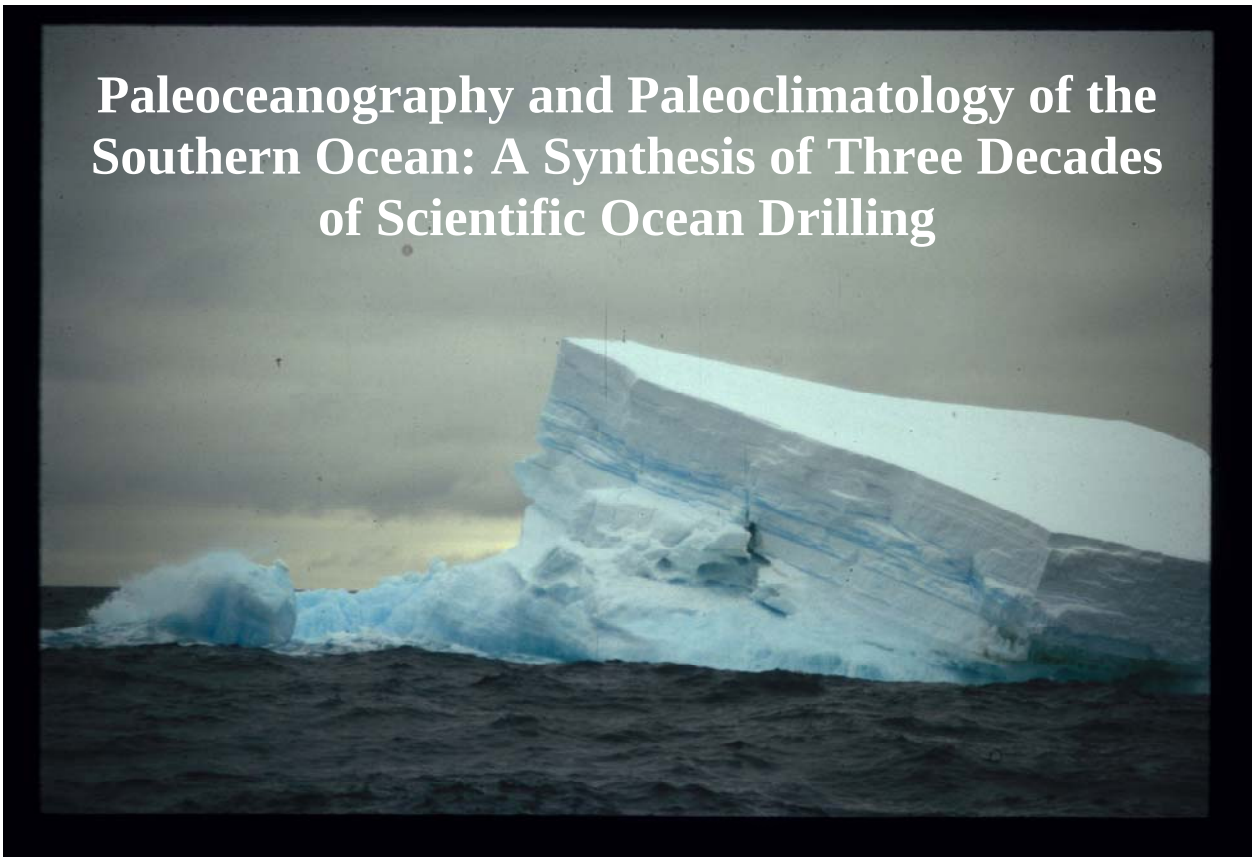
Paleoceanography and Paleoclimatology of the Southern Ocean: A Synthesis of Three Decades of Scientific Ocean Drilling



January 21-23, 2005
Benson Earth Sciences Building
University of Colorado, Boulder

Convenors:

Detlef Warnke
California State University Hayward

Gabriel Filippelli
Indiana University ~ Purdue University Indianapolis

Jose Abel Flores
University of Salamanca

Thomas Marchitto
University of Colorado, Boulder

A Synthesis Workshop funded by the United States Science Support Program (USSSP) of Joint Oceanographic Institutions, Inc., with additional support from the University of Colorado (Earth Sciences) and IUPUI (Geology)

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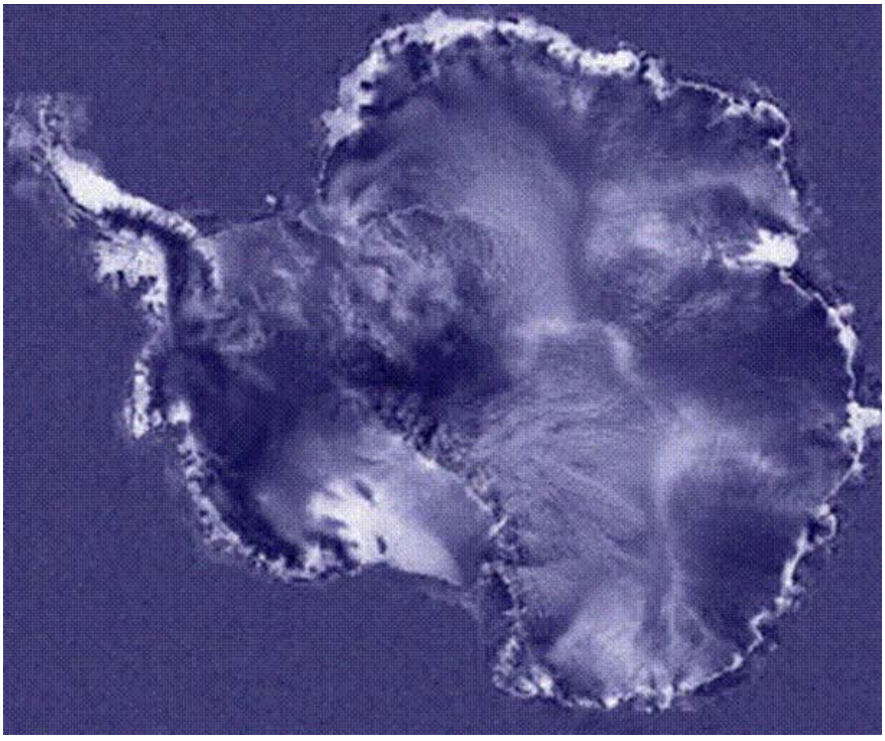
Co-Convenors: D. Warnke, G. Filippelli, J.-A. Flores, T. Marchitto

One of the greatest successes of the Ocean Drilling Program has been the exciting results recovered from the Southern Ocean (SO), which was the focus of ten DSDP/ODP drilling legs. The SO is a critical component in the development and persistence of Antarctic glaciation, is a sensitive mixing pool of global water masses, a locus of high biological sedimentation, and contains high resolution records of climate forcing and response. The focus of this Synthesis Workshop is on the biogeochemical history of the SO, including:

- Productivity proxies, rates, records, variations, and role of climate
- Sedimentary records of organic carbon, calcium, silica, nutrients, and biogenic proxies: The role of the SO as a biogeochemical sink
- Development and dynamics of the APFZ
- Thermal structure and evolution of the SO
- The role of limiting nutrients



Participants:

Peter Barker	UK
Wolfgang Berger	Scripps Institution of Oceanography
Andrea Caburlotto	OGS, Italy
Bernhard Diekmann	AWI Potsdam
Carlota Escutia	University of Granada
Gabriel Filippelli	Indiana University ~ Purdue University Indianapolis
Jose Abel Flores	University of Salamanca
Rainer Gersonde	AWI Bremerhaven
David Harwood	University of Nebraska
David Hodell	University of Florida
Kelly Kryz	Joint Oceanographic Institutions, Inc.
Jennifer Latimer	University of Michigan
Kathy Licht	Indiana University ~ Purdue University Indianapolis
Tom Marchitto	University of Colorado, Boulder
Ellen Martin	University of Florida
Peter Molnar	University of Colorado, Boulder
Simon Nielson	University of Florida
Suzanne O'Connell	Wesleyan University
Harunur Rashid	Massachusetts Institute of Technology
Christina Riesselman	Stanford University
Howie Scher	University of Florida
Reed Scherer	University of Northern Illinois
Amelia Shevenall	University of California, Santa Barbara
Peter Schultheiss	GeoTek Ltd., UK
Lora Teitler	California State University Hayward
Detlef Warnke	California State University Hayward

Southern Ocean Synthesis Workshop Agenda

Friday, Jan. 21

8:00 - 8:30 Continental breakfast

8:30 - 9:00 Introduction, expectations, goals, mechanics

9:00 - 3:30 Plenary talks and initial discussions

Session I Cenozoic development and ice sheet-SO interaction

9:00 - 9:30 Cenozoic context to Southern Ocean development (Peter Barker)

9:30 – 10:00 Geomorphology and ice dynamics in Antarctica (Carlota Escutia)

10:00 – 10:30 Ice-sediment dynamics from continents to the SO: LGM – present (Kathy Licht)

10:30 – 11:00 Break

11:00 – 11:30 Discussion of known/unknowns and initial recommendations

Session II Pleistocene Dynamics of SO paleoceanography

11:30 – 12:00 Pleistocene sedimentation patterns in the SO (Bernard Diekmann)

12:00 – 12:30 Pleistocene variability of the SO surface: implications for climate development (Rainer Gersonde)

12:30-1:30 Lunch

1:30 – 2:00 Paleoecological history of the SO (Jose Abel Flores)

2:00 – 2:30 Nutrient dynamics and nutrient limitation in the SO (Jennifer Latimer)

2:30 – 3:30 Discussion of known/unknowns and initial recommendations; formation of initial breakout groups

3:30 – 4:00 Break

4:00 - 5:00 Breakout group discussions

5:00 - 6:30 Posters (wine and cheese sponsored by JOI, Inc. and Geology, IUPUI)

7:00 Group Dinner at Dolan’s

Saturday, Jan. 22

8-8:30	Continental breakfast
8:30-9:30	Initial breakout group report preparation
9-10:30	Initial breakout group reports/discussion
10:30-11	Break
11-12:30	Second breakout group meeting
12:30-1:30	Lunch
1:30-2:30	Reports from second breakout groups; consensus, further discussion/question
2:30-3:30	Breakout group draft synthesis presentation for Sunday
3:30-4	Break
4-5:30	Draft synthesis paper preparation
5:30-6:30	Posters (wine and cheese sponsored by JOI, Inc. and Geology, IUPUI)
7:00	Group Dinner at Carelli's

Sunday, Jan. 23

8-8:30	Continental breakfast
8:30-9:30	Synthesis products discussion, author/title commitments
9:30-10:30	What we still don't have answers for—strategies to get answers, based on IODP sponsored site-survey cruises and drilling expeditions
10:30-11	Break
11-12:30	Marching Orders, timelines, workshop evaluation

Meeting Logistics

Hotel:
Best Western Boulder Inn
770 28th Street
Boulder Colorado 80303
T: (303) 449-3800 F: (303 402-9118
www.Boulderinn.com

Making Reservations:
To reserve your room you may call the hotel at 800-233-8469 and reference JOI to receive rates of $59 for one or two queen beds, or you can email the hotel if you prefer boulderinnsales@aol.com. The hotel will need to know your arrival/departure date and will require a credit card number to guarantee

Meeting Location/Dates/Times:
Benson Earth Sciences Building
Main Meeting Room #: Benson 380
Break out rooms: 340E and 240D
January 21-23
08:00 – 17:30

Continental Breakfast, Lunch, and Dinner will be provided from the morning of January 21 through lunch on January 23.

Driving Directions:
From Denver International Airport, take I-70W to I-25N to US-36W. Follow US-36 to Boulder. The second exit is Baseline Rd. This exit will take you to a stoplight.
Cross Baseline and stay in right lane, you will come to a stop sign. We are straight ahead.

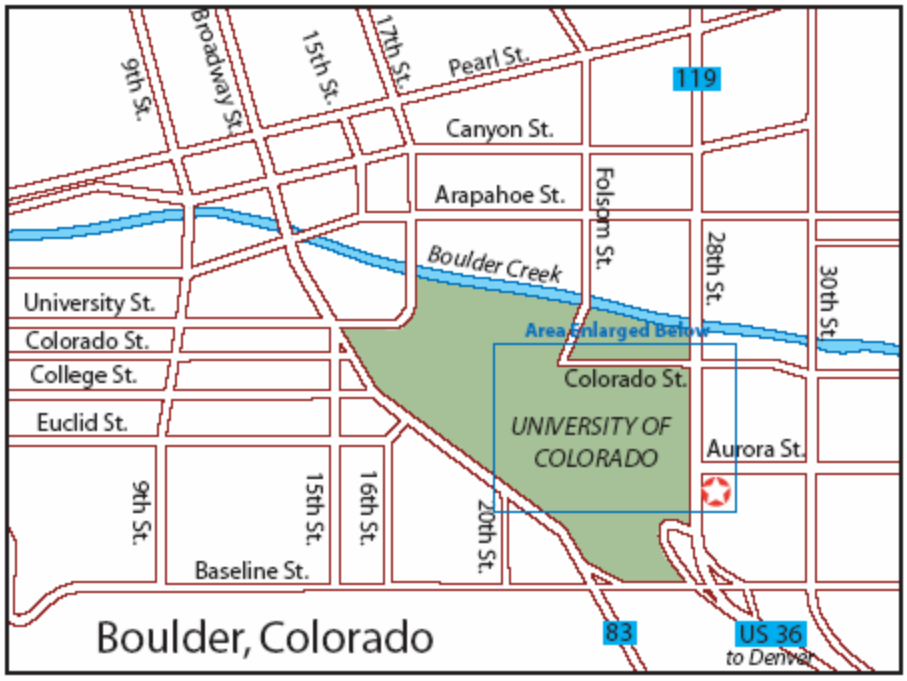
Shuttle Service Denver International Airport (DIA) to Boulder:
Boulder Express
http://www.boulderexpress.com/ ($15.00 One Way/ $30 Round Trip)
Super Shuttle Denver
http://www.supershuttledenver.com/ ($18 One Way / $32 Round Trip)

Filing Expense Report:
US attendees will need to file an expense report in order to receive reimbursement of the $900. Please access a form at the following web page: www.joiscience.org, go to travel support and then forms. Meal per diem in Boulder: breakfast/$9.00, lunch/$11.00, dinner/$24.00.

Southern Oceans Workshop

University of Colorado, Boulder

January 21 - 23, 2005



Best Western Boulder Inn
770 28th Street
Boulder, CO 80303
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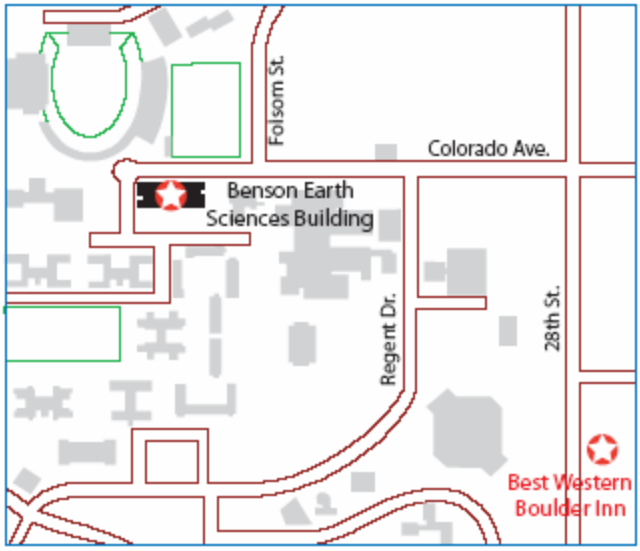
Meeting Room in the:
Benson Earth Sciences Building,
University of Colorado



Abstracts

Cenozoic context to Southern Ocean development

Peter Barker, 25 Church Street, Great Gransden SG19 3AF, UK (pfbarker@tiscali.co.uk)

The two main oceanographic features of the modern Southern Ocean are the ACC and AABW (more accurately, southern-origin deep and bottom water SOBW), both associated in some way with Antarctic continental glaciation. Global palaeoclimate and palaeocirculation have been profoundly affected by them, and the earth's climate system cannot be understood unless they too are understood. All three started during the Cenozoic, and have been governed by changes on a tectonics-related as much as an orbitally-related timescale. Many aspects of their history and interactions remain very poorly known, but are accessible to ocean drilling.

What we know about Antarctic glaciation comes from a wide range of sources - direct information from DSDP28, ODP113, 119, 178 and 188 that sampled the continental margin, and from onshore geology and independent Ross Sea drilling. Less direct information (benthic oxygen isotopes and Mg/Ca ratios, clays, IRD) is also mainly from drilling, but from a wide range of locations, a minority of them within the Southern Ocean. Inferences about SOBW history draw on the same sources. Abrupt glacial onset close to the Eocene-Oligocene boundary is widely recognised, but the size of that early ice sheet, and many aspects of subsequent glacial history, remain uncertain. Future work may best be concentrated on additional margin drilling to resolve such uncertainties, despite difficulties of access and recovery. The glacial cause of SOBW production is widely accepted, but may not be entirely correct, and its time variation has not been examined.

The Cenozoic history of the Antarctic Circumpolar Current has been studied by work on samples from many drilling legs (DSDP 28, 29, 35, ODP 113, 114, 119, 120, 177, 181, 183, 189) and a very small number of onshore exposures, but with minor exceptions these drilling legs were not designed to examine ACC history: such work to date has been largely opportunistic, and a wide range of estimated times of ACC onset has been proposed. Tectonic studies in gateway regions have also led to a wide range of speculative times of onset (certainly 16-34 Ma, possibly wider), despite general agreement on ocean floor ages. More recently, the previously accepted causal relationship between the ACC and glaciation (that the ACC caused glaciation by thermal isolation of the continent) has been questioned, along with the interpretational basis of much of the published speculation. Essentially, little is known with any certainty of the history and climatic influence of the ACC, yet additional Southern Ocean drilling, specifically designed and carefully executed, is almost certainly the only way in which it may be determined.

The Scotia Sea Region is Ideal for Determining the Onset and Development of the Antarctic Circumpolar Current

Peter Barker[1] and Ellen Thomas[2]

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[2]Dept of Earth and Environmental Sciences, Wesleyan Univ., Middletown CT 06457, USA; and Center for the Study of Global Change, Dept of Geology and Geophysics, Yale Univ., New Haven CT 06520-1809, USA.

The strength of interaction between tectonics, ocean circulation and climate is a major concern of palaeoclimate research. Key indicators of this strength are the time of onset and development of the Antarctic Circumpolar Current (ACC), and thus its likely effects on climate, particularly Antarctic glaciation. Developments in numerical climate modelling, marine geology, tectonics and physical oceanography cast doubt on widely held assumptions of a causal relationship between ACC onset and the initiation of glaciation, through thermal isolation of the continent, at around the Eocene-Oligocene boundary. Here we argue that the time of ACC onset and development remain to be determined, and may best be determined in the Scotia Sea region ("Drake Passage"), south of South America. There lies the greatest tectonic uncertainty, concerning when a complete deep-water circumpolar pathway was created, so that the ACC as we know it today could first develop. There also, the ACC is topographically constrained, and the region is relatively well known. Determination of the time of onset would show the extent to which ocean circulation changes affected Antarctic glaciation, and could draw attention to other key questions, such as the nature of Southern Ocean circulation in the period (possibly Oligocene and even early Miocene) when Antarctica was glaciated but before a complete circumpolar deep-water pathway existed. We assess the parameters that might be capable of determining ACC onset, and show that sedimentary sections suitable for drilling are available in the Scotia Sea region.

Origin, Timing and Significance of Millennial-Scale Ice-Rafted Detritus Events in the Southern Ocean during the Last Ice Age

Robert F. Anderson, Lloyd H. Burckle, T. Guilderson, D.A. Hodell, S.L. Kanfoush, S.H.H. Nielsen and M.H. Perfit

Abstract

Outstanding questions of Southern Ocean marine geology include whether or not the Antarctic ice-sheets experienced periods of instability, and if these periods can be traced as extensive sheets of Ice-Rafted Detritus (IRD) deposits in the open ocean.
How can IRD deposits be recognized in sediment-cores, and be separated from lag deposits? Can the IRD provenance be distinguished? Do extensive IRD-layers become deposited during periods

of warmth and unstable ice-sheets, or doing cold periods allowing the ice-bergs to survive more often to the open ocean?
A collaborative effort is being undertaken by the University of Florida, the Lamont-Doherty Earth Observatory, Utica College and the Lawrence Livermore National Laboratory effort to answer those questions. By approaching the questions with multiple proxies, we hope to establish the timing of and conditions for episodes of ice-rafting in the Atlantic sector of the Southern Ocean during the last 130 ka. Methods include mineralogical and geochemical analysis of IRD and volcanoclastics, as well as micropaleontological investigation to establish the climatic conditions during ice-rafting events.
The project is just starting up. Sediment cores used include *Thomas Thompson* and *Robert Conrad* cores. The groundwork is being laid using high-resolution magnetic susceptibility measurements on *Islas Orcadas* cores from the Antarctic Research Facility. The preliminary results of that work will be presented here.

Integrated Study of Ice-Rafted Debris, Temperaturess, and Stable Isotopes on a Spliced Record (piston cores and ODP Site 177-1090) From the South Atlantic

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We have conducted an integrated study of ice-rafted debris (IRD) and stable isotopes on a spliced record (TN057-6-PC4/ODP Site 177-1090, about 43° S, 9°E) raised on the Agulhas Ridge, in the South Atlantic. The site is just north of the northern boundary of the present-day Polar-Front Zone (PFZ), and is in a very sensitive location to record both ice rafting and stable-isotopic-ratio changes. Our combined record reveals a pattern of ice-rafting episodes that may be characteristic for the subantarctic South Atlantic, at least for locations N of the PFZ. Ice rafting occurs during the waxing stages of each glaciation, and ends at, or before, the peak of each glaciation. IRD peaks are also associated with strong stadials during "cold" interglacials, e.g. MIS 7. A little IRD shows up during the entire interval studied here, from the Holocene to mid-MIS 14. We suggest that the IRD record at this site is essentially a temperature record on glacial-interglacial timescales. If the temperature is low enough, enough icebergs survive to melt at this location. If the temperature is too warm, only an occasional iceberg survives to deliver debris. A peculiar aspect of the combined record is the fact that during Ice-rafting events (IREs), the planktic oxygen-isotopic ratios are higher at the end of an IRE compared to the beginning. Further, by comparing our records with the Summer Sea Surface Temperature record of Becquey and Gersonde (2002) for a nearby (respectedly the same) site (PS2489-2/ODP177-1090), we see

that the temperature is generally very similar at the beginning and the end of an IRE. The same age model provided by Venz and Hodell (2002) was used for both sites, allowing such direct comparisons of the data. Assuming as a working hypothesis that the IRD record is a pure temperature record, and ignoring the salinity effect for the present, then this difference in oxygen-isotopic ratios must be the ice volume effect. For MIS 12, the difference in planktic oxygen-isotopic ratios at the beginning and the end of the IRE is about 1.3 permil, which translates to 130 m sea level equivalent. The present-day temperature at the site is about 10° C (Levitus and Boyer, 1998). To attain a temperature of about 4° C (presently located at about 47° S in this area), as indicated by the SSST record of Becquey and Gersonde (2002) for the IRE during MIS 12, the Polar Front Zone (the zone of major iceberg melting and boundary between different sedimentary provinces) had to move north by about 4° of latitude (about 240 nautical miles). This estimate differs slightly from other estimates (e.g. see poster by Burckle nearby). Nevertheless, it is clear that the PFZ had to move north and south on glacial-interglacial and shorter timescales, and could not have remained stationary, as has been postulated.

LATE NEOGENE SILICEOUS MICROFOSSIL-BASED PALEOCLIMATE AND PALEOCEANOGRAPHIC AND CRYOSPHERIC HISTORY FROM THE SOUTHERN OCEAN AND ANTARCTIC MARGIN

HARWOOD, D.M.[1], BOHATY, S.M.[2], LEVY, R.H.[1], SCHERER, R.P.[3], WHITEHEAD, J.M.[4]

1 - ANDRILL Science Management Office, Department of Geosciences, University of Nebraska-Lincoln, Lincoln, NE 68588-0340 USA;
2 - Earth Sciences Department, University of California - Santa Cruz, Santa Cruz, CA 95064 USA;
3 - Department of Geology and Environmental Geosciences, Northern Illinois University, DeKalb, IL 60115, USA;
4 - Institute for Antarctic and Southern Ocean Studies, University of Tasmania, Hobart, Tasmania, Australia

Diatoms and silicoflagellates provide important proxy information to guide interpretations regarding the timing, frequency and magnitude of paleoclimatic, paleoceanographic and cryospheric changes in the southern high latitudes. Comparison of several Neogene paleoenvironmental events is now possible through refined, high-precision correlation that results from the compilation and synthesis of biostratigraphic and chronostratigraphic data using the CONOP [constrained optimization] program. Studies of outcrops and drillcores on the Antarctic margin, combined with Southern Ocean drillcore data, reveal the potential for tracing coeval paleoenvironmental changes from interior Antarctic basins, across the continental shelf and into Southern Ocean depths, across prominent oceanic frontal zones. Distinct, warm surface-water events, associated with ice sheet margin retreat, substantial reduction of sea-ice, and reduced temperature gradients across the Polar Frontal Zone are identified during the Late Miocene 10.7-9.0Ma (e.g. Pagodroma Group, Jason Diamicton), the Pliocene 4.5-4.1Ma, 3.65Ma, (e.g. ODP sites 745, 748, 751, 1165; Sorsdal Formation), and early Pleistocene 1.07Ma (e.g. MIS-31 at the Cape Roberts Project CRP-1 drillcore).

Apparently disparate interpretations that result from different proxy records provide opportunities to test and constrain assumptions that guide interpretations. New information to be recovered through the ANDRILL (ANtarctic DRILLing) Program in the southwestern Ross Sea, which will initially target Pliocene and Pleistocene strata, will provide important, and overdue, southern high latitude data from a variety of proxy indicators [see http://andrill-server.unl.edu]. This report compiles stratigraphical and paleontological information in order to (1) construct a composite history of climatic change in the southern high latitudes, (2) establish questions that will be tested through recovery of expanded Plio.-Pleistocene sections, (3) increase our understanding of modern and past processes; (4) place Antarctic records in a chronostratigraphic context that can be compared with high-resolution records from the mid and low latitudes; and (5) build a Late Neogene dataset for input into climate and ice sheet modeling studies of the SCAR "Antarctic Climate Evolution" (ACE) initiative.

The opening of Drake Passage inferred from Nd isotopes

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Howie D. Scher (hscher@ufl.edu)
Department of Geological Sciences, University of Florida, Gainesville, FL 32611-2120

Estimates for the timing of the opening of Drake Passage range from the late Eocene to early Miocene. Nd isotopes from fossil fish teeth at ODP Sites 1090 (Cape Basin) and 689 (Maud Rise) over this time interval record changes in water mass composition. Beginning at 39 Ma $\varepsilon_{Nd(T)}$ values in the Atlantic sector of the Southern Ocean (Site 1090) increase from -8 to -5.9 ε_{Nd} in less than 1my. This final value is more radiogenic than values documented for any part of the ocean other than the Pacific or Caribbean over the past 60 m.y. The presence of Pacific-type Nd isotopes at Site 1090 in the late middle Eocene suggests at least shallow flow through Drake Passage, which may have been transferred to the deep ocean through ventilation processes. Shallow flow at this time is also supported by productivity records. Another rapid increase in $\varepsilon_{Nd(T)}$ occurs at ~28.5 Ma, resulting in values of -6. The timing of this increase coincides with estimates for a deep opening (Lawver and Gahagan, 2003) and an increase in biogenic silica deposition. Thus, the late Oligocene increase may represent opening of Drake Passage to deep-water flow and establishment of a surface-to-deep Antarctic Circumpolar Current. Trends observed at intermediate depths (Site 689) are distinct, but also support the presence of Pacific waters by 37 Ma. This interpretation of the Nd data suggests that at least surface flow was established at Drake Passage prior to the development of large ice sheets on Antarctica.

Neodymium isotopic evidence for Tethys derived Warm Saline Deep Water

Howie D. Scher and Ellen E. Martin
Department of Geological Sciences, University of Florida

Evidence for production and export of Warm Saline Deep Water (WSDW) to southern high latitudes during the Paleogene is equivocal and widely debated. The strongest support for this theory comes from discrete intervals of benthic $\delta^{18}O$ inversions between vertically offset sites on Maud Rise, ODP Sites 689 and 690, interpreted as temperature inversions. Nd isotopes in fossil fish teeth reflect water mass mixing and are unaffected by changes in temperature, salinity, nutrients, or productivity. We present Nd isotope records for Sites 689 and 690 from the middle Eocene to the late Oligocene that have been correlated by Sr isotope chemostratigraphy. Nd isotope data indicate the incursion of a distinct water mass at depth during the middle and late Eocene, and portions of the Oligocene. During these intervals ε_{Nd} values at site 690 are 1 ε_{Nd} unit less radiogenic than at site 689, reaching minimum values of -9.3 to -10. ε_{Nd} minima at site 690 coincide with $\delta^{18}O$ inversions and are too nonradiogenic to reflect seawater derived from a Southern Ocean source. The Maud Rise Nd isotope data is best explained by the export of Tethys sourced WSDW to the Southern Ocean. Authigenic shelf deposits from obducted Tethys margin sediments indicate that shallow Tethys seawater had ε_{Nd} values of -9.2 to -9.7, suggesting that deeper waters were less radiogenic. The pulsed export of WSDW to the Southern Ocean from a low latitude source accounts for the coincidence of ε_{Nd} minima at Site 690 with $\delta^{18}O$ inversions between Sites 689 and 690.

Late Cenozoic warm events; Southern Ocean and elsewhere

Lloyd Burckle and Stephen Barker, LDEO, Palisades, New York 10964

The modern Polar Front Zone (PFZ) in the Southern Ocean is marked by a transition from low (to the south) to high $CaCO_3$ content in surface sediments. During the Last Glacial Maximum (LGM) this boundary shifted north by up to 6º latitude in the Atlantic sector of the Southern Ocean and less so in the Indian and Pacific Oceans. We suggest that this represents a displacement of surface water isotherms and argue that $\%CaCO_3$ in sediments may be used as an index of paleotemperature in the Southern Ocean. We demonstrate the utility of this approach by focussing on peaks in $CaCO_3$ observed south of the modern PFZ throughout the Cenozoic. Examples include an event just below the Jaramillo magnetic subchron thought to be synchronous with Marine Isotope Stage 31, possibly the warmest period of the Pleistocene (Froelich *et al.*, 1991). Four distinct $CaCO_3$ peaks occur between the Thvera and Sidujfall magnetic subchron (4.40-4.47 myBP) of the Gilbert chron (early Pliocene). Within the mid to late-Pleistocene, high $CaCO_3$ accumulation in the Southern Ocean during MIS 11 is contemporaneous with increased $CaCO_3$ accumulation at low and northern high latitudes and a simultaneous decrease in global $CaCO_3$ preservation (i.e. the Mid-Brunhes Dissolution Interval, MBDI). This interval is also marked by the global proliferation of *Gephyrocapsa* sp (coccolithophorid), a possible candidate for explaining such an increase in pelagic $CaCO_3$ production.

Late glacial to Holocene climatic and oceanographic record of sediment facies from the southern Scotia Sea off the northern Antarctic Peninsula

H. I. Yoon, B.-K. Park, Y. Kim, and K. C. Yoo

Polar Research Institute, Korea Ocean Research & Development Institute, Ansan P.O. Box 29, Seoul 425-600, South Korea

Two gravity cores were collected from the southern Scotia Sea during the 13th KARP (Korea Antarctic Research Program) expedition to determine the late Quaternary climatic and oceanographic history of the area. Sedimentologic and geochemical analyses combined with AMS C-14 determination represent the most detailed record of late Pleistocene climatic/oceanographic change, to date in Antarctica. During the Last Glacial Maximum, the southern Scotia Ocean received large amounts of sorted terrigenous sediments emplaced by bottom currents from an extensively glaciated Weddell Sea continental margin. Drifting icebergs calved from the glacial fronts have dispersed glacial sediments over a broad area of the study area. The bottom current deposits in glacial phase comprise two sedimentary facies: (1) bioturbated gravelly mud (Facies II), formed by sluggish bottom current caused by reduced dense water production originated from the ice sheet on the Weddell shelf, (2) indistinctly layered diatomaceous mud (Facies I), deposited by sporadic bottom currents caused by intensified sea-ice formation in polynya during the glacial stage. Deglaciation in the southern Scotia Sea was dated from about 12,500 yr BP until ay least 8,700 yr BP, with increasing TOC, diatom abundance, and decreasing MS value, sand content up core. At this time, subglacial meltwater streams began to emanate from the Weddell Ice Sheet with peak of ice-rafting. Sediment-laden turbid plumes from melting glacier and deglaciated Weddell shelf have probably caused high influx of fine suspended sediments into the realm of contour currents, Weddell Gyre circulation, ultimately forming laminated gravelly mud (Facies III) in the southern Scotia region. These currents probably resulted from water exchange between the Weddell Ice Shelf and Circumpolar Warm Deep Water during the retreating phase of the last glaciation. The deglaciation was probably followed by a period of open marine conditions with variable extent of sea ice (variable TOC content) between 8,700 and 2,400 C-14 yr BP. During this period, bottom water production occasionally appears to have diminished or ceased due to the disintegration of some of the Weddell ice shelf, and biogenic input became increased forming diatomaceous mud and ooze (Facies IV). Around 2,400 yr BP, a decrease in TOC and diatom abundance reflects the formation of more extensive and seasonally persistent multiyear sea ice. The Weddell Ice Shelf, now rapidly retreating, advanced at this time, and as a result, bottom water formed might play a role in transporting terrigenous sediments into the study area, forming diatomaceous sandy mud (Facies V). These results indicate environmental variability throughout the late Quaternary that was consistent across most portions of the maritime Antarctic Peninsula. In addition, the timing of climatic transitions correlates with Northern Hemisphere, indicating the possibility of coherent climatic variability in the late Quaternary, at least for the high latitudes.

FE FLUXES AND TERRIGENOUS PROVENANCE IN THE SOUTHERN OCEAN

Jennifer C. Latimer[1], James D. Gleason[1], Gabriel M. Filippelli[2], Ingrid Hendy[1]

[1] Department of Geological Sciences, University of Michigan, Ann Arbor, MI
[2] Department of Geology and Center for Earth and Environmental Science, Indiana/Purdue University at Indianapolis, Indianapolis, IN

Terrigenous fluxes are important in terms of delivering trace nutrients, particularly iron to the deep sea. Southern Ocean (SO) terrigenous fluxes were higher during glacial intervals compared with interglacial intervals, possibly fueling higher rates of primary productivity. Despite the importance of trace metal delivery, terrigenous provenance and Fe fluxes have not been adequately quantified

Samples from the southeastern Atlantic Ocean (ODP 177) were used to evaluate changes in terrigenous fluxes and provenance to the SO across a range of latitudes (41-53S). Site 1092 (47 S, 1974 m water depth experienced low sedimentation rates and no sediment focusing, making this site ideal for characterizing potential dust inputs. However, the timing and magnitude of change in Fe accumulation rates (FeAR) do not agree with ice core dust records. Maximum FeAR at Site 1092 are >200 umol Fe/cm2/kyr, which is significantly higher than dust flux estimates from ice cores (20-40 umol Fe/cm2/kyr), but low compared to drift sites (1089 and 1094) which have FeAR >20 mmol Fe/cm2/kyr.

To examine potential sediment provenance changes, we used Al/Ti and Fe/Ti ratios from bulk sediment geochemistry as proxies for down core changes in detrital material source. Additionally, we used Sr and Nd isotopes from the northern (1089) and southern (1094) most sites to evaluate terrigenous provenance at the LGM and during the Holocene. The down core elemental ratios suggest significant variability in provenance on glacial/interglacial time scales. The isotope data further supports variable provenance to the south Atlantic, both temporally and with latitude. We suggest the variability in flux and provenance are related to changes in hydrography and hemipelagic sedimentation.

The George V Land Continental Margin (East Antarctica): new Insights Into Bottom Water Production and Quaternary Glacial Processes from the WEGA project

Andrea Caburlotto

The George Vth Land represents the ending of one of the largest subglacial basin (Wilkes Basin) of the East Antarctic Ice Sheet (EAIS). Furthermore, its coastal areas are zone of significant production of High Salinity Shelf Water (HSSW).
Piston and gravity cores and high resolution echo-sounding (3.5 kHz) and Chirp profiles collected in the frame of the joint Australian and Italian WEGA (**W**ilk**E**s Basin **G**l**A**cial History) project provide new insights into the Quaternary history of the EAIS and the HSSW across this margin: from the sediment record filling and draping valleys and banks along the continental shelf, to the continuous sedimentary section of the mound-channel system on the continental rise.

The discovery of a current-lain sediment drift (Mertz Drift, MD) provides clues to understanding the age of the last glacial erosive events, as well as to infer flow-pathways of bottom-water masses changes. The MD shows disrupted, fluted reflectors due to glacial advance during the LGM (Last Glacial Maximum) in shallow water, while undisturbed sediment drift deposited at greater water depth, indicates that during the LGM the ice shelf was floating over the deep sector of the basin.
The main sedimentary environment characterising the modern conditions of the continental rise is dominated by the turbiditic processes with a minor contribution of contour currents action. Nevertheless, some areas (WEGA Channel) are currently characterised by transport and settling of sediment through HSSW, originating in the shelf area. This particular environment likely persisted since pre-LGM times. It could indicate a continuous supply of sedimentary material from HSSW during the most recent both glacial and interglacial cycles. This would be consistent with the results obtained in the continental shelf suggesting that the Ice Sheet was not grounding over some parts of the continental shelf.
Furthermore, the comparison of the studied area with other Antarctic margins indicate that, contrary to what happens on the Antarctic Peninsula margin, the relation between the Quaternary sedimentation and the glacial – interglacial cycles are less evident in the lithofacies observed on the continental rise area. This characteristic suggests a different glacial dynamic along the Wilkes Land continental margin that is less sensitive to the small climatic changes, with respect to the western (Antarctic Peninsula) margin.

Petrographic and isotopic composition of Ross Embayment till

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Ross Embayment LGM till provenance was investigated by comparing the coarse sand composition, as well as the Nd and Sr isotopic composition of East and West Antarctic source areas with till samples from across the Ross Sea. Till samples from beneath the Whillans and Kamb ice streams of West Antarctica and from lateral moraines flanking six East Antarctic outlet glaciers have distinct petrologic signatures. The characteristic assemblage of West Antarctic samples includes felsic intrusive and detrital sedimentary lithic fragments, plagioclase and abundant quartz. In contrast, most East Antarctic till samples contain abundant mafic intrusive and detrital sedimentary lithic fragments as well as less abundant quartz. The distinctive composition of these source areas can be linked to thirty-three samples from cores of LGM till distributed across the Ross Sea. Western Ross Sea till samples exhibit mineralogic and lithological similarities to East Antarctic till samples, although these western Ross Sea tills contain higher percentages of felsic intrusive, detrital sedimentary and extrusive volcanic lithic fragments. Eastern Ross Sea till samples are compositionally similar to West Antarctic till, particularly in their dearth of mafic and extrusive volcanic components. Central Ross Sea till

exhibits compositional similarities to both East and West Antarctic source terranes, marking the confluence of the East and West Antarctic Ice Sheets during the LGM.

Distinct East and West Antarctic signatures are also apparent in the Nd and Sr isotopic data from <63μm till fractions, with East Antarctic still showing substantial variation in ε_{Nd} values. Samples from the Darwin Glacier area show the lowest ε_{Nd} values (-15), reflecting the presence of reworked Archean rocks, whereas the Beardmore Glacier tills have high values (-6) indicative of the Cambro-Ordovician granitic rocks. The isotopic data also show distinct fingerprints for the western, central and eastern Ross Sea tills. Samples from the eastern Ross Sea have Nd and Sr isotopic compositions equivalent to tills from West Antarctica. In the western Ross Sea, the sampled tills have high ε_{Nd} values (-4 to –7) perhaps reflecting the incorporation of material eroded from the Ferrar igneous province. Tills from the central Ross Sea, however, have ε_{Nd} values ranging from -7 to –12.5, with tills from the western margin of the central trough have distinctly lower ε_{Nd} values than those from the eastern margin (-9 to –12.5 vs. –7 to –8). These data indicate that tills from the central Ross Sea trough margin may contain a component of both East and West Antarctic derived till.

Middle Miocene Antarctic cryosphere development: Results from Southern Ocean benthic foraminifer Mg/Ca

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Abstract

A benthic foraminifer Mg/Ca-derived bottom water temperature record has been produced for the ~17 to 13.5 Ma interval. This record indicates that Southern Ocean bottom waters cooled 2.1°C across the ~1‰ oxygen isotope ($\delta^{18}O$) increase at ~14 Ma. A record of Antarctic ice volume ($\delta^{18}O_{sw}$) generated from benthic foraminifer Mg/Ca and $\delta^{18}O$ records suggests that a majority of the global $\delta^{18}O$ increase relates to Antarctic ice growth and that this event was the third and final in a series of ice growth events beginning at ~15 Ma. Comparison of ice volume, bottom water, and surface water temperature records indicates that Antarctic ice growth occurred when bottom and surface water temperatures were relatively warm. This relationship suggests that Antarctic ice sheets were sensitive to changes in meridional moisture flux during an interval of inferred low atmospheric pCO_2.

Title: Milankovitch Forcing at the Eocene/Oligocene Climate Transition from Benthic Foraminiferal Isotope Analysis

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A critical component missing from our knowledge of Antarctic cryosphere evolution is a comprehensive understanding of the role of orbital forcing in ice sheet development during the Eocene/Oligocene climate transition. Existing marine records lack the resolution and preservation to reconstruct variability in the high-frequency precessional band, thought to be potentially significant in early Oligocene ice sheet development and stability. A new E/O boundary section from Ocean Drilling Program Site 1263, on the northwest flank of Walvis Ridge in the eastern South Atlantic Ocean, yields a benthic foraminiferal isotopic record with an average time step of 3.5 kyrs, sufficient to resolve the 19- and 23-ky precessional Milankovitch bands. The E/O boundary at this site is associated with a gradual increase in sediment color lightness (L*), attributed to an increase in carbonate content and accumulation rate and a general improvement in microfossil preservation. The 1263 L* increase is accompanied by an enrichment of ~1.4‰ in $\delta^{18}O$ and ~0.8‰ in $\delta^{13}C$ of bulk carbonate across the 5-meter interval that represents the period between 33.7 and 33.4 Ma. Multiple single-species isotope analyses of *Oridorsalis umbonatus*, *Nuttallides trumpeyi*, and *Cibicidoides spp.* produce consistent isotope values across a series of horizons, however deviation from these patterns observed in some larger specimens may be indicative of reworking. Using smaller specimens, we will present a high-resolution oxygen isotope record across the E/O transition interval in order to evaluate the significance of precessional forcing in early Oligocene glaciation.

Precise correlation of the MIS-31 interglacial from the Antarctic coastal zone to the Southern Ocean and beyond

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The Cape Roberts Project (CRP) recovered marine stratigraphic records from an Antarctic coastal environment in the southwestern Ross Sea, proximal to the East and West Antarctic ice sheets (77°S). Although the target strata were Paleogene, CRP-1 recovered Pleistocene successions including evidence

of an extreme warm event during the late-early Pleistocene. Precise dating by multiple methods constrained deposition of this carbonate-rich sedimentary unit to a single interglacial period, Marine Isotope Stage 31 (MIS-31), which coincides with the base of the Jaramillo paleomagnetic Chron (C1r.1n, 1.072 Ma). Planktonic microfossils in the deposit indicate significantly warmer than present spring and summer surface waters, and a prolonged and dramatic reduction in coastal sea-ice cover. The coincidence of MIS-31 with a palaeomagnetic reversal allows confident global correlation of the event, allowing interhemispheric temporal comparison of sea surface temperature (SST) changes and, possibly, thermohaline circulation. We have now generated new oxygen and carbon isotopic data spanning MIS-31 from planktonic and benthic forams from ODP Leg 177, Site 1094, the southernmost site of that leg, for comparison with CRP-1 and global deep-sea records. High-resolution deep-sea oxygen isotope and other proxy records, including CRP, indicate a complex structure for MIS-31. The warmest part of the interglacial began abruptly, immediately following the Chron C1r.1n reversal in both northern and southern hemisphere records, coincident with the highest northern hemisphere insolation of the last 3 million years. This unusual interglacial may represent a significant step in the transition to late Pleistocene glacial-interglacial cycles.

A highly dynamic Late Neogene East Antarctic Ice Sheet margin: evidence from the Prydz Bay/Prince Charles Mountains region

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While the debate concerning the age and environment of deposition of the Sirius Formation in the Transantarctic Mountains continues, there is convincing evidence in the Prydz Bay-Prince Charles Mountains region for major retreat and advance of the East Antarctic Ice Sheet (EAIS) margin several times during the Late Neogene. *In situ* marine diatom-bearing sediments, sporadically with *in situ* molluscs, show that very large-scale fjordal environments, both ice-proximal and ice-distal, existed up to 300 km south of the present Amery Ice Shelf edge. In addition, several horizons have specific indicators of water temperatures considerably above that in the nearby ocean today. During intervals of retreat, there is no evidence that vegetation took advantage of the opportunity to re-colonise the area.

The implications from these results are that we should not assume that the Ross Sea region is the type area for recording the history of the EAIS and that major data sources lie elsewhere, ready to contribute to resolving the dynamism/stability debate.

It is now critical that alternative scenarios based on the Prydz Bay-Prince Charles Mountains region be tested by geological and geophysical studies onshore in other areas of the margin, and

by drilling and coring offshore from Wilkes Land especially off major outlet glaciers such as Vanderford, Denman, Scott, Mertz and Ninnis Glaciers, where they may show independent evidence of retreat/advance history of the margin of the Wilkes/Pensacola and Aurora Sub-glacial Basins.

Fulfilling the Promise of the DSDP/ODP Legacy with Multiparameter Logging of Archive Cores

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Since 1968, the Deep-Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP) have been storing their recovered sediment and rock cores in purpose-built, refrigerated repositories. Approximately 300 km of core was recovered by DSDP and ODP at an estimated average cost of $2,000,000/km. Half of every core recovered is kept as an archive half, normally only available for viewing (subsampling requires special permissions). Sound archiving policies and storage techniques over the years have ensured that these half cores have remained well preserved for analyses that were not made, or were not technically possible, at the time of recovery. The archive half-cores are well suited for automated non-destructive geophysical measurements ("core logging"), including many of those that provide essential data for reconstructing Earth's climatic history, such as high-resolution magnetic susceptibility, natural gamma spectroscopy, and UV/VIS/IR spectrophotometry. Most of the cores have either not been logged for all the relevant parameters or have not been logged at the spatial intervals necessary for high resolution climatic studies. Consequently, a very large, untapped reservoir of paleoclimatic and other data awaits extraction from these well-preserved archive half-cores.

Recently we used a new Geotek MSCL-XYZ core logger at the IODP West Coast Repository to log archive core halves recovered by D/V Glomar Challenger in 1983. We wished to obtain a high-resolution paleoclimate record for DSDP Site 594, east of New Zealand, Southwest Pacific, to complement the record obtained more recently from nearby ODP Site 1119, cored in 1998. The new MSCL-XYZ system is specifically designed to allow multiparameter, non-destructive geophysical data to be collected easily at high spatial resolutions from archive core halves. Because the data acquisition from archive cores can be slow, either because of the measurement itself or the frequency at which the data is required, the system holds multiple 1.5 m-long core sections (currently up to 9) and can be left to run unattended for hours or days at a time.

We obtained complete data sets of natural gamma, magnetic susceptibility, spectral color and RGB digital line scan images for the top 150m of the sediment column at Site 594 . No useful core log data was previously available for this site. The data set of primary interest was natural gamma, which will be compared with the downhole natural gamma record from Site 1119. To our knowledge this is the first time that a high-resolution natural gamma data log has been recovered from an archive core half. Detailed magnetic susceptibility records were also obtained despite low signal levels, using 10 sec sampling time throughout. The excellent quality of the spectral color and RGB image data, despite the partially ephemeral nature of these properties, is a testament to the core storage techniques employed over 21 years. As core working halves become depleted, pressure is mounting to allow subsampling from the archive core-halves. The community now has the tools necessary to take advantage of what could be a final opportunity to collect continuous geophysical data on ocean cores drilled over the past three decades.

Does the nutrient distribution discrepancy between the Northern Indian Ocean basins during the LGM mean intrusion of Southern Ocean water?

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New isotope and trace element data from one of the marginal seas in the northeastern Indian Ocean, the Andaman Sea, show lower $\delta^{13}C$ values in benthic foraminifera during the Last Glacial Maximum (LGM) than the Holocene.
However data from the western Bay of Bengal show no such difference. A slight gradient in $\delta^{13}C$ values exists between the eastern and western side of the basin. LGM $\delta^{13}C$ values in the Andaman Sea are akin to the $\delta^{13}C$ values of deeper Arabian Sea water. Boyle et al.(1995) have suggested that the deeper Arabian Sea $\delta^{13}C$ values tend to track the $\delta^{13}C$ values of eastern Tropical deepwater. Ahmad and Labeyrie (1994) reported a $\delta^{13}C$ DIC gradient of 0.3-04 (‰) between the LGM and Holocene from the Arabian Sea suggesting their Antarctic origin (i.e., low, depleted ^{13}C values). Our new $\delta^{13}C$ data from the Bay of Bengal questions this interpretation.

Magnetostratigraphic highlights of ODP Legs in the Southern Oceans.

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Leg 182, in the Great Australian Bight, Leg 189 around Tasmania, and Leg 194 off the Great Barrier Reef on the Marion plateau, all involved major carbonate sections that tested the magnetic instrumentation on the JOIDES Resolution. The principal highlights of the magnetostratigraphy of these legs were (1) the discovery during Leg 182 of an extended Brunhes section of carbonates in the Great Australian Bight that was hundreds of meters thick and use of high resolution magnetostratigraphy within this section to resolve dating to better than a few thousand years, (2) documentation in Hole 1172 of Leg 189 of the timing of the transition from "Greenhouse" to "Icehouse" with the rapid deepening of the Tasmanian Gateway. (3) acquisition of records from Sites 1193, 1194 and 1195 of Leg 194 gave ages for the sequence boundary at each site consistent with biostratigraphy, which was used to evaluate the late middle Miocene eustatic sea level fall. These examples demonstrate the ability to establish reliable magnetostratigraphy in carbonate sections

Two Highly-Resolved Geochemical Records of Holocene Variability: A Comparison Between West Antarctica and East Antarctica

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Based on results from Ocean Drilling Project Site 1098 in the Palmer Deep, we have a highly resolved record of West Antarctic Holocene climate evolution as traced by terrigenous provenance, terrigenous accumulation, nutrient utilization, and surface and export production. To date, there are few comparable records from the East Antarctic Margin despite its critical role in deep ocean circulation. Here we compare results from a 25 meter core recovered from Iceberg Alley on the MacRobertson shelf of East Antarctica with the results from the Palmer Deep, West Antarctica. Both cores are characterized as laminated diatomaceous muds comprising a two-component system of biogenic opal and terrigenous material. Both of these sedimentary sequences span the Holocene and capture the termination of the deglaciation event at 10kyr. The geochemical parameters we used to characterize these sediments include XRF scanned and discrete ICP-ES major and trace element analyses and their associated ratios, biogenic opal, and carbon and nitrogen isotopes.

The Palmer Deep geochemical records are strongly delineated between the Holocene Climate Optimum (HCO) and the Neoglacial. Specifically, both surface and export production are elevated through the HCO, which is indicative if a warmer period. Additionally, the terrigenous provenance record of Al/Ti shows that the source of sediment to the basin during the HCO was different than during the Neoglacial. In contrast, the Iceberg Alley record does not show a difference between the HCO and the Neoglacial. Rather, there are high-frequency changes that

appear to vary over an unchanged average throughout the Holocene. Why the Iceberg Alley records do not reflect the same structure exhibited in the Palmer Deep records remains to be determined.

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Laura de Santis

The George Vth Land represents the ending of one of the largest subglacial basin (Wilkes Basin) of the East Antarctic Ice Sheet (EAIS). Furthermore, its coastal areas are zone of significant production of High Salinity Shelf Water (HSSW).

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Furthermore, the comparison of the studied area with other Antarctic margins indicate that, contrary to what happens on the Antarctic Peninsula margin, the relation between the Quaternary sedimentation and the glacial – interglacial cycles are less evident in the lithofacies observed on the continental rise area. This characteristic suggests a different glacial dynamic along the Wilkes Land continental margin that is less sensitive to the small climatic changes, with respect to the western (Antarctic Peninsula) margin.

Late Neogene (0 to 9 Ma) interbasinal and vertical benthic $\delta^{13}C$ gradients in the Atlantic sector of the Southern Ocean

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Carbon isotope records from sites 982 (North Atlantic), 1090/704 (Southern Ocean), and 849 (deep Pacific) were used to estimate inter-ocean $\delta^{13}C$ gradients for the last 9 myr. Vertical $\delta^{13}C$ gradients were reconstructed by comparing records along a depth transect in the South Atlantic including Sites 1088 (2093 m), 704 (2532 m) and 1090 (3709 m). During the last 9 Ma, benthic $\delta^{13}C$ values of deep-water in the Southern Ocean decreased in a series of steps away from the North Atlantic and toward the Pacific endmember, eventually surpassing deep Pacific values during glacial periods of the late Pleistocene. Abrupt changes in deep-water ventilation occurred at ~6.6, 2.7, and 1.5 Ma. At the same time, the benthic $\delta^{13}C$ of intermediate water in the Atlantic sector of the Southern Ocean evolved differently from deep waters, resulting in an increase in the intermediate-to-deep $\delta^{13}C$ gradient ($\Delta^{13}C$). The $\Delta^{13}C$ increased in steps at ~2.7 and 1.5 Ma documenting the development of a chemical divide in the Atlantic sector of the Southern Ocean between well-ventilated water above ~2500 m and poorly ventilated water below. We suggest these changes in interbasinal and vertical gradients were the result of both decreasing Northern Component Water, and increasing sea ice cover and stratification of Antarctic surface waters during the late Neogene. Because Antarctic surface water processes and deep-water ventilation rates ultimately influence the CO_2 composition of the atmosphere, these processes would have acted as a positive feedback to late Neogene climate cooling.

Notes