7)
9. Tectonics and climate change (interactions between climate change, the ice sheet, and Antarctic tectonism).

**Regional/technical components**
10. Data management (geologic and geophysical data)
11. Technological development (drilling/coring/sampling systems, geophysical data acquisition).

We appreciate fully that it is the responsibility of SCAR to appoint personnel onto the Scientific Research Programme’s committee.

**3. Proposed functions of the programme**

The main function of the programme lies in the acquisition and compilation of “ground truth” geoscience data, and the use of these data in developing a suite of palaeoclimate models (both continent-wide, Southern Ocean-based, and sectorial) for the Antarctic region for significant periods of climate change through Cenozoic times. These periods, detailed in thirteen subsections below, and outlined in Table 2, include:
- late Eocene-early Oligocene cooling,
- Oligocene-Miocene boundary (Mi-1 glaciation)
- middle-late Miocene cooling,
- Pliocene warm periods,
- Pliocene-Pleistocene cooling,
- Quaternary periods of unusual warmth and extreme cold,
- warming since the Last Glacial Maximum,
- Holocene “stable” period, insolation seasonality maximum.

While these activities will concentrate on periods subsequent to the Palaeocene, it should be noted that ACE will also encourage and support palaeoenvironmental data collection from earlier periods that allow us to understand the immediate pre-glacial history of Antarctica. For example, drilling in the Bellingshausen Sea and the Larsen Basin may provide key evidence for the Palaeocene thermal maximum, which would be of direct relevance to ACE in terms of the pre-glacial climate setting of Antarctica.

We have identified the following main programme functions for ACE as:

1. Encouraging and facilitating communication and collaboration among research scientists working on any aspect of the evolution of Antarctic climate. This would be achieved by organizing workshops and symposia to present new results, exchange ideas, share/compile information and coordinate/plan laboratory and field operations. These would be coordinated with the activities of autonomous programmes such as ANDRILL and IMAGES;
2. Advising the research community on the types of geoscience data required for palaeoclimate modelling and effective model-data intercomparison, and critical locations (and ages) for which such data are needed;
3. Providing advice/assistance as needed on technical issues related to geoscience field and laboratory programmes and to palaeoclimate modelling studies (it should be noted that the project will not, and cannot, oversee or manage national or international field or laboratory projects or facilities (other than to help guide the SDLS));
4. Promoting data access and data sharing (and data-contributions to the SDLS, Antarctic data centres, and World Data Centres [WDC]) to facilitate and expedite data syntheses needed for developing new field programmes and enhancing palaeoclimate models. This function includes direct guidance of the Antarctic Treaty-mandated SDLS; and
5. Summarizing and reporting the results of these efforts to the scientific and wider community on an ongoing basis at workshops and symposia. A formal report would be made and presented to SCAR after a 6-year period.

<table>
<thead>
<tr>
<th>Themes</th>
<th>Notes</th>
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<tbody>
<tr>
<td>3.1 Modelling themes</td>
<td>Work in all themes to be constrained/checked by geological data on continent-wide and regional basis.</td>
</tr>
<tr>
<td>3.1.1 Ice sheet modelling</td>
<td>Field-led. Will test hypotheses established from geological interpretations.</td>
</tr>
<tr>
<td>3.1.2 Coupled ice sheet and climate modelling</td>
<td>Process-led. Will in time be extended to coupled ice sheet-climate-ocean-sea ice modelling.</td>
</tr>
<tr>
<td>3.1.3 Coupled ice sheet and sediment modelling</td>
<td>Process-led. To constrain glacial dynamics and glacier characteristics from the sedimentary record. Compare to observed offshore sediment record.</td>
</tr>
<tr>
<td>3.2 Time-based themes</td>
<td>Themes relating to the stratigraphic record, which will then be linked to ice sheet and climate modelling for each period to provide constraints and tests for both stratigraphic and ocean-ice sheet-climate models.</td>
</tr>
<tr>
<td>3.2.1 Eocene-Oligocene transition</td>
<td>This key interval includes the major global cooling event in the Cenozoic era, likely representing an important expansion of Antarctic ice volume. The stratigraphic record is needed from more areas with accessible older strata, as the record is not known well at present, and needs to be related to tectonic reconstructions of the critical ocean gateways (Drake Passage and South Tasman Rise region).</td>
</tr>
<tr>
<td>3.2.2 Oligocene-Miocene boundary</td>
<td>Node in obliquity – Mi-1</td>
</tr>
<tr>
<td>3.2.3 Middle Miocene record</td>
<td>Isotopes show a shift to cooler climates at ~14 Ma, which may represent the intensification of Antarctic Circumpolar Current and thermal isolation of Antarctica from the rest of the globe. This shift is still not well understood and needs to be correlated with proximal palaeo-environmental records from Antarctica and tectonic reconstructions.</td>
</tr>
<tr>
<td>3.2.4 Pliocene record</td>
<td>The early Pliocene includes an interval of significant global warming. Consensus on this much-debated period (i.e., proposed major reduction in ice volume involving significant melting of ice sheets in some areas) requires new offshore proximal records integrated with</td>
</tr>
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advanced modelling. The late Pliocene also requires investigation, as it includes an abrupt cooling that is associated with a major increase in the size of northern hemisphere ice sheets. This introduced a new major control on sea level that may have significantly affected subsequent Antarctic ice sheet fluctuations.

### 3.2 Ice sheet models

#### 3.2.5 Pleistocene intervals of extreme warmth and cold

Work based primarily on Ocean Drilling Program cores has led to the recognition of several stages within the Pleistocene characterized by extreme warmth (e.g. Stage 11, ~400 kyr B.P.) when global ice volume was at a minimum, or cold (e.g. Stage 16, ~600 kyr B.P.) when the ice sheets were larger than during our most recent glacial maximum. Understanding ice sheet behaviour at these times may help us understand the feedbacks that influence the gain of the cryospheric response to Milankovitch forcing.

#### 3.2.6 Last glacial cycle

Integration of ice core, internal ice-sheet layer, and Antarctic margin sediment records is required for full documentation of Antarctic Ice Sheet behaviour through a glacial cycle.

#### 3.2.7 Holocene

Records from shelf basins indicate large changes in sea ice conditions and ice shelf extent during a period of negligible anthropogenic greenhouse gas emissions. This provides an opportunity for understanding natural sources of modern background variability.

### 3.3 Process-oriented themes

#### 3.3.1 Terrestrial landscapes

Using chronological technologies available only in the last decade.

#### 3.3.2 Influence of tectonics on the behaviour of the ice sheet

Involving tectonic evolution, uplift of mountain ranges, changes in heat flow, displacements of landmasses, and isostatic and flexural response to changing ice and sediment loads.

#### 3.3.3 Change in ocean topography & circulation

Involving the history of ocean-basin morphology, opening of gateways and movement of water masses.

#### 3.3.4 Climatic influences on development of the sedimentary record

Tracing transport pathways, from the ice sheet to deep sea, and from interior basins into subglacial lakes and examining interglacial/glacial margins proximal to deep-sea sedimentary processes.

**Table 2. Themes and sub-themes of interest condensed from those identified by the ACE community at the 2001 Erice meeting.**

### 3.1 Modelling Themes

Numerical modelling of former climate and glacial processes is central to the ACE programme. We envisage projects within three areas of glaciological modelling: ice sheet modelling; coupled ice, climate and ocean modelling; and coupled ice and sediment transport modelling.

#### 3.1.1 Ice sheet modelling

Changes to the Antarctic ice sheet affect climate by direct modification to the hypsometry of the Earth’s surface and its albedo and by regulating the transfer of fresh water to and from the oceans. The Antarctic Ice Sheet is also one of the Earth’s major heat sinks. In addition, ice sheets are agents of large-scale erosion and deposition. Therefore, the ice cover of Antarctica acts in numerous ways to affect the environment of our planet’s past, present and future. Because of this, the ability to model the Antarctic Ice Sheet numerically is valuable not only to glaciologists but also to Earth Science in general.

Numerical ice sheet models are usually organised as a 2-D grid or mesh (comprising many individual cells) over the area of ice sheet. Calculations of ice flow are made at each cell based on well-established physical principles. The interaction of ice flux between grid cells describes the time-dependent evolution of the ice sheet to changes in (a) imposed surface mass balance (the inputs and outputs of the ice sheet) and (b) mechanisms internal to the ice sheet. The most important data used as boundary and forcing conditions in an ice-sheet model are subglacial topography and surface mass balance.

Ice-sheet models typically comprise three main components. These are: the temporal evolution of ice thickness, which also incorporates the areal expansion and contraction of the ice sheet; a reduced model of how stresses and velocities vary within an ice mass (the key assumption is that longitudinal stresses are minimal and therefore that a local stress balance exists); and the temporal evolution of the internal temperature field of the ice sheet. In addition, there are many subsidiary models for effects such as isostasy (the deflection of underlying lithosphere to the load of an ice sheet); basal slip of the ice over its underlying substrate; the pattern of snow accumulation on and ice/snow melt from the upper ice-sheet surface; and the effect of temperature on the viscosity of ice.

A second category of large-scale ice-flow models is that of ice shelves (floating ice) and fast-flowing ice streams (which are thought to have many of the features of ice shelves). The physics controlling the flow of ice shelves and streams is more complex than that controlling ice-sheet flow. In particular, longitudinal and transverse stresses are often the dominant components of the force balance. Stress and
velocity fields must therefore be determined simultaneously throughout the entire ice mass (as opposed to the local stress balance discussed above for ice sheets). Longitudinal and transverse stresses are important because ice shelves and streams are characterised by reduced (or, in the case of shelves, zero) basal traction.

A feature of all large-scale ice flow models is the extreme non-linearity of the underlying equations that they attempt to solve. This is a consequence of the empirical law thought to govern ice flow, in which strain rates vary with the cube of applied stress. In addition, there are several other features that introduce non-linearity into the system. For instance, the exponential relationship between the viscosity of ice and its temperature, and the coupling between ice flow and temperature via frictional heat generation.

3.1.2 Coupled Ice Sheet Climate and Ocean Modelling

Most prior modelling studies of ancient Antarctic ice sheets have used empirical parameterizations based on modern climatologies to provide meteorological input (surface mass balance forcing) for the ice sheet model (Huybrechts, 1990; Huybrechts, 1993). While this approach is well suited to testing the sensitivity of Antarctic ice sheets to changes in bedrock topography and/or different temperature and precipitation scenarios, it does not explicitly test the response of the coupled climate-cryosphere system to evolving boundary conditions and climatic forcing over long, geologically relevant time scales. An alternative approach uses a climate model, responding to changes in palaeogeography, bedrock elevation, atmospheric CO₂, and orbital cycles to provide the ice sheet model mass balance forcing.

Several coupled climate/ice-sheet modelling schemes have been developed and tested. Until recently, however, these models have mostly been applied to the Northern Hemisphere Quaternary glacial cycles. One approach uses a climate model component that is computationally efficient enough to run continuously over long time intervals. Energy Balance Models (EBMs) can be run continuously for millions of model years, but they provide only simplistic representations of climate. For example, there is no explicit simulation of precipitation, which is of obvious importance to understanding long-term ice sheet dynamics. Another scheme uses Earth Models of Intermediate Complexity (EMICS), with a more sophisticated representation of the atmosphere and a dynamical ocean component.

Ice sheet models are perhaps most well known in the context of predicting ice-sheet response to climate change. In particular, much work has been done on the response of the present-day Greenland and Antarctic Ice Sheets to anthropogenic warming in the coming millennia, and to past changes over the last glacial-interglacial cycle. These models can also be used to examine ice sheet changes much further back in time, although they have yet to be used extensively for this purpose.

Use of numerical ice sheet models to test geologically-derived hypotheses concerning the Antarctic ice sheet is novel and timely given the ability of the models and the abundance of geological data now available.

![Figure 3. Schematic representation of the coupled GCM-ice sheet modelling scheme used by DeConto and Pollard (2003a) in their simulations of Paleogene East Antarctic ice sheets.](image-url)
annual temperature and precipitation generally agree with observations. Despite some seasonal deficiencies around the coast, these models are capable of producing realistic mass-balance over Greenland and Antarctica, and can be used to model the three dimensional response of polar climate to a wide range of forcing scenarios. Regional Climate Models (RCMs) offer even higher resolution than GCMs (a few tens of km), with the potential to resolve regional-scale variations around the coast and the margins of ice sheets. RCMs are now being applied over present Antarctica, and they have great potential to solve regional palaeoclimatic problems. However, at the scale of Antarctica, they approach the computational limits of GCMs. Because they represent a restricted spatial domain, they do not account for the effects of global-scale climate change/forcing unless it is prescribed or provided by a prior GCM simulation.

Although GCMs can be coupled with dynamical ice sheet models, even those GCMs with simple, non-dynamical (slab) ocean components are too computationally demanding to run for more than a few decades at a time. For time-continuous problems over orbital or longer timescales, asynchronous GCM-ice sheet coupling scheme can be used to capture the important feedbacks between the Antarctic ice sheet and the atmosphere, while maintaining the computational efficiency required to run long (10^4-10^6 year) simulations. In most asynchronous coupling methods, the ice sheet model is run continuously while the GCM is run just often enough to capture the essence of the relevant forcing (i.e., every several thousand years to account for changing orbital cycles). Some methods use a “matrix” of prior GCM simulations, using canonical combinations of boundary conditions spanning the full range anticipated in the long-term simulation. Interpolated climatologies from the suite of GCM simulations are then used to drive continuous ice sheet simulations. These techniques have recently been successfully used to simulate the initial (Paleogene) history of the East Antarctic Ice Sheet (Figs. 3 and 4) and are now being applied to other time periods throughout the Cenozoic.

These models offer an unprecedented opportunity to test the possible response of the Antarctic climate-cryosphere system to evolving boundary conditions and climatic forcing. However, rigorous comparison with the geologic record will be required to verify the results and place them in the context of actual palaeo-climatic and palaeo-environmental changes. In addition, detailed and accurate boundary conditions, based on geologic and geophysical data, will be required for many different time periods in the geologic past. These include reconstructions of global and Antarctic palaeogeography (plate position, shorelines, topography, bathymetry and vegetation). One role of ACE is to facilitate both the compilation of boundary conditions to be used for the latest generation of climate-ice sheet models, and to provide data for the validating the model output.

3.1.3 Coupled ice sheet and sediment modelling

Conditions at the base of continental ice sheets can be important in the long-term evolution of ice and bedrock, and may be critical in explaining some aspects of ice-sheet behaviour. Two main factors are basal hydrology and the presence of deformable sediment between bedrock and ice. Widely distributed deforming sediment may play significant roles in the large-scale morphology and long-term evolution of ice sheets (Alley et al., 1987a,b; Alley, 1991; MacAyeal, 1992; Clark, 1994; Clark et al., 1996; Clark and Pollard, 1998). Deforming sediment is observed today
below many mountain glaciers (Boulton, 1996) and fast-moving West Antarctic ice streams (Kamb et al., 2001), where the lubrication due to sediment enables extremely high velocities compared with the surrounding ice.

Furthermore, sediment drifts around the margins of major ice sheets are one of the few surviving indicators of past ice sheet history. The observed Cenozoic deposits on continental shelves and slopes around Antarctica (Cooper et al., 1995; Barker et al., 1998; Davey et al., 2001; Naish et al., 2001) provide opportunities for very rich data-model comparisons for the period since the onset of major Antarctic glaciation in the Oligocene. Some of the broader questions amenable to this approach are as follows:

1. Did basal sediment influence the sizes and profiles of early Antarctic ice caps and the growth and subsequent variations of continental-scale ice sheets?

2. What is the long-term continental inventory of sediment for Antarctica? How much of the off-shore drifts are composed of pre-existing regolith vs. ice-quarried bedrock till? Do the offshore sediment drifts represent the bulk of the sediment transported to the coast since the Oligocene, or only a small fraction with the rest dispersed to the deeper ocean? These questions address long-term erosion rates and landscape evolution caused by Antarctic glaciation, with consequences for weathering and CO₂ drawdown (Robert and Kennet, 1997). An analogous inventory for North American ice sheets and Atlantic deposits of the last 3 Ma has been made by Bell and Laine (1985).

3. Has the distribution of sediment affected patterns of erosion of Antarctic bedrock and thus the observed bedrock morphology today?

Co-evolution of Antarctic ice and sediment can be modelled over continental or regional domains by a coupled climate-ice sheet-sediment model. A model of deforming subglacial sediment can be coupled to the ice sheet model to account for bulk sediment thickness and transport by horizontal shear, induced by the basal-ice shear stress when basal temperatures are at the melt point. New till can be accounted for by the quarrying action of ice on bedrock. In ice-free regions, the model till can be eroded and transported fluvially following the steepest downhill path to the coast.

A weakly non-linear rheology has been used for subglacial deforming sediment (Clark and Pollard, 1998; Jenson et al., 1996), although a more nearly plastic rheology has been deduced recently under West Antarctic ice streams (Kamb et al., 2001), which (just like its non-linear counterpart) may yield substantial sediment transport due to the vertical migration of the failure plane (Tulaczyk, 1999). Sediment can also be transported via entrainment into the lower ice layers, but the relative contribution of this process is uncertain (Hildes, 2001).

In addition to deformation in the subglacial till layer, transport of sediment as suspended or bed load by subglacial streams or channels can contribute significantly to the overall sediment flux, especially near the margins of ice sheets and glaciers in summer, when surface melt provides a plentiful supply of meltwater to the base. This process can dominate the sediment flux at the snouts of temperate glaciers discharging into the fjords and Gulf of Alaska today (Hunter et al., 1996a; 1996b). We will add simple model components for basal hydrology regimes and subglacial fluvial sediment transport, and investigate their role versus subglacial till deformation over long time scales, and whether each regime leaves recognizable depositional signatures in the observed marginal sediments. This analysis should be very significant for periods during the early phases of ice sheet history when it is thought to have been temperate and then, later, polythermal (Powell et al., 2000; 2001).

The ice sheet-sediment model can span the entire Antarctic continent using a ~40 km polar stereographic grid, or can be run regionally for particular drainage basins with resolutions down to ~10 km. The finer resolution is necessary for the western Ross Sea region to assess ice transport from East Antarctica through deep Transantarctic Mountain valleys.

Coupled ice sheet and sediment modelling is particularly potent as a glaciological tool when model results are linked to measurements. Such model-data comparisons can be used to determine the locations of major sediment accumulation, predict Cenozoic age-depth relations, identify sediment provenance, clay mineralogy and grain sizes, assess orbital-scale variations within the sedimentary record, explain observed present-day bed roughness, and predict amounts and persistence of sediment in the locations of major subglacial lakes such as Lake Vostok (see link with SALE programme, p22).
3.2 Time-Based Themes

Several long-term drilling programmes of 10 to 20 years are necessary to answer the open questions concerning Antarctic climate/ice sheet evolution. The ANTOSTRAT Program started this long-term drilling program with the submission of five drilling proposals. The successor to the ANTOSTRAT Programme, the ACE Programme, will continue to encourage the two remaining IODP proposals to drill the Wilkes Land and Ross Sea margins.

The ACE programme will also promote and encourage new drilling expeditions using both IODP and mission specific platform technologies, such as shallow drilling (SHALDRIL) or sea ice and ice shelf-based drilling (ANDRILL) techniques, now in the testing stages. In sectors of the Antarctic continental shelf, such as the Wilkes Land margin, prograding forested strata outcrop at the seafloor allowing older strata to be cored. A transect of shallow (50-150 m penetration) sites across the Wilkes Land continental shelf could achieve the objectives related to obtaining the record of the timing of glacial onset (Eocene-Oligocene?), and the record of large fluctuations in the glacial regime (Miocene?). Other locations around the Antarctic continental margin need to be identified for a coordinated drilling effort.

Earth Science research along the Antarctic continental margin has concentrated on the areas traditionally visited by ship, such as the Antarctic Peninsula, Ross Sea and Prydz Bay regions, or areas easily accessible by aircraft from the different international bases. Limited access to many sectors of the Antarctic margin has resulted in areas having only reconnaissance-type data sets. ACE will promote, encourage and, when necessary, coordinate the collection of data by different national programs in less explored sectors of the Antarctic margin that show potential for identification of new Eocene-Oligocene and mid-Oligocene targets. Work will be encouraged in areas where the potential exists for older strata at shallow depths both on the continental shelf and deep sea, and where there may also be continuous seismic reflectors across the margin that favour the connections between the proximal and the distal records.

The central goal of ACE is to coordinate the integration of improved geological data and Antarctic palaeoclimate modelling at different time slices, including the Eocene-Oligocene onset of glaciation and the mid-Oligocene transition. ACE will be active in searching for new drilling platforms and capabilities. ACE will follow the development of a proposal by the European Polar Board of ESF to construct a deep-drilling research ice-breaker, the Aurora Borealis, dedicated to polar research. Presently the ice-breaker is scheduled to operate in the central Arctic Ocean all seasons of the year. ACE should take an active role in promoting the inclusion of Antarctic margin expeditions in icebreaker operations.

3.2.1 Eocene-Oligocene events

The Eocene and Oligocene epochs are key time intervals in the development of the Antarctic Ice Sheet. Based on deep-sea “proxy” records (e.g., oxygen isotope, global sea-level, ice-rafted debris, etc.), the Eocene and Oligocene represent a time of global cooling that culminates in the development of the first Antarctic ice sheet and an important expansion of Antarctic ice volume. The Eocene (~52 to ~34 Ma) is characterized by a global cooling trend that culminates at the Eocene-Oligocene (~34 Ma) boundary with global cooling during the remainder of Cenozoic era. The mid-Oligocene transition (~30 Ma) represents another major cooling event, which is associated with a major eustatic fall that likely represents a large Antarctic ice sheet expansion.

The ACE program envisions the following questions to be of first-order interest with respect to the Eocene-Oligocene transition:
1) What is the time of first arrival of grounded ice along different segments of the Antarctic shelf?
2) What is the temporal and spatial evolution of the Antarctic ice sheet through the Oligocene Epoch and across the mid-Oligocene transition?
3) Under what boundary conditions did the ice sheet reach the continental shelves around Antarctica?
4) Under what boundary conditions did the ice sheet expand during the mid-Oligocene transition?
5) What is the history of water mass evolution during Eocene-Oligocene and mid-Oligocene times?
3.2.2 Oligocene-Miocene boundary Mi-1 glaciation

The Oligocene-Miocene boundary marks a significant transition in the development of the Antarctic cryosphere, where small dynamic ice sheets of the late Oligocene rapidly expanded to continental scale in the early Miocene. The transition is recorded in benthic foraminiferal δ18O records as a positive 1.0 per mil shift, representing the first of the Miocene glaciations (Mi 1). Mg/Ca reconstructions imply little or no change in temperature and that the ice volume increase was equivalent to 90m of sea level lowering (based on a Late Quaternary calibration). Sediment cores recovered in Western Ross sea indicate orbital modulation of the ice sheet during the transition, and corroborate proxy ocean records (Naish et al., 2001). It is argued that the Mi-1 event occurred as a consequence of a unique set-up of orbital parameters during an interval of declining CO2 that led to a prolonged period of cold summer orbits, during which time a large ice sheet established. This has important implications not only for modelling the climate drivers, but also for timescale development, as the orbital configuration has been used to astronomically calibrate the age of the Oligocene-Miocene boundary (Shackleton et al., 2000). However, a new calibration based on an integrated chronology for western Ross Sea drillcores seems to preclude the use of astrochronology. Future work in this area includes:

- Regional correlation of the Mi 1 event along the Transantarctic Mountain front in Victoria Land Basin through integration of drillcore and newly acquired seismic data.
- Analysis of the vegetation records in sedimentary cycles spanning the Mi1 event to constrain terrestrial climate changes.
- Ice sheet dynamics across the Oligocene-Miocene boundary will be modelled using coupled GCM-Ice Sheet model and the sensitivities of CO2 and orbital configuration assessed.

3.2.3 Middle Miocene record

The middle-to-late Miocene period represents a time of significant ice sheet expansion in Antarctica. The Zachos et al. (2001) deep sea stable isotope record shows a mid-Miocene “climatic optimum” centred at about 15 MA, followed by strong enrichment of oceanic δ18O over the next 6 Myrs. It is during this interval that East Antarctic glacial ice is thought to have evolved into a major and permanent ice sheet. One outstanding question revolves around the notion that this transition represents ice sheet development in East Antarctica. New seismic-stratigraphic data from the Ross Sea reveals at least 5 major intervals of ice shelf advance and retreat in the middle Miocene (Chow and Bart, 2002). Much of this ice is sourced in West Antarctica, suggesting the presence of a large and dynamic ice sheet in a part of Antarctica that is conventionally thought to be of lesser importance at this time. The presence of significant and dynamic ice in East versus West Antarctica in the middle and middle-to-late Miocene is a question that ACE participants plan to answer via a combination of modelling coupled with geophysical and geological analysis.

One of the most vexing questions concerns the stability of Antarctic climate and ice during the late Miocene. A variety of indicators from the McMurdo Dry Valleys suggest the maintenance of stable, hyper-arid, cold-desert conditions since 13 MA (Marchand et al., 2002). However, microfossil studies in the Transantarctic Mountains, and sedimentological work within Antarctic fjords is suggestive of significant climatic dynamism extending from the late Miocene through the Plio-Pleistocene. A degree of heterogeneity in climate response is expected considering the size and diverse landscapes of Antarctica. Yet the existing state of knowledge is sufficiently contradictory that the community has evolved into two camps when it comes to describing late Neogene conditions in Antarctica: the stabilists and dynamicists. This is another obvious target for dedicated analysis using a combination of climate and ice sheet simulations with careful assessment of the paleontologic and sedimentologic data from around Antarctica.

3.2.4 Pliocene record

The Pliocene Epoch is a critical time for understanding the nature of the Antarctic ice sheet as IPCC projections of global temperature rise suggest that we will reach Pliocene levels...
within the next hundred years. Geological evidence combined with modelling is needed to determine the size of the ice sheet and its dynamic behaviour. Indirect evidence, such as sea level changes and ocean floor sediments, suggest that ice volumes were subject to cyclical variability. It is believed that, since Northern Hemisphere ice sheets were not fully developed, sea level changes were driven by fluctuations of the Antarctic Ice Sheet. Many scientists believe that it was the relatively unstable West Antarctic Ice Sheet (WAIS) that was responsible for these changes, but the role of the much larger East Antarctic Ice Sheet (EAIS) remains controversial.

Key to this argument is the timing of the transition of the EAIS from a polythermal, dynamic condition to a predominantly cold stable state. Two opposing and vigorously defended views prevail. The long-standing view is that the EAIS became stable in mid-Miocene time, evidence of which is primarily from the longevity of the landscape and well-dated surfaces and ash deposits in the Dry Valleys region along the western border of the Ross Sea. Another controversial view is that terrestrial glacial deposits, known as the Sirius Group, scattered through the Transantarctic Mountains, indicate dynamic ice sheet conditions as recently as Pliocene time, based on diatom biostratigraphy and preserved vegetation. The latter viewpoint is supported by work on deposits known as the Pagodroma Group along the flanks of the largest outlet glacier, the Lambert, on the continent. Each argument is internally consistent and the biggest challenge is to reconcile the differing views. If the EAIS was indeed subject to major fluctuations until Pliocene time then, taking into account IPCC projections, we have cause to be concerned about the possibility of the EAIS becoming unstable within the next century.

The Pliocene question is best addressed by (1) identification of suitable near-shore late Miocene-Pliocene sedimentary basins to gain a high-resolution record of ice sheet fluctuations, as is currently planned in the McMurdo Sound area by ANDRILL; (2) improved dating of the controversial Sirius Group glacial deposits onshore; (3) discrimination of glacial processes and products under different climatic and tectonic regimes; and (4) ice sheet numerical modelling taking advantage of known ice sheet limits at critical times.

3.2.5 Pleistocene glacial cycles and intervals of extreme warmth and cold

Studies of Antarctic ice cores show that Pleistocene climate variability in the different sectors of the southern high latitudes has occurred out of phase (Masson et al., 2000; Steig et al., 1998). This raises questions about the response of the southern high latitudes to external climate drivers, such as orbital insolation, solar variability, and internal amplifiers such as thermohaline circulation and carbon-cycle changes (Rahmstorf, 2002) that operate at both Milankovitch and millennial-decadal time scales. These questions highlight a need for appropriate time series of climate variability from all sectors of the Southern Ocean. Recovery of sediment sequences with expanded Pleistocene sections, such as those from beneath the McMurdo Ice Shelf as proposed by the ANDRILL programme, will permit the study of the structure and timing of glacial and interglacial cycles in the Southern Ocean at millennial timescales that extend well beyond the last four major climate cycles. In addition, several groups organized under the IMAGES programme have proposed to collect long piston cores for Pleistocene research from several different sectors of the Southern Ocean. With new high resolution Pleistocene time series from both the Antarctic margin and offshore sites, we can determine if the abrupt climate changes that have been documented from the Atlantic and Indian sectors (e.g. Cortese and Abelmann 2002, Kanfoush et al. 2002, Kunz-Pirrung et al. 2002, Mazaud et al., 2002, Bianchi and Gersonde, in press), and in polar ice cores (e.g., Dansgaard et al. 1993) have also occurred in the Pacific basin.

During the last decade, many palaeoceanographic studies focused on millennial climate variability. They show that the thermohaline circulation underwent instabilities (Charles et al., 1996; Vidal et al., 1997) linked to climate variability. The palaeoceanographic record documents mainly the North Atlantic Ocean, and modelling experiments have explored the variability of North Atlantic Deep Water formation forced by fresh water flux from ice surge events (Stocker and Wright, 1991; Manabe and Stauffer, 1997; Ganopolski and Rahmstorf, 1998, 2001). However, Keeling and Stephens (2001) emphasise the importance of Southern Ocean sea-ice during glacial periods and suggest that the glacial “on/off” modes of global circulation were linked to a very different deep-water formation in the Southern Ocean. This conceptual approach is consistent with Last Glacial Maximum isotopic data indicating a
strong bathyal front between intermediate and deep waters (Kallel et al., 1988; Herguera et al., 1992; Slowey and Curry, 1995) and deep-water temperatures that were near the freezing point (Duplessy et al., 2002; Schrag et al., 2002). At the moment there are only a few records that document deep Southern Ocean variability during glacial stages 2 and 3 (Ninneman and Charles, 2002). Additional cores to address these issues at this time period will be recovered as part of the IMAGES and ACE science plans.

Work proposed under IMAGES and ACE will also help us document the Pleistocene stability of the West Antarctic Ice Sheet (WAIS) as well as areas of the East Antarctic Ice Sheet (EAIS) that are grounded below sea level. We will reconstruct meltwater events based on reconstructing salinity and sedimentological analyses (grain-size, ice-raftered debris distribution) from sites sensitive to the stability of the WAIS and EAIS. This will improve our understanding of the vulnerability of the ice sheet during Pleistocene climatic optima and its potential impact on 1) global thermohaline circulation as a southern source of melt water discharge (e.g., Mikolajewicz, 1998), and 2) sea level rise well beyond present sea level stand, e.g., during marine isotope stages 9 and 11 (Rohling et al., 1998). A draw-down of the WAIS would increase sea level by 5-7 m and thus have a major impact on life on Earth. This estimate ignores possible contributions from less stable portions of the EAIS.

3.2.6 Last Glacial Cycle and Deglaciation

There are currently 3 different ideas about the onset of deglaciation: 1) changes in the water balance of the North Atlantic, the source region for much of the global thermohaline circulation, serve to propagate the deglacial signal worldwide (e.g., Bender et al., 1994); 2) changes in the Southern Ocean, as recorded in some ice cores, lead deglaciation as seen in Greenland ice (e.g., Blunier et al., 1998); and 3) synchronicity in the timing of high latitude climate change in both hemispheres, and with some tropical records suggests that tropical forcing is a key initiator of deglaciation (e.g., Denton et al., 1999; Seltzer et al., 2002; Visser et al., 2003). It may seem surprising that this controversy has not already been settled. The most important confound for establishing synchronicity, or its absence, among the available paleoclimate records revolves around chronology development. It is notoriously difficult to date LGM ice layers and sediments to an accuracy of better than 1 to 2 kyr. It is also difficult to separate local climate or geomorphic signals from large transformations that are regionally or globally important. For example, based on sediment records from lakes Titicaca (Bolivia) and Junin (Peru), Seltzer et al. (2002) suggest that southern tropical warming began up to 5,000 years before significant deglacial warming in the Northern Hemisphere and in Antarctica. If correct, this is strong evidence for a tropical trigger. However, Clark (2002) suggests that the Andean lake records cannot be appropriately compared with most North American lake records of deglaciation because the early formation of pro-glacial lakes in the Andes traps sediment and obscures the timing of all subsequent deglacial activity in the Junin and Titicaca basins. What is needed to resolve the deglacial synchronicity issue are better records from rapidly-deposited deglacial sequences across a range of latitudes and longitudes in the Southern Ocean, that use sedimentary or glacial outlet indicators to directly track regional climate systems. Currently there are too few precisely dated records of the LGM from the Southern Ocean.

3.2.7 The Holocene

The global instrumental record establishes the existence of a relatively small number of fundamental modes of coupled air-sea interaction that are collectively responsible for most known climate variability (or instability) at interannual to multi-decadal timescales. Chief among these coupled modes are the El Niño-Southern Oscillation (ENSO) system, Pacific Decadal Oscillation, Arctic Oscillation, North Atlantic Oscillation, Tropical Atlantic Dipole, and Southern Ocean (or Antarctic Circumpolar) Wave. All of these climate systems involve ocean thermal anomalies, atmospheric feedbacks, and significant climate responses on land. Although the instrumental record informs us about the existence and modern expression of these coupled ocean-atmosphere systems, it is not sufficient to resolve past changes in their dynamics and impacts or the relative importance of centennial to millennial climate phenomena. The palaeoclimate record is the only known source of information on the long term behaviour of these climate pacemakers. However, existing knowledge of Holocene variability is heavily
biased towards terrestrial archives. There is very little information about the global ocean background climate state against which we observe and define the recent dramatic warming trends, particularly in the Southern Ocean. Nevertheless, rapidly accumulating deposits exist along the continental margin of Antarctica, and a few sites further north, that are suitable for reconstructing Holocene ocean conditions at decadal and possibly interannual timescales. The science issues to be addressed include the following:

• Many researchers now believe that the link between high and low latitude climate change on interannual and decadal timescales is best expressed as the so-called “Circumpolar Wave”, an apparent propagation of sea surface temperature anomalies and atmospheric pressure patterns forced by tropical ocean variability. Existing instrumental records of this possible mode of global climate variability are too short to provide meaningful insights about the mechanisms involved. Long, annually resolved sediment records are required to test the idea that the tropics and high latitudes are connected through the same basic physical processes that govern ENSO cycles.

• How does solar forcing influence the distribution of sea ice and primary production in the Southern Ocean? Pronounced solar cycles with periods of 200 and 80 years have been identified in cores from the Antarctic Peninsula. The cause is not yet known, nor is the full aerial extent of their manifestation.

• Although some ice cores show only minor variability in the mid-Holocene, many terrestrial sites and some polar marine sites show large excursions during the mid-Holocene. In some cases these excursions, due presumably to changes in insolation seasonality, are larger than the full glacial to interglacial excursion. Southern Ocean sea ice and winds appear highly sensitive to insolation forcing and IMAGES cores can be used to examine forcing and response during periods of the Holocene when atmospheric $pCO_2$ levels varied only slightly.

3.3 Process-Based Themes

3.3.1 Terrestrial landscapes

The landscape evolution of ice-free areas, backed up by recently developed geochronological techniques, opens up a new window on the climatic and glaciological processes associated with the evolution of the Antarctic Ice Sheet. The record, extending back to the Eocene/Oligocene transition, is based on argon/argon dating ($^4\text{Ar}/^3\text{Ar}$) of glass shards in volcanic ash in surficial deposits and surface exposure dating using cosmogenic isotopes, mainly in the Dry Valleys of the Transantarctic Mountains (Sugden et al., 1995; Nishizumi et al., 1991). The latter technique has demonstrated that some landforms, and even till-covered glacier ice, are relict from Miocene time (Marchant et al., 2002). The technique also has the potential to date ice sheet thinning during the Holocene (Stone et al., 2003).

Most detailed work has been carried out in Victoria Land in the Ross Sea sector of the Transantarctic Mountains, where the terrestrial record agrees well with the offshore CIROS and Cape Roberts Project cores. It is now important to establish how representative this record is, and to extend the approach to other sectors of Antarctica with exposed mountains and coasts. In East Antarctica priorities might include the Lambert basin, the Atlantic and Indian Ocean coastal sectors and the Transantarctic Mountains bounding the Weddell Sea embayment. In West Antarctica, priorities are mountains in the Ross Bellingshausen Sea sectors, the Ellsworth Mountains and the Antarctic Peninsula.

Focus on terrestrial landscape evolution can provide climatic and environmental constraints at different times. The existence of pre-glacial fluvial landforms with superimposed tills reflecting the advance of small, warm-based local glaciers into beech forests, as is the case of Sirius Group deposits, may well reflect the transition to glaciation of Antarctica at the Eocene/Oligocene transition. The geochemistry of regolith and the nature of tundra polygons pre-dating ice sheet glaciation tell of conditions during the growth of the maximum mid-Miocene Antarctic ice sheet. Landforms, striations and meltwater channels on mountain summits constrain the thickness, direction of flow and the basal thermal regime of this maximum ice sheet. Pliocene deposits in several coastal areas of East Antarctica and the tip of the Antarctic Peninsula constrain relative sea level and climate at the time. Mountains protruding through the thinner margins of the ice sheet can be used as dipsticks to constrain the
morphology of the ice sheet during Pleistocene maxima, a point of particular relevance to establishing the thickening associated with the grounding of the Ross and Filchner-Ronne ice shelves (Stone et al., 2003). Finally, the terrestrial record can establish the history of Holocene thinning or variability of individual glacier basins and ice shelves, thus providing essential information on the Holocene trajectory of sea level and the Antarctic Ice Sheet against which to judge modern changes. The exciting prospect is of a firmly dated and spatially-extensive terrestrial record of landscape evolution for use in the development of models of ice sheet dynamics and evolution.

3.3.2 Influence of tectonics on the behaviour of the ice sheet

Modelling of Oligocene and Miocene climates requires accounting of tectonic evolution, including events such as opening of ocean gateways and uplift of mountain ranges. A widespread idea is that ice sheet development on Antarctica has been associated with the opening of ocean gateways that have enabled the Antarctic Circumpolar Current to isolate the continent. The critical gateways lie to the south of Tasmania and in Drake Passage (Barker and Burrell, 1977; Shipboard Scientific Party, 2001). Published estimates suggest that the Tasman gateway opened at the end of the Eocene (~34 Ma) and that a deep-water pathway through Drake Passage was established at the end of the Oligocene (~23 Ma), but further work is needed to refine and improve constraints on these estimates.

The Transantarctic Mountains, with maximum elevations >4 km, buttress the modern East Antarctic Ice Sheet and form the boundary between it and the West Antarctic Ice Sheet. However, when considering ancient ice sheets it is important to take account of changes in elevation of this 2000 km-long mountain range. Another important mountain range extends along the spine of the Antarctic Peninsula, which has a central plateau at an elevation of about 2 km along most of its 1000 km length. This mountain range forms an important climatic divide, with temperatures about 6°C warmer on the Pacific margin compared with points at the same latitude on the Weddell Sea margin (Reynolds, 1981). Topographically-forced snow accumulation over the Antarctic Peninsula results in a net surface mass balance that is more than three times the Antarctic average (Vaughan et al., 1999), and highlights the possibility that the Transantarctic Mountains might have been a focus for accumulation and ice sheet nucleation in past climates that were warmer and wetter than today. Apatite Fission Track data suggest that exhumation (and probably uplift) of the Transantarctic Mountains began at about 55 Ma, probably at a rate of about 200 m/Myr for the first 10-15 Myr (Fitzgerald, 1992; 2002). The timing of uplift of the Antarctic Peninsula remains uncertain (Elliot, 1997). Further work that better constrains the timing and rates of uplift of these mountain ranges, and others such as the Gamburtsev Mountains in central East Antarctica, would contribute to the objectives of ACE.

There is increasing evidence that subglacial geology has an important influence on the location of fast glacial flow pathways (e.g. Retzlaff et al., 1993; Larter et al., 1997; Bell et al., 1998; Anandakrishnan et al., 1998). There is also debate about the extent to which subglacial tectonic and volcanic events affect the basal conditions and stability of the West Antarctic Ice Sheet (Blankenship et al., 1993; Bentley, 1993). Thus, geophysical investigations that improve knowledge of subglacial and continental shelf geological features also contribute to ACE objectives.

Accurate models of Quaternary ice sheets need to take into account the flexural response of the lithosphere to changes in ice load. On longer time scales models also need to take into account changes in loading due to erosion and deposition of sediments (ten Brink et al., 1995). To model the flexural response of the lithosphere correctly, estimates of regional variations in its effective elastic thickness are required. In the absence of any direct evidence (e.g. measured flexure in response to a volcanic load of known age) such estimates must usually be based on studies of the tectonic and thermal history of the lithosphere (e.g. Stern and ten Brink, 1989).

3.3.3 Tectonics and climate: the influence of palaeo-seaways

Almost three decades ago Kennett (1977) proposed that a major cause of the Cenozoic evolution of both Antarctic glaciations and global palaeoceanography was the tectonic opening of Drake Passage and a passage south of Australia, which were necessary for the initiation of Antarctic Circumpolar Current (ACC) (Lawver and Gahagan, 1998). This dramatic climate shift
is marked by an abrupt change in \(^{18}\)O during the Eocene-Oligocene transition at about 33 Ma that led to the first ice sheets developing on Antarctica. The opening of these seaways occurred during the Early Oligocene, although the precise timing is not well constrained. The associated magnetic anomaly observed in the Scotia Sea is chron C10 (29 Ma), but there is a significant segment of the ocean floor between this anomaly and the continental margins without magnetic anomalies (Tectonic Map of the Scotia Sea, 1995). Whereas the oceanic circulation during the Mesozoic was tranquil under the influence of equitable climates and oceanic thermohaline homogeneity, Cenozoic climate and oceanic circulation increasingly deteriorated (Berggren and Hollister, 1977). A latitudinal thermal heterogeneity caused by high latitude cooling and accelerated surface and bottom water circulation in the oceans characterizes the Cenozoic climate.

The real influence of Antarctic tectonics through the opening and closing of seaways on this climatic evolution is still a subject of debate. Prior to the development of permanent Antarctic ice sheets, a shallow seaway may have existed between East and West Antarctica in Early Cenozoic, although its ability to influence circulation patterns is not well established (Lawver and Gaehagan, 1998). A primitive passage may have also existed through the northern tip of the Antarctic Peninsula into Powell Basin before the opening of Drake Passage (Lawver et al., 1992). The tectonic fragmentation of the continental bridge that existed between South America and the Antarctic Peninsula was, however, the most probable cause for the development of deep seaways and the setup of the ACC. The timing and significance of these tectonic events is still a subject of debate, but most authors agree that it had profound effects on the evolution of the Cenozoic climate. One important objective within ACE will be to investigate the change scenarios of Cenozoic palaeo-seaways around Antarctica and to assess the influence of this on the climate evolution.

3.3.4 Climatic influences on development of the sedimentary record

Although our knowledge about glacial and glacimarine sedimentary processes has advanced significantly over the past 15-20 years, quantitative sedimentological models for glacimarine systems remain rare. Those that are available involve relatively simple algorithms that describe a particular process such as: sediment deformation in a subglacial bed, subglacial water flow (and recently, supercooling), submarine jet discharge, particle settling from turbid overflow plumes, turbidity currents, debris flows, ice shelf and iceberg rafting, and debris incorporation into sea ice with subsequent rafting (e.g. Iverson et al., 1998; Alley, 1992; Gordon et al., 2001; Alley et al., 1998; Morehead and Syvitski, 1999; Harris and Wiberg, 2001; Hill et al., 1998; Mohrig et al., 1999; Dowdeswell and Murray, 2000). None of the glacimarine models are integrated and few, if any, are linked to forcing variables such as glacial processes, marine currents, and variability in biogenic productivity, climatic changes, tectonism, etc. Furthermore, many other processes are still unaccounted for, and appropriate input variables, sediment fluxes, magnitudes and rates of processes, and feedbacks and leads or lags are unknown or poorly constrained. If we are to gain a better understanding of the past environmental changes in Antarctica, we need to establish reliable models based on a strong understanding of glacial and marine processes and how they interact spatially and temporally to construct those records.

Other branches of marine sedimentology and stratigraphy are in the process of establishing quantitative modular models, experimental scaled models and larger-scale sequence stratigraphic models (e.g. Paola et al., 2001). The models are being designed so that ultimately they can be used with climatic input variables and have an output that constructs a sequence stratigraphic package on a continental margin. The glacial and glacimarine communities, specifically those conducting research in Antarctica, need to start such model construction. By doing so, in the future, real sedimentary architecture and stratigraphy of the continental shelf may be compared with that generated synthetically using known input variables so as to better constrain how the real succession may have formed. The models could also help (i) constrain glaciological and hence climatic models, (ii) constrain interpretations of glacial fluctuations on “high” resolution timescales, and (iii) predict the best drilling sites/targets for future drilling initiatives, which
ultimately will provide the data to constrain the models more reliably.

It is only by using these types of modelling capabilities that we can hope to discriminate eustatic signals from glacial signals in continental shelf successions. That is because these types of continental margins are very complex in the factors that force and drive marine sedimentary packages (Powell and Cooper, 2002). In this setting accommodation space, package geometries and facies motifs are dependent on the temporal and spatial interaction of tectonic subsidence, glacial isostatic loading and unloading, changes in two base-levels of glacial advance-retract and sea level rise-fall cycles, glacial and non-glacial erosion, sediment fluxes and accumulation rates, and the relative rates, and lead and lag times of each of these factors.

4. Time-line and milestones

Advance scheduling of workshops and symposia, and special sessions at major conferences, is important for fostering collaboration, exchange of ideas and further planning. The ACE steering committee will develop and maintain a schedule of such meetings extending forward at least 3 years. We have already undertaken five of the nine meetings proposed in our outline bid (assessed by SCAR XXVII in Shanghai):

1. June 2002; ACE workshop on palaeoclimatology modelling, Amherst, USA.
2. July 2002; Antarctic palaeoclimatology session at Western Pacific AGU meeting, Wellington, New Zealand.
3. July 2002; Symposium at SCAR XXVII in Shanghai, China.
4. December 2002; ACE session at Fall AGU meeting in San Francisco, USA.
5. April 2003; ACE outreach meeting EU-AGU-EGS in Nice, France (ACE flyer distributed).
6. April 2003; ACE working group meeting after EUG-AGU-EGS in Nice, France.
7. December 2003; ACE session at Fall AGU meeting in San Francisco, USA (convened by Tony Payne, David Pollard, Martin Siegert and Robert DeConto).

The schedule for the year (prior to ACE becoming a Scientific Research Programme) will include the following meetings:

8. July 2004; ACE contributions to the SCAR XXVIII Open Science Meeting, Bremen, Germany.
9. July 2004; ACE workshop at Bremen SCAR Meeting (1-day). This workshop follows the SCAR Open Science Meeting and will allow the geosciences community to respond to recommendations and to begin to prepare group science proposals to pursue ACE activities.
10. December 2004; ACE session at Fall AGU meeting in San Francisco, USA.

The tasks, deliverables and time-lines we envisage are outlined in Table 3. This should be viewed as a guide, as it is difficult to be prescriptive in charting future progress in research.

<table>
<thead>
<tr>
<th>Theme</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
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<tr>
<td>MODELLING - nested regional &amp; continental models</td>
<td>Workshop on the use of ice sheet and climate models, in Boston.</td>
<td>Completion of first regional model (Prydz Bay).</td>
<td>Completion of regional model (TAM-McMurdo).</td>
<td>Linked sectorial and continental model for EAIS.</td>
<td>Publish state-of-the art report on data and modelling AIS history and behaviour from a perspective of both long term (10^5 to 10^6 years) and short-term (1 to 10^2 years) climate change over the last 5 million years.</td>
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Table 3. Outline of tasks, deliverables and timelines for work to be carried out under the aegis of the ACE programme from 2005 to 2009.

5. Logistic requirements and costs

A programme of this scale will require a significant time commitment from the committee members, which will have to be covered by them personally and their home institutions. The costs we request here are basic operational costs to allow the committee to meet once a year (though they will undoubtedly meet additionally at other scheduled meetings), and to provide seed funding for two workshops or symposia each year. Our estimate of the annual budget request from SCAR for ACE is as follows:

- Travel and accommodation for committee members $ 1500/person for 10 persons $ 15,000
- Seed funding for workshop expenses (e.g., publication of report, some travel assistance) $ 8,000
- Costs for website and newsletter $ 2,000

**TOTAL $ 25,000**

Note: Supplemental funding requests (above the base monies requested) over the years will be for: inviting experts to SALE meetings; covering the expenses related to convening topical workshop and inviting key participants; funding the development of specialized educational and promotional material; allowing for smaller meeting of the ACE program management on a more frequent basis; and paying the expenses for the ACE Chief Officer to attend and present ACE activities at important international meetings.
6. Links with other SCAR activities

The ACE proposal has formal links with two other SCAR SRP proposals. The first is Subglacial Antarctic Lake Environments (SALE), and the second is Antarctica and the Global Climate System (AGCS).

ACE and SALE will collaborate on the acquisition of such records. Second, the ice sheet history quantified through numerical modelling as part of the ACE programme will offer important constraints on the formation and development of subglacial lake environments. ACE will provide SALE with model results in order for the history of subglacial lakes to be established in the context of ice sheet and climate evolution.
Investigating Antarctic history over glacial-interglacial periods is appropriate to the study of both modern and ancient environments. ACE and AGCS aim to investigate this history as a component of much broader and distinct science plans. Further, each SPPG has compatible yet discrete specialisms that are well suited to studying the glacial-interglacial history of Antarctica. ACE contains expertise in ice-sheet/climate modelling, marine and terrestrial geology, marine geophysics and radio-echo sounding. AGCS includes expertise in atmospheric modelling and ice coring. This combined expertise covers the full suite of knowledge required to build a sub-programme on the Quaternary history of Antarctica. We propose that an action group, made up of appropriate personnel from both ACE and AGCS, be established to run this sub-programme.

It should be noted that while ACE and AGCS have compatible interests in Quaternary studies of Antarctica, the remaining components of each respective science plan differ markedly.

7. Links with the International Polar Year (IPY)

The IPY provides a unique opportunity to plan, fund and undertake international collaborative research in the polar regions. By the time of IPY (2007-8), the ACE programme will be fully functioning. It is therefore highly appropriate that ACE, as an existing major international Antarctic research programme, seeks to become involved in IPY research in order to fulfil the ambition of this intense period of investigation. The plan for IPY activities is divided into five themes. The ACE programme is directly relevant to one of these themes, and will make major contributions to two others. Details of how ACE activity will contribute to the IPY are provided below.

The ACE programme will result in scientific findings directly relevant to Theme #2 of IPY: To quantify, and understand, past and present environmental and human change in the polar regions in order to improve predictions. The ACE programme will provide answers to the following two questions that will be asked in this theme: (1) How has the planet responded to multiple glacial cycles? and (2) What critical factors triggered the cooling of the polar regions? The proposed function of the ACE programme will allow the investigation of past changes in Antarctica during several time slices. Question 1 will be answered as part of the ACE investigation into the Pleistocene glacial cycles and intervals of extreme warmth and cold (Section 3.2.5) and the Last Glacial Cycle and Deglaciation (Section 3.2.6). Question 2 will be addressed in ACE through analysis of Eocene-Oligocene events (Section 3.2.1), and the Oligocene-Miocene boundary Mi-1 glaciation (Section 3.2.2), and also in the process-based theme on Tectonics and climate (Section 3.3.3).

Further, ACE findings will contribute to two other IPY themes. In IPY Theme #3, processes relating to global teleconnections will be investigated. To understand contemporary processes, models (both conceptual and numerical) need to be built and tested against the known record of past changes. To this end, ACE will provide the necessary process-based information concerning the causes and consequences of past changes in Antarctica at a variety of timescales relevant to IPY Theme #3. Two questions within IPY Theme #4 (To investigate the unknowns at the frontiers of science in the polar regions) are of direct relevance to ACE. The first concerns the character of the sub-ice and deep-ocean ecosystems. Such systems exist as a consequence of the modern environment and past environmental changes. The ACE programme will allow subglacial conditions to be evaluated through the Cenozoic, which will allow us to predict the long-term history of, for example, Lake Vostok (as discussed in Section 6; links with the SALE programme). The second question will determine the effect of the solid earth on ice sheet dynamics. ACE ice sheet modelling investigations of the Influence of tectonics on the behaviour of the ice sheet (Section 3.3.2) will have a direct input to this question.

As is evident in these brief details, the ACE programme will have explicit and purposeful links with IPY plans. Consequently, a successful ACE programme will lead to a significant component of the IPY ambition being fulfilled.

8. Outreach and education

ACE will endeavour to support and encourage the next generation of Antarctic scientists in three ways. First, an online lecture series paralleling the findings and outcomes of the
ACE programme will be made available to schools, colleges and universities via the ACE website. These lecture materials will comprise downloadable power-point presentations, and will match ACE’s scientific programme (detailed in Section 3). Second, we will encourage young scientists to take part in ACE workshops by offering bursaries for travel and subsistence. Although the level and number of the bursaries will be dictated by funds available, it is hoped that at least two bursaries will be available for each workshop/meeting. The condition of each bursary will be a report by the holder about their research and workshop experiences, which will be posted on the ACE website. Third, we will facilitate an exchange scheme between our respective institutions to allow young scientists to take part in fieldwork and to sample the research culture of other nations. Similar schemes operate within, for example, the Worldwide University Network, and it is anticipated that external funds (from such schemes) will be used to support the exchanges arranged through ACE.

9. Achievements to date
ACE was awarded SPPG status following SCAR XXVII in Shanghai (July 2002). Since its creation, ACE has undertaken a series of meetings and symposia as we hope SCAR would expect of a SPPG. Furthermore, the scientific programme within ACE is already underway, with the first papers directly related to the ACE science plan published in *Nature* in January 2003 (DeConto and Pollard, 2003a; Barrett, 2003) and in *Geology* in March 2004 (Taylor et al., 2004). The following is a timeline of achievements, which testifies that ACE is already becoming an active programme of research, which facilitates world-class scientific investigation.

- June 2002; ACE workshop on palaeoclimate modelling, Amherst, USA. A workshop report is available from the ACE website ([http://www.ace.scar.org/wkrpt.pdf](http://www.ace.scar.org/wkrpt.pdf))
- June 2002; Submission to SCAR of the ACE SPPG proposal.
- July 2002; ACE website launched ([www.ace.scar.org](http://www.ace.scar.org)). The site is maintained at the University of Massachusetts by Robert DeConto.
- July 2002; SCAR award Scientific Programme Planning Group status to ACE.
- December 2002; A full day ACE session at Fall AGU meeting in San Francisco, USA. The sessions comprised 14 talks and 8 poster presentations, with contributions from Peter Barrett, Robert DeConto, David Pollard, Martin Siegert, Ross Powell, David Harwood, and Robert Dunbar.
- April 2003; ACE meeting at the EGU/AGU Spring meeting in Nice, France.
- May 2003; Submission to SCAR of the ACE SRP proposal.
- October 2003; Report from the SCAR Executive meeting (Brest, France July 2003), in GeoReach 2.4, detailing the recommendation of the Executive Committee to fund ACE as a SRP.
- Forthcoming, special issue of *Global and Planetary Change* (edited by Fabio Florindo and David Harwood).
- Forthcoming, Fabio Florindo and Peter Barrett will be chairing a session entitled ‘Cenozoic Antarctic Glacial History’ at the International Geological Congress, Florence August 2004.

10. References


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Further details, including short biographies, of those listed above are provided in Appendix A.
APPENDIX A.

Short biographies of those who have contributed to the ACE proposal are provided below.

**Peter Barrett.** Antarctic Research Centre, Victoria University of Wellington, New Zealand. (email peter.barrett@vuw.ac.nz). Peter Barrett is Professor of Geology and Director, Antarctic Research Centre, at Victoria University of Wellington. He earned his Ph.D. for the stratigraphy and environmental history of the Beacon Supergroup in the central Transantarctic Mountains in 1968 from the Ohio State University. He sailed as sedimentologist on the RV GLOMAR CHALLENGER in 1972 for the first drilling for glacial history off the Antarctic margin. Since then he has led a several drilling projects in McMurdo Sound for their climatic and tectonic record (most recently the Cape Roberts Project), as well as carrying out field studies of contemporaneous deposits on land, and facies analogues in New Zealand.

**Alan Cooper** is emeritus geophysicist at U.S. Geological Survey and Consulting Professor at Stanford University Department of Geological and Environmental Sciences (email: acooper@usgs.gov). He earned his Ph.D. in Geophysics in 1974 from Stanford University and has worked on framework geology of continental margins around the Pacific Ocean. He spent the past 20 years conducting offshore geophysical and drilling operations to investigate the geology and paleoenvironmental history of the Antarctic margin. In 1989, he initiated and thereafter coordinated the Antarctic Offshore Stratigraphy Project (ANTOSTRAT), which laid the groundwork for the ACE project.

**Robert DeConto.** Department of Geosciences, University of Massachusetts, USA (email: deconto@geo.umass.edu). Rob DeConto is a Professor of Geosciences at the University of Massachusetts. He earned his Ph.D. in climatology and Earth system modeling from the University of Colorado and the National Center for Atmospheric Research in 1996. Rob's research is focused on new ways of combining numerical climate and ice sheet modeling with geological and geophysical observations to better understand the climate and ice sheet variability of Antarctica over a wide range of timescales. He is active in both the theoretical/modeling and field aspects of Antarctic research and is a Principal Investigator of ANDRILL.

**Robert Dunbar.** School of Earth Sciences, Stanford University, USA (email: dunbar@pangea.stanford.edu). Rob Dunbar is Professor of Geological and Environmental Sciences at Stanford University. His research interests link oceanography, climate dynamics, and geochemistry. Prof. Dunbar’s research group works on topics related to global environmental change, with a focus on the coastal ocean, air-sea interactions, and polar processes. In January, 2004, he was named the J. Frederick and Elisabeth B. Weintz University Fellow in Undergraduate Education. This fellowship is in recognition of teaching and mentoring of Stanford undergraduates.

**Carlota Escutia,** Instituto Andalúz de Ciencias de la Tierra (Consejo Superior de Investigaciones Científicas), Spain. (email cescutia@ugr.es). Carlota Escutia is a research scientist at the Instituto Andalúz de Ciencias de la Tierra. She earned her Ph.D. in marine sciences in 1992 from the Universidad Politécnica de Cataluña-Universidad de Barcelona. From 1992 to 2002 she worked as a postdoctoral fellow and visiting scientist at the USGS Menlo Park (California) and as an Assistant Research Scientist-Staff Scientist at the Ocean Drilling Program-Texas A&M University (Texas). She works on the broad subject of seismic stratigraphy and sedimentology of siliciclastic continental margins. Her research focuses on sedimentary margin architecture and sedimentary processes with the main objective of understanding global environmental change, geohazards and resource assessment. With these objectives in mind she has been conducting studies in Antarctica, the Mediterranean, Atlantic Gulf of Cadiz, and Lake Baikal (Russia). She coordinated the ANTOSTRAT Wilkes Land working group, chaired numerous committees and presently serves as a member of one the IODP advisory panels: the Site Survey Panel.

**Fabio Florindo.** Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy (e-mail florindo@ingv.it). Fabio Florindo is Senior Scientist at the INGV from 2001. He earned his Ph.D. in Palaeoceanography from the University of Southampton (U.K.). His research focuses in palaeomagnetism
and environmental magnetism with applications to palaeoclimate and palaeoceanography. In the last few years most of his research focused on increasing the resolution of understanding of ice sheet and climate history and their role in the evolution and development of climate. He is one of the lead proponents of the multinational ANDRILL (ANtarctic DRILLing) project.

**Jane Francis** is Professor of Palaeoclimatology and director of the Centre for Polar Science at the University of Leeds. Her research uses fossil plants as a tool for climate interpretation and information about past floral biodiversity and its response to climate change. Her current work focuses on understanding past climate change during both greenhouse and icehouse periods, particularly in Antarctica. She was awarded the Polar Medal for her polar research in 2002.

**Michael Hambrey**, Institute of Geography & Earth Sciences, University of Wales, Aberystwyth, UK (email mjh@aber.ac.uk), where he is Director of the Centre for Glaciology. He obtained a PhD in 1974 from the University of Manchester on the structural glaciology of Norwegian glaciers. His work has focused primarily on glacial processes and reconstructing earth's glacial record (Precambrian and Cenozoic) in the Polar Regions. His Antarctic interests, from 8 field seasons, are concerned with the Cenozoic glacial sedimentary record in the Transantarctic Mountains, the Prince Charles Mountains and James Ross Island.

**David Harwood**, Department of Geosciences, University of Nebraska-Lincoln, Lincoln, NE 68588-0340, USA (email dharwood1@unl.edu). David Harwood is a professor of micropaleontology and stratigraphy at the University of Nebraska. He earned his Ph.D. in Antarctic micropaleontology and stratigraphy at The Ohio State University in 1986. He has been investigating the history of Antarctic Cenozoic glaciation from terrestrial deposits, glacial marine deposits in outcrop and drillcore and from Southern Ocean drillcore sites and is the Director of the ANDRILL Science Management Office.

**Alan Haywood**, Geological Sciences Division, British Antarctic Survey, Cambridge, UK (email ahay@bas.ac.uk). Alan Haywood is currently Principal Investigator of the British Antarctic Survey's GEACEP Programme (Greenhouse to Ice-house Evolution of the Antarctic Cryosphere & Palaeoenvironment). He earned his Ph.D. in numerical climate modelling and palaeoenvironmental reconstruction in 2001 from the University of Reading and has worked on modelling past climate and environmental change since that time. His research focuses on the reconstruction of past climates (particularly for the Neogene) and on evaluating the outputs of advanced numerical climate models against proxy climate and environmental data. He is currently a member of the UK High Performance Computing steering committee.

**Robert Larter**, British Antarctic Survey (BAS), Cambridge, UK. (email r.larter@bas.ac.uk). Robert Larter earned his Ph.D. in Antarctic marine geophysics in 1991 from the University of Birmingham. He has extensive experience in application of marine geophysical techniques to studying the glacial history of, and effects of glacial processes on, the Antarctic continental margin. His research focuses on the Pacific sector or the Antarctic margin. He has participated in 11 Antarctic and sub-Antarctic marine geoscience cruises since 1984, including two cruises as an invited scientist on foreign vessels. He has been Chief Scientist on three research cruises on the BAS vessel RRS James Clark Ross.

**Tim Naish**, Geological Time and Past Environments Section, Institute of Geological and Nuclear Sciences (GNS), NZ (t.naish@gns.cri.nz). Tim Naish is leader of the Antarctic palaeoclimate programme at GNS. He earned his PhD in sequence and cyclostratigraphic analysis of Quaternary sea-level changes in shallow-marine continental margins in 1995 from the University of Waikato, NZ and continued this research during a post-doctoral research fellowship at James Cook University, Queensland. His current research focuses on the analysis of glacial and sea-level signatures in ice-marginal marine environments. He will co-lead the ANDRILL programme drilling of the Ross Ice Shelf site, and is a member of the ANDRILL Science Steering Committee.
**Tony Payne.** School of Geographical Sciences, University of Bristol, UK. (email a.j.payne@bristol.ac.uk). Tony Payne is Proleptic Reader at the University of Bristol and co-director of the Centre for Polar Observation and Modelling (a NERC-funded Centre of Excellence). He has a Ph.D. in ice sheet modelling (Edinburgh 1988). His research is concerned primarily with modelling the response of ice masses to climate change, although he has wider interests in the numerical modelling of environmental systems.

David Pollard received his bachelor's degree in Mathematics from Cambridge University in 1973, and a master's degree in Aeronautics from the California Institute of Technology in 1974. He then joined the Division of Geological and Planetary Sciences at Caltech, and received his Ph.D. in planetary meteorology in 1979. He worked on Earth energy-balance climate and ice-sheet models as a postdoctoral associate at Caltech and Oregon State University in Corvallis, then worked from 1983 to 1988 as a commercial project-management software developer and in JPL quality assurance, gaining experience in large software systems. He rejoined academia in 1988 as a research associate at NCAR in Boulder, Colorado, where he worked for 9 years on all aspects of the GENESIS global climate model. In 1997 he moved to the Earth System Science Center at Penn State as a research associate, and continues to work on global and regional climate and ice-sheet model development and applications.

Ross Powell. Department of Geology and Environmental Geosciences, Northern Illinois University, USA. (email ross@geol.niu.edu). Ross Powell a Professor of Geology at Northern Illinois University. He earned his Ph.D. in glacial sedimentological processes in 1980 from the The Ohio State University and has worked on many process- and stratigraphic/palaeoclimatic-related studies in Antarctica and other high-latitude areas since that time. His research focuses on quantifying the processes that go to make a stratigraphic record in environments where glaciers, rivers, and sea and lake waters interact, and how such ancient records may be interpreted relative to glacial and climatic changes. He is currently a US representative to the GSSG, he is on the SALE and ACE SPPGs, and the Permafrost Action Group of the GSSG; formerly he was a member of two Groups of Specialists - GLOCHANT and SALEGOS.

Martin Siegert. School of Geographical Sciences, University of Bristol, UK. (email m.j.siegert@bristol.ac.uk). Martin Siegert is Professor of Physical Geography at the University of Bristol. He earned his Ph.D. in numerical ice sheet modelling in 1993 from the University of Cambridge and has worked in the broad subject of Antarctic glaciology since this time. His research focuses on the use of radar to the identify and characterise subglacial processes, and the investigation of the long-term history of the Antarctic ice sheet. He is co-Chair of the Subglacial Antarctic Lake Exploration (SALE) SPPG.

Gary Wilson. Department of Geology, University of Otago, NZ. (email gary.wilson@otago.ac.nz). Gary Wilson is a Senior Lecturer in physical stratigraphy and palaeomagnetism and director of the Otago Palaeomagnetic Research Facility. He earned his PhD in sedimentology in 1993 from Victoria University of Wellington, NZ. His primary research interest is in paleoclimatology and the role of Antarctica in the role of the global climate system. Science graduating, he has held the Byrd Fellowship at the Ohio State University and a lectureship at the University of Oxford, UK. He is convenor of the McMurdo ANDRILL (Antarctic Drilling) Science implementation committee (MASIC).